



Geochemical shifts, ecological consequences, and onset of meromixis in a mine water impacted boreal lake

Karoliina Kehusmaa · Mira Tammelin ·
Tommi Kauppila · Peter Österholm · Saija Saarni

Received: 28 May 2025 / Revised: 1 October 2025 / Accepted: 11 November 2025
© The Author(s) 2025

Abstract Mine waters are often severely detrimental to nearby waterbodies and can even disturb the circulation regime of a lake. We investigated the recent sediment record of a small, presently meromictic lake, which receives sulphate and metal-rich waters from a closed polymetal mine. We wanted to examine the overall impacts of mining on the lake and detect the onset and development of meromixis. Our hypothesis was that the loading from the mine would lead to notable geochemical and palaeoecological changes, and that we could identify the shift in the circulation regime using multiple proxies. We cored the deepest part of the lake and obtained discrete samples for the geochemical and diatom analyses. We detected clear shifts corresponding to the periods before, during, and after mining in the main proxies. Sulphur and metalloids associated with acid mine drainage

increased during mining, and the dominant cyclotelloid species changed in the diatom assemblage. The onset of meromixis seems to have occurred during the closure of the mine in late 1980s as the redox conditions in the tailings changed. Our findings highlight the impacts of saline mine waters on lake circulation, and the wide-ranging consequences of releasing mine waters into the aquatic environment.

Keywords Palaeolimnology · Mine environment · Diatoms · Stratification · Sulphate

Introduction

The global demand for minerals is growing significantly as governments and businesses aim to reduce their greenhouse gas emissions (e.g. IEA, 2021). Growing concern over supply chain risks has led the European Union to adopt the Critical Raw Materials (CRM) Act, which aims to increase and streamline the production of several minerals in the EU (European Commission, 2023). Finland has had a strong mining sector for centuries, with several metal mines in or nearly in operation and numerous companies prospecting for potential mine sites at present (Vasara et al., 2023). However, mining activities can also be a significant point source of contaminants particularly for the aquatic environment. These contaminants can be metals, salts, and chemicals used in mining processes, and their effects can persist long after mining

Handling Editor: Jasmine Saros.

K. Kehusmaa (✉) · M. Tammelin · S. Saarni
Department of Geography and Geology, University
of Turku, 20014 Turku, Finland
e-mail: kskehu@utu.fi

M. Tammelin
Finnish Environment Institute, Helsinki, Finland

T. Kauppila
Geological Survey of Finland, Kuopio, Finland

P. Österholm
Geology and Mineralogy, Åbo Akademi University, Turku,
Finland

operations have ceased (e.g. Ek and Renberg, 2001; Salonen et al., 2006; Fischer et al., 2020). In addition to the environmental impacts of active mines, 32 closed or abandoned mines with potentially harmful drainage waters or acid-producing wastes have been identified in Finland (Tornivaara et al., 2018).

Lakes can be classified as holomictic or meromictic depending on whether the waters circulate or not (Hakala, 2004). In the boreal climate zone, lakes are typically dimictic, a type of holomictic which means that the water column circulates during spring and autumn and is thermally stratified during summer and winter (Wetzel, 2001). Saline, dense mine waters can disturb this circulation pattern and lead to meromixis, where the water column is separated into two layers of different density by a chemical gradient (Moncur et al., 2006; Boehrer & Schultze, 2008; Kehusmaa et al., 2023). In a meromictic lake, only the upper layer (mixolimnion) circulates, while the bottom layer (monimolimnion) is isolated from the atmosphere and turns anoxic, consequently accumulating substances in chemically reduced form from the mixolimnion (Boehrer et al., 2017). Mine pit lakes sometimes turn or are purposefully made meromictic (Schultze et al., 2017), but natural lakes whose mixing regime has been disturbed due to mine waters are poorly documented. Meromixis caused by high-electrolyte mine waters can be considered a part of the emerging threat of freshwater salinisation, which affects different freshwater habitats worldwide with potentially serious ecological and economic consequences (e.g. Kaushal et al. 2021; Cunillera-Montcusí et al. 2022).

Long-term monitoring data from lakes are often lacking, but the reference conditions of a lake, the impacts of mining, and potential recovery since the cessation of mining can be investigated from lake sediments with a palaeolimnological multi-proxy approach (Smol, 2010, 2019; Bennion et al., 2011). The anoxic conditions of the bottom water in meromictic lakes prevent biogenic disturbance of the sediment, which makes meromictic lakes ideal palaeolimnological archives, particularly if the lake accumulates seasonal laminae (Zolitschka et al., 2015). The mining of sulphide ores often results in acid mine drainage (AMD), which can be observed as elevated concentrations of toxic substances such as sulphur and trace metals in lake sediment (Salonen et al., 2006; Blowes et al., 2014; Moncur et al., 2014; Sivarajah et al., 2019) and can potentially lead to

eutrophication in the lake through disturbances in the phosphorus cycling (Caraco et al., 1989; Lamers et al., 2002).

In addition to chemical and physical properties, lake sediment records preserve biological remains that can be used as proxies when investigating past environmental changes. Diatoms (class *Bacillariophyceae*) are a large group of unicellular microalgae commonly used in palaeolimnological studies (e.g. Battarbee et al. 2001; Smol and Stoermer 2010). They are species-rich and are found ubiquitously in aquatic environments around the world. Differentiation between species is based on the morphology of their siliceous cell walls (frustules) which preserve well in sediments. Different species have different environmental tolerances and optima, which makes the study of diatom species assemblages and their shifts attractive when investigating the past water quality of a lake (e.g. Duda et al. 2023; Stenger-Kovács et al. 2023).

In this study, we investigate the recent sediment record of the presently meromictic Valkeinen located near the closed Kotalahti Ni-Cu mine. We aim to identify and assess the impacts of the mine on the lake, with a particular focus on detecting the onset and development of meromixis in the sediment record. Combining diatoms with geochemical proxies, such as downcore element concentrations, accompanied with a reliable dating of the sediments, gives us a comprehensive view of the pre-mining, active mining, and post-mining conditions of the lake ecosystem. We hypothesise that the lake was previously holomictic, and that the diatom species assemblages and sediment geochemistry both reflect the mine associated phases, but they, and the onset of meromixis, can be identified more reliably with a combination of these proxies than by using either proxy alone.

Materials and methods

Study site

Valkeinen is a small headwater lake situated in Eastern Finland (Fig. 1). Annual mean air temperature in the area is +3.7 °C, and annual mean precipitation is 611 mm (Finnish Meteorological Institute 2021). The lake has a catchment area of 0.93 km² and a

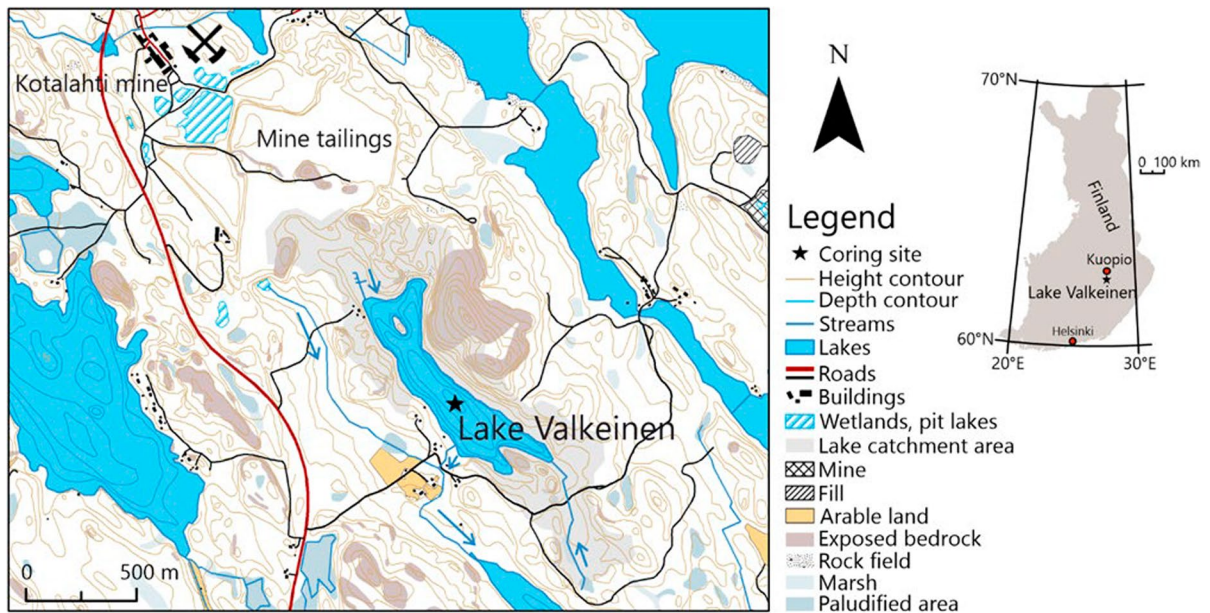


Fig. 1 Map of Valkeinen and Kotalahti mine. White areas are forested. Data obtained from the National Land Survey of Finland topographic database 04/2018 (CC BY 4.0) and the Finnish Environment Institute (2014a)

maximum depth of 16 m (Finnish Environment Institute 2014a, 2014b). The catchment is mostly forests and semi-natural areas (77%) and inland waters (21%) (Finnish Environment Institute 2014b). Valkeinen is presently meromictic, with a chemocline at ca. 8 m water depth. The lake water is circumneutral, with slightly lower pH in the monimolimnion. Electrical conductivity is ca. $500\text{--}600\ \mu\text{S cm}^{-1}$ in the mixolimnion and ca. $600\text{--}700\ \mu\text{S cm}^{-1}$ in the non-circulating monimolimnion. Temperature fluctuates seasonally in the mixolimnion, while the monimolimnion is thermally stable at ca. $4\ ^\circ\text{C}$. The present water quality of the lake is described in more detail in Kehusmaa et al. (2023).

Valkeinen receives water from the closed Kotalahti Ni-Cu mine as surface runoff (Fig. 2). According to Turunen et al. (1960), there has been small-scale industrial activity in the Kotalahti area preceding the mine at least from the beginning of the nineteenth century, first a flour mill, and later a sawmill. The ore deposit was discovered in 1954, the mine and related buildings were constructed in 1957–1959, and the mine was in operation from 1959 to 1987 (Turunen et al., 1960). The ore deposit was in a Sve-cokarelian (ca. 1877 Ma) ultramafic–mafic intrusive complex, and the main ore minerals were pyrrhotite,

pentlandite, chalcopyrite, and pyrite (Papunen & Koskinen, 1985). The ore contained on average 0.66% Ni, 0.26% Cu, and 3.76% S (Puustinen, 2003) and was mined from three underground mines and two open pit mines to the north-west of Valkeinen (Räisänen et al., 2015). One of the open pit mines was filled with tailings waste after a cave-in during the operation. The underground mine was deepened in 1971 from the 250 m level to 600 m level (Papunen & Koskinen, 1985), and during the last years of active mining the exceptionally sulphide and Ni-rich “Jussi” orebody located under the tailings area was exploited (Puustinen et al., 1995). In total, 13.7 Mt of rock was mined, and the 75 ha tailings area contains 9.4 Mt of material (Räisänen et al., 2015).

After mining ceased, the underground mines were flooded with surface water and sulphate-reducing bacteria were used to decrease metal concentrations in the overflow water (Vestola & Mroueh, 2008). The tailings area was covered with soil to revegetate the area (Räisänen et al., 2015). Most of the waters from the tailings area flow north, first to wetland basins, then to a treatment plant, before being piped to Oravilahti, a bigger waterbody north-east of Valkeinen (ISAVI 2014). Seepage waters from the tailings area have near-neutral pH and contain

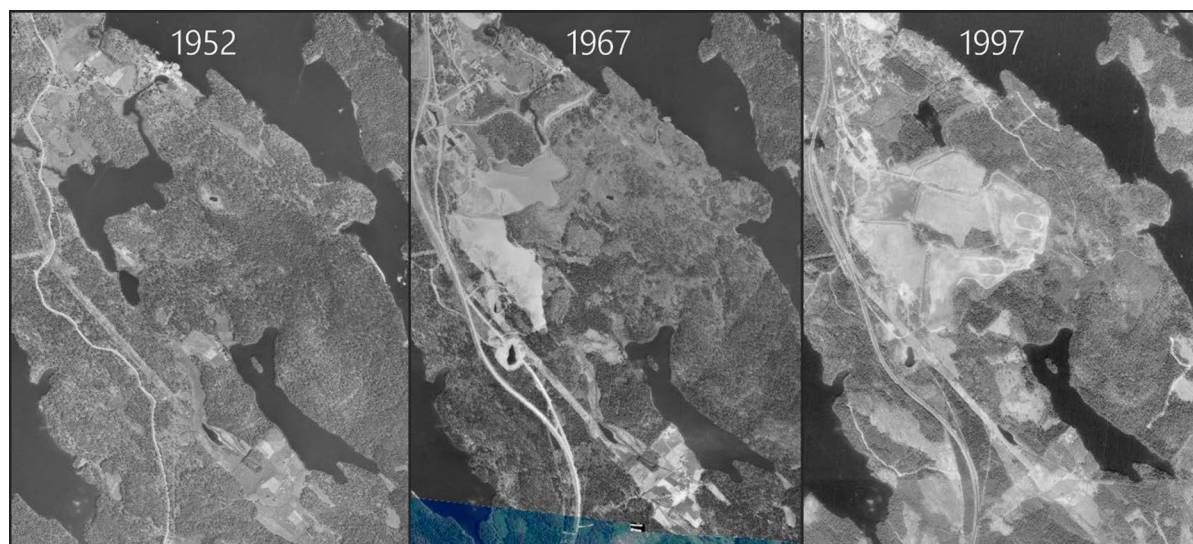


Fig. 2 Aerial photographs of Valkeinen and the Kotalahti area before mining (1952), during mining (1967), and after mining (1997). Photographs obtained from the geodata portal Paikkatietoikkuna of the National Land Survey of Finland (CC BY 4.0)

on average $3000 \text{ mg L}^{-1} \text{ SO}_4$, and $1600 \text{ } \mu\text{g L}^{-1} \text{ Ni}$, whereas Cu concentrations are low (Kauppila & Räsänen, 2015).

Sediment coring and analyses

The deepest part of Valkeinen was cored in February 2018 through ice. The surface sediment was cored using a HTH gravity corer (Renberg & Hansson, 2008), and 1-cm subsamples were extruded into plastic bags in the field. The 1-cm subsamples were stored in a freezer at $-18 \text{ }^\circ\text{C}$ until further processing. For ^{137}Cs dating and geochemical analyses, the frozen subsamples were melted and $\sim 30 \text{ g}$ of homogenised wet sample was measured to resealable plastic bags. A small amount of the remaining subsample was transferred to 15 ml plastic centrifuge tubes to be used for subfossil diatom assemblage analyses.

The ^{137}Cs dating was done at the Geophysical Laboratory of the Geological Survey of Finland. The laboratory conducts measurements within Pb shielding using a multichannel gamma-ray spectrometer (Brightspec) with NaI(Tl) scintillation detector. Lakes in Southern Finland and Sweden often show a pronounced ^{137}Cs peak originating from the fallout of the 1986 Chernobyl accident which can mask the peak of the 1963 nuclear bomb tests (e.g. Klaminder et al., 2012; Ojala et al., 2017; Appleby et al., 2023).

Although the ^{137}Cs dates are of limited use beyond these peaks, they have been used as the sole dating method in studies focusing on recent events (e.g. Parviainen et al., 2012; Vähäkuopus et al., 2020). As the active years of the Kotalahti mine coincide with the ^{137}Cs peaks, and there was no need for exact chronology for the pre-mining sediment, the ^{137}Cs approach was deemed a suitable dating method. The chronology of the sediment record was extrapolated from the two dates obtained from the ^{137}Cs activity, although the identification of the 1963 peak was more uncertain.

Diatom slides were prepared according to the procedure of Battarbee et al. (2001). At least 300 diatom valves were identified to species level from selected samples ($n=20$) with an optical microscope at $1000\times$ final magnification. The floras of Krammer & Lange-Bertalot (1986, 1988, 1991a, b), Krammer (1992), Lange-Bertalot & Moser (1994), and Houk (2003) were used for species identification. The databases of Porter (2008), Spaulding et al. (2021), and Guiry & Guiry (2025) were used for updated nomenclature. Chrysophyte cysts were also counted from the same views as diatoms to obtain the ratio of diatom frustules to chrysophytes (Smol, 1985; Werner & Smol, 2005).

Individual rarefaction was used to normalise taxonomical richness between samples (Birks & Line,

1992; Spellerberg & Fedor, 2003). Rarefaction was calculated with PAST software version 3.21 (Hammer et al., 2001), and C2 software version 1.7.7 (Juggins, 2007) was used for plotting the diatom stratigraphy. The diatom species turnover, i.e. gradient length, was analysed using detrended correspondence analysis (DCA; Hill & Gauch Jr. 1980) using detrending by segments and without downweighting of rare species (Birks, 2010). Based on the moderate gradient length, variation within the diatom samples was further explored with correspondence analysis (CA, Hill 1973). Rare species were downweighted in this analysis, and the geochemical data were passively plotted on the ordination diagram as supplementary data. The multivariate ordinations were performed on square root-transformed diatom data using CANOCO software version 4.56 and CanoDraw version 4.14 (ter Braak & Šmilauer, 2002). All taxa were included in statistical analyses, but only taxa with a relative abundance of over 3% in any sample were included in the stratigraphical and ordination plots.

For geochemical analysis, the subsamples ($n=20$) were sent to the accredited external laboratory Eurofins Environment Testing Finland Oy (SFS-EN ISO/IEC 17025:2017). The topmost diatom sample 1–2 cm was substituted for the 2–3 cm sample for geochemical analysis due to insufficient sediment material. The samples were freeze-dried and then analysed

with inductively coupled plasma optical emission (ICP-OES) and inductively coupled plasma mass spectrometry (ICP-MS) after microwave-assisted nitric acid (HNO_3) digestion according to the U.S. Environmental Protection Agency method 3051A (USEPA, 2007). A total of 33 elements, of which 15 were selected for further consideration, were analysed from the sediment samples. The accuracy and precision of the results was assessed with a blank sample, a certified reference material (SRM 1573a—Tomato Leaves), and a replicate sample (Table 1). Molar ratios of Mn/Fe and S/Fe were calculated to obtain additional information about the redox conditions in the sediment (Makri et al., 2021; Rothe et al., 2015), and K/Zn was used as a proxy of industrial pollution (Salminen et al., 2021).

Results

Sediment characteristics and dating

The sediment of Valkeinen was mainly brown organic-rich mud (gyttja). The top part of the sediment core was black and had a sulphidic smell, with occasional lighter horizontal layers. From ca. 20 cm downwards, the sediment was brownish, with occasional darker possibly sulphidic layers. A clear

Table 1 The results of the laboratory quality control tests for the geochemical analysis. Accuracy was assessed with a blank sample, a certified reference material (CRM), and precision with a replicate sample. All measurements in mg kg^{-1}

Element	Blank sample	CRM (Tomato Leaves)	Original sample (39–40 cm)	Replicate sample (39–40 cm)
Al	<15	212	18,200	18,400
Ca	<50	46,900	6230	6430
Mg	<10	10,700	3150	3160
K	<50	26,600	1390	1520
Na	<50	108	219	240
P	<20	1940	9820	9840
As	<0.03	0.104	2.8	2.91
Fe	<50	284	60,800	60,600
Mn	<1	222	2700	2690
Ti	<2	2.5	477	510
S	<20	9030	6840	6700
Co	<0.05	0.54	13.3	13.9
Cu	<0.3	4	43.1	44.8
Ni	<0.3	1.3	38.4	40.9
Zn	<1	24.4	60.8	60.2

marker horizon for the age of the sediment sequence was detected from the ^{137}Cs analysis (Fig. 3a). The prominent peak (877 Bq kg^{-1}) in the ^{137}Cs concentration at sediment depth 8–9 cm represented the Chernobyl nuclear accident of the year 1986, and the slightly elevated values at 15–19 cm sediment depth were possibly related to the nuclear weapons tests of the 1950s and 1960s. The elevated activity of 15 cm sediment depth was dated to the year 1963 (Fig. 3a, Klaminder et al. 2012). Based on the ^{137}Cs analysis, the linear accumulation rate (LAR) of sediment in Valkeinen was ca. 2.6 mm year^{-1} for the top part (0–9 cm) and ca. 3 mm year^{-1} for the 9–15 cm part. The 3 mm year^{-1} accumulation rate was also used for the bottom part of the sediment sequence. The active mining phase of 1957 to 1987 was therefore at sediment depth 8–16 cm, and, according to the LAR, the bottom samples represented the late nineteenth century (Fig. 3b). The exact dates below the 1986 horizon were, however, uncertain due to possible post-depositional changes in the ^{137}Cs record.

Sediment geochemistry

The concentrations of most elements of interest (Al, Ca, Mg, K, Na, P, As, Fe, Mn, Ti, S, Co, Cu, Ni, Zn) and element molar ratios (Mn/Fe, S/Fe, K/Zn) were quite stable in the pre-mining bottom half of the sediment sequence (Figs. 4, 5). From sediment depth 19 cm to 8 cm, typical mining-related elements such as S, Co, Ni, Zn, and, to a lesser degree, Cu, increased, while silicate-derived Ti and Al decreased. Ni and Co showed prominent peaks at 8 cm sediment depth. In the top 7 cm of the sediment sequence, most of the mining-related elements decreased, while silicate-derived Ti, Ca, Mg, K, and Na increased, some particularly at depth 5 cm. P concentration was similar to Ti but increased in the two topmost samples. Redox-sensitive Fe and Mn exhibited rather similar trends in concentration from the bottom until the depth of 17 cm, after which their concentrations shifted to opposite trends. Mn/Fe and S/Fe ratios likewise increased from sediment depth 19 cm towards the top, until a

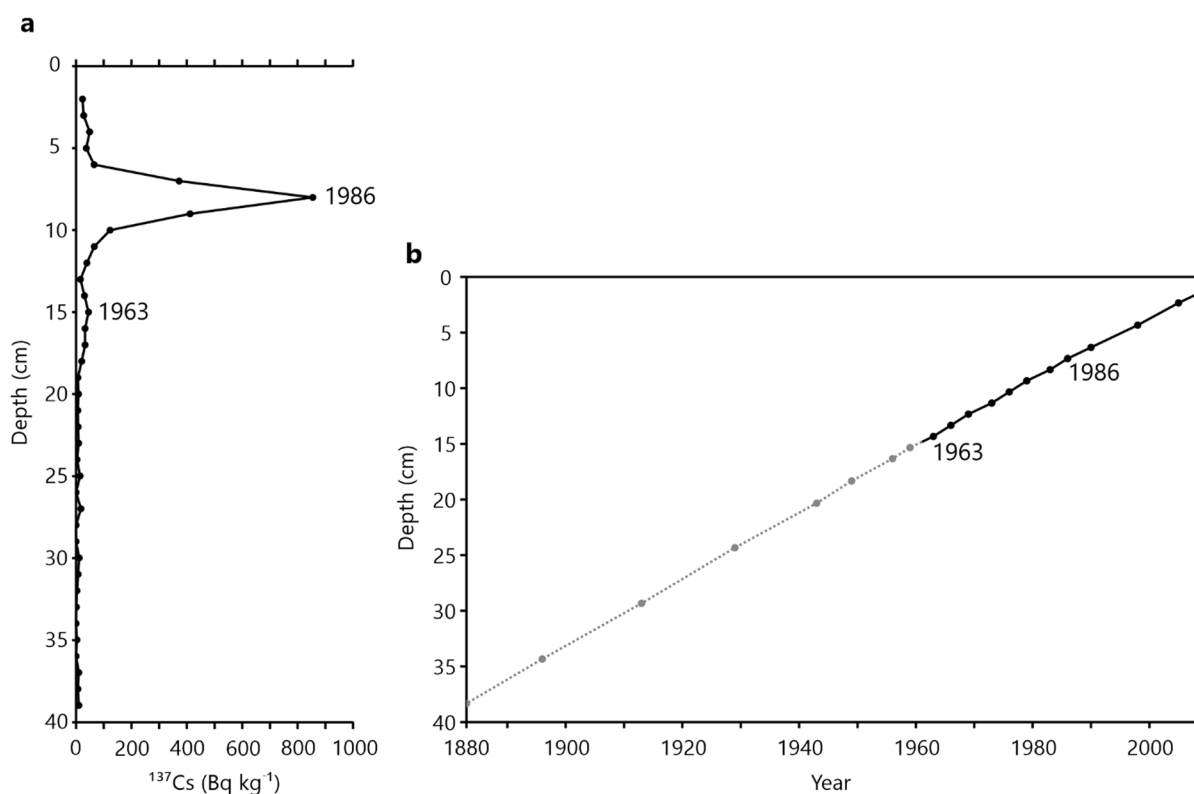


Fig. 3 **a** ^{137}Cs concentration of short core discrete samples, **b** age-depth model of the core. The grey dashed line indicates more uncertain dates

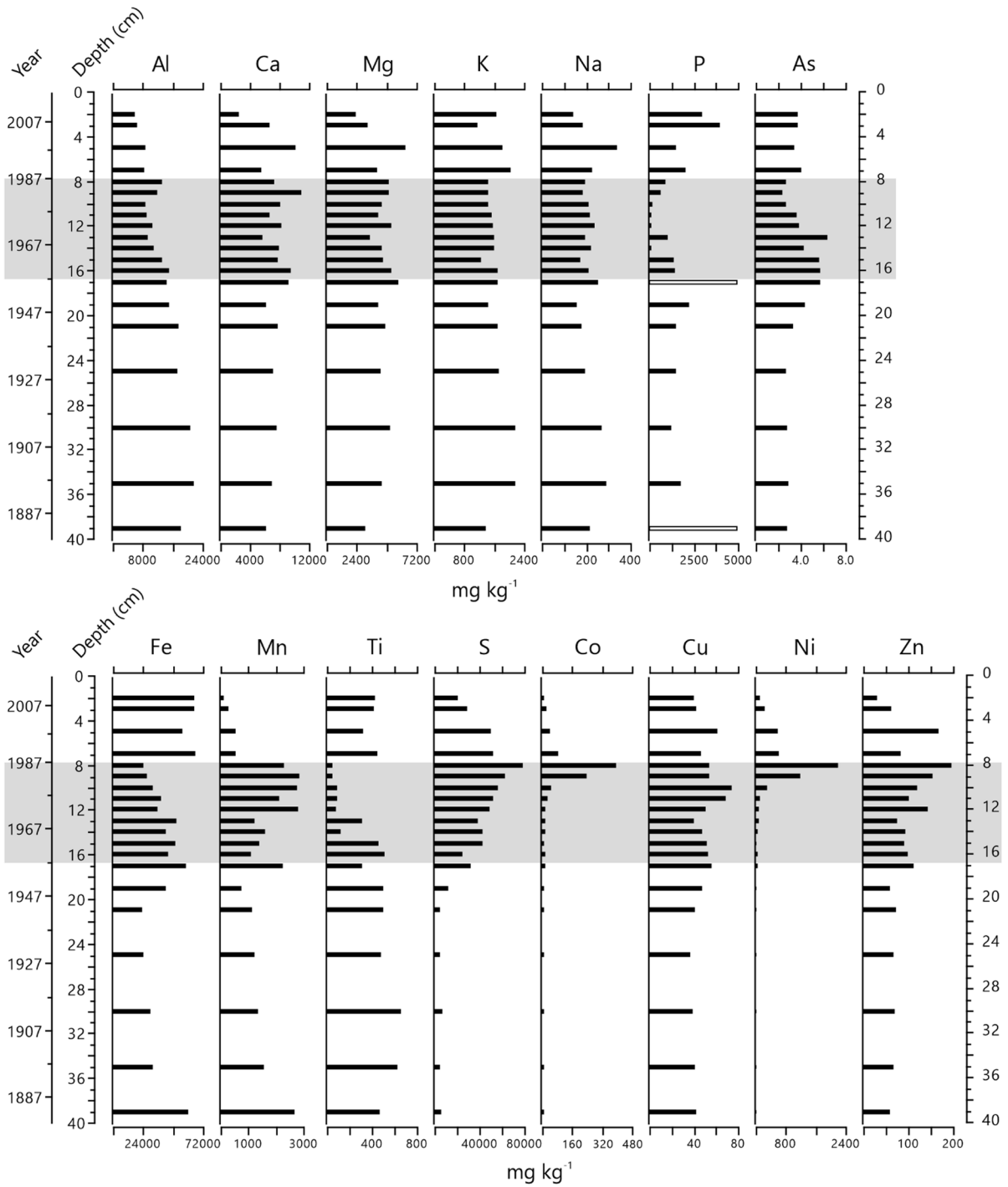
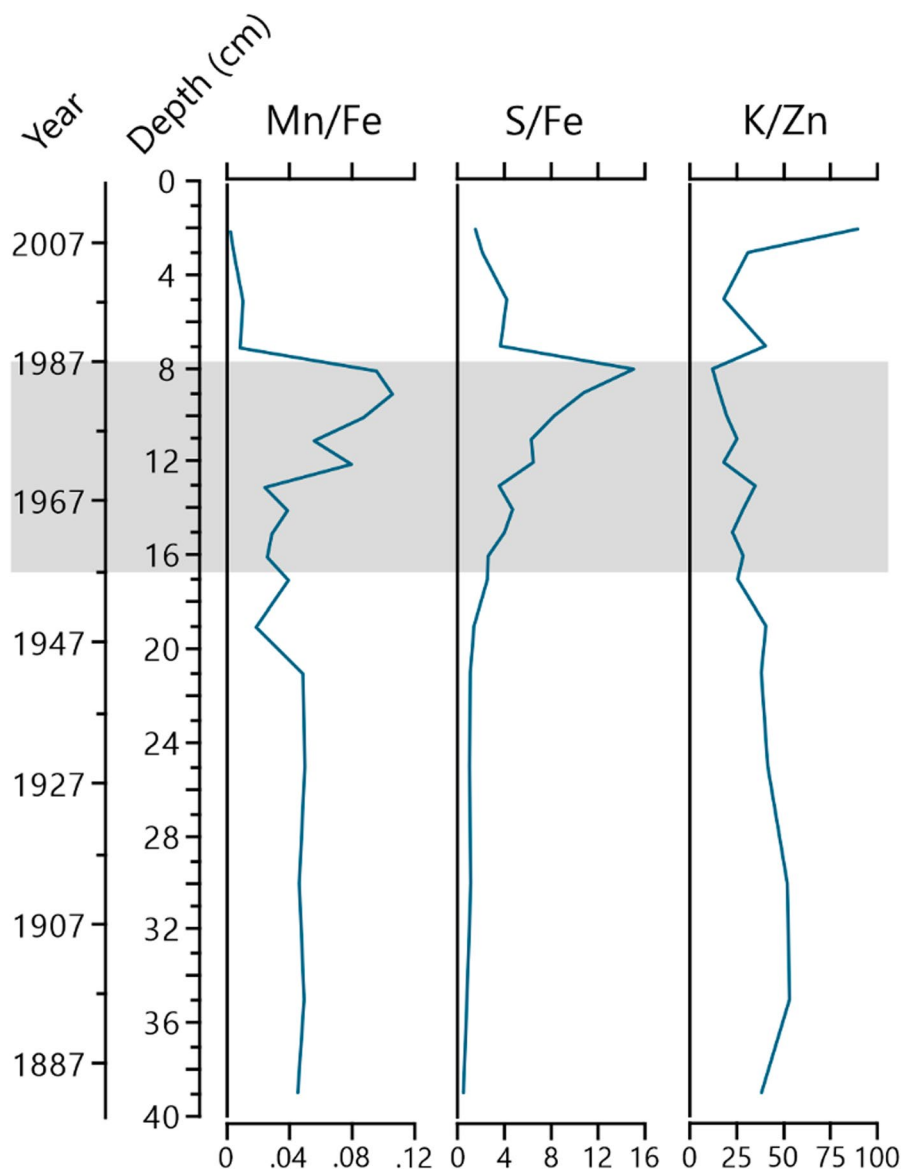


Fig. 4 Selected element concentrations of short core discrete samples. The x-axis for P concentrations is cut off at 5000 mg kg⁻¹, and the samples with no fill exceed it (sample 17–18 cm

5060 mg kg⁻¹ P, sample 39–40 cm 9820 mg kg⁻¹ P). Samples with darker background indicate active mining. Age is calculated from the linear accumulation rate (LAR) of sediment

Fig. 5 Element molar ratios Mn/Fe, S/Fe, and K/Zn. Samples with darker background indicate active mining. Age is calculated from the linear accumulation rate (LAR) of sediment



sharp decrease in the depth of 7 cm was followed by stable values in the top samples. K/Zn ratio had a slight overall decreasing trend from the bottom to the top but showed more fluctuation from the depth of 19 cm towards the top, with a sharp increase in the topmost sample.

Diatom analysis

The analysed diatom samples of Valkeinen were dominated by planktonic cyclotelloid species (Fig. 6). The most abundant species in most samples was a

small, faint cyclotelloid most reminiscent of *Discostella pseudostelligera* (Hustedt) Houk & Klee 2004. Other common cyclotelloid species were *Pantocsekiella rossii* (Håkansson) K.T.Kiss & E.Ács 2016 and *Lindavia radiosa* (Grunow) De Toni & Forti 1900. *D. pseudostelligera* dominated pre- and post-mining samples but decreased during the active mining phase at 15–10 cm sediment depth, where *P. rossii* was the dominant species. Small fragilarioid species, such as the *Staurosira construens* Ehrenberg 1843 complex and *Pseudostaurosira brevistriata* (Grunow) D.M.Williams & Round 1988, were also rather

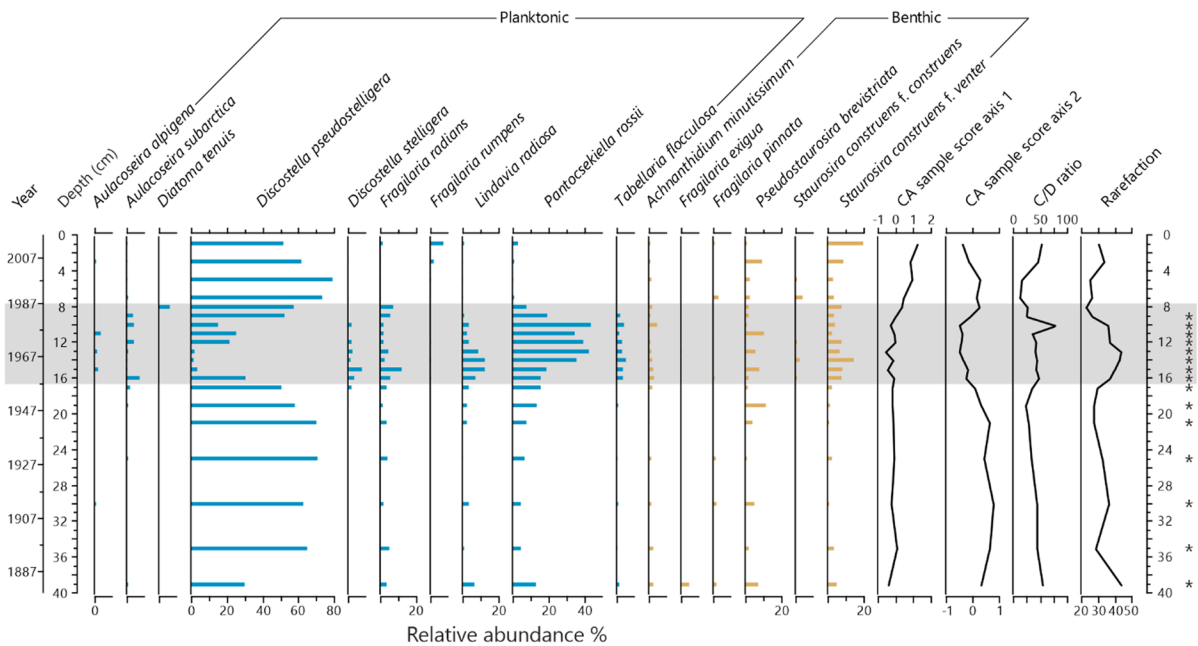


Fig. 6 The diatom species assemblages of Valkeinen. Only species with >3% relative abundance are shown. Species are grouped according to their habitats into planktonic (blue bars) and benthic (brown bars). Additional line graphs are correspondence analysis (CA) sample scores for axis 1 and 2, chrys-

ophyte cysts-to-diatoms (C/D) ratio, and taxonomic richness (rarefaction). Asterisk denotes slides with synurophyte algae present. Samples with darker background indicate active mining. Age is calculated from the linear accumulation rate (LAR) of sediment

abundant. *S. construens* increased after the onset of the mining and had a maximum abundance in the topmost sample. Together, cyclotelloids and fragilarioids accounted for at least 70% of identified valves in all but one sample (15 cm). Rarefaction-estimated taxonomical richness varied from 23 taxa at the depth of 8 cm to 44 taxa at 13 cm. Chrysophyte cysts were found in all samples, and their ratio to diatoms (C/D ratio) was lowest at 5–7 cm, which coincided with the dominance of the small cyclotelloid species and low richness in the diatom species. Synurophyte algae scales were present in samples below the depth of 9 cm.

Ordinations

The DCA-based species gradient length of the diatom samples was 2.18 standard deviation (SD) units. The CA sample scores of the first and second ordination axes remained relatively stable in the lower part of the core (Fig. 6). The most notable changes in the sample scores were in the topmost 19 cm and 10 cm in the second and first axis, respectively. In the ordination diagram (Fig. 7), samples 39–17 cm plot

mainly to the upper left quadrant, samples 15–10 cm to the lower left quadrant, and samples 9–1 cm to the right side of the diagram based on their diatom assemblages. The bottommost sediment samples in the upper left quadrant are characterised by higher abundances of elements typical of silicates, such as Al and Ti, and lower abundances of typical mining-related elements such as S, Cu, and Zn, compared to the other two groups. The samples in the lower left quadrant differ from the uppermost samples, for example, by their higher abundance of Mn and lower abundance of Ni.

Discussion

Pre-mining

The mixing regime of Valkeinen may have been irregular even before the onset of mining at Kotalahti. Although most lakes in the boreal region are dimictic, irregular circulation is a common phenomenon in small, sheltered headwater lakes such as Valkeinen

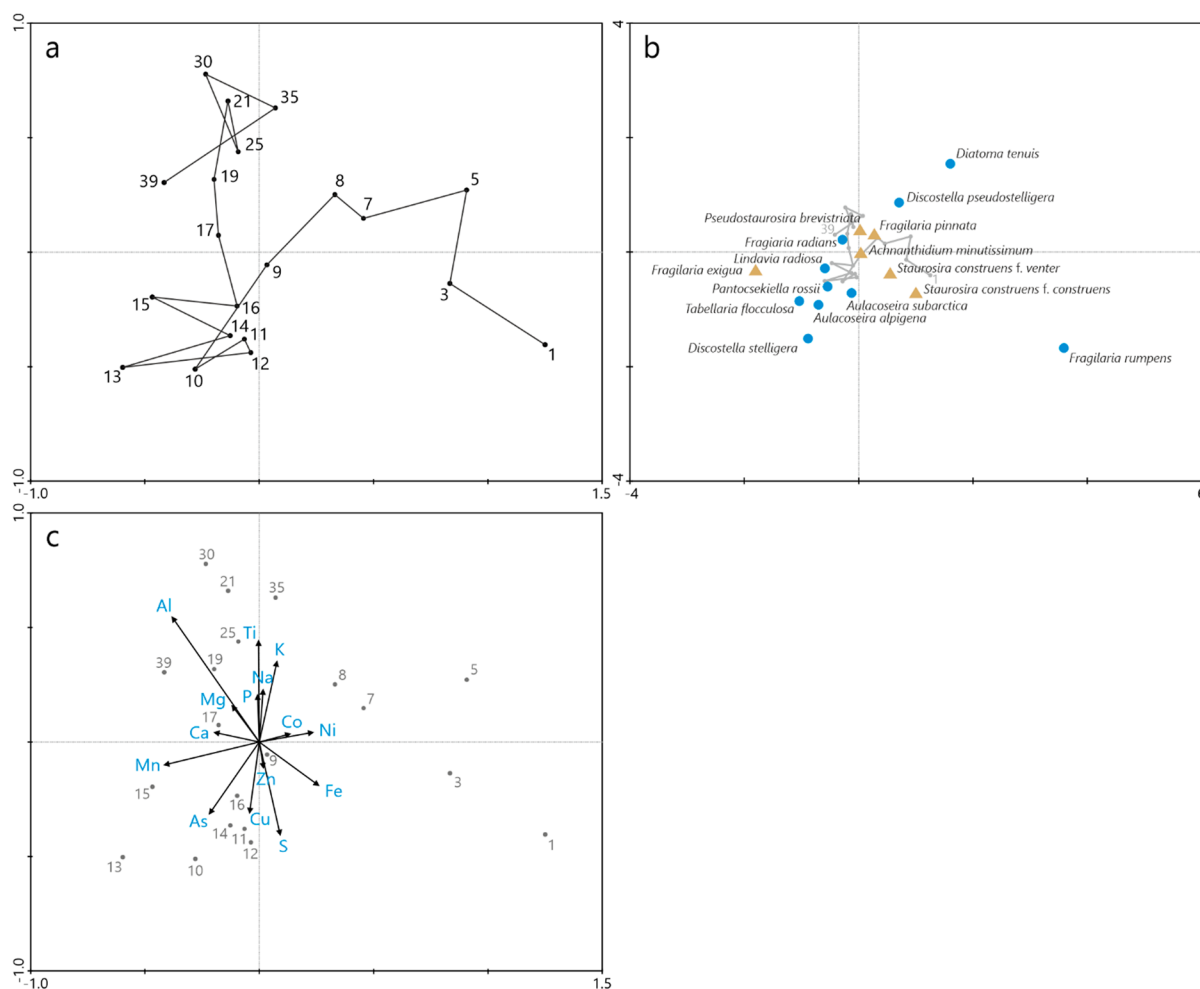


Fig. 7 Correspondence analysis ordination diagrams of Valkeinen, **a** diatom samples, **b** diatom species with >3% relative abundance, with planktonic species plotted with blue dots, benthic species with brown triangles, and samples with grey

under the species, **c** diatom samples plotted with grey dots and passively plotted supplementary geochemical data plotted with black vectors

(Hongve, 2002; Hakala, 2004; Simola & Arvola, 2005). This is indicated by the remarkable abundance of cyclotelloid species (Fig. 6), which have been linked to stronger stratification in lake water (Rühland et al., 2015; Edlund et al., 2022). Diatom species richness in Valkeinen is relatively low throughout the sequence compared to other, mainly shallower lakes from the same region in Finland (Tammelin et al., 2017) due to the abundance of the small cyclotelloid *D. pseudostelligera*, whose domination of the assemblages is reminiscent of the most anthropogenically salinised lakes of Tammelin et al. (2017) and Tammelin & Kauppila (2018). Cyclotelloids are competitive

in stratified lakes because their small size and buoyant shape enable them to more easily remain in the surface water compared to, e.g. *Aulacoseira* species, which are heavier and more cylindrical in shape and therefore rely on currents to stay near the surface (Rühland et al., 2015). Cyclotelloid species are also more efficient in nutrient uptake, which gives them a further advantage during summer stratification as surface waters become depleted of nutrients (Ptacnik et al., 2003; Winder et al., 2009; Rühland et al., 2015).

The whole sediment sequence is likely influenced by human activities in the area, but conditions

in the lake were stable before the onset of mining activities, as several element concentrations, including those derived from silicate mineral inputs, such as Ca, Mg, K, and Na (Fig. 4), and ratios (Mn/Fe, S/Fe, K/Zn, Fig. 5) are constant in the bottom part of the sequence. The pre-mining diatom assemblages likewise show little variation, as the bottom samples form a distinct group in the upper left quadrant of the ordination, and are associated with the silicate-derived elements, particularly Al and Ti (Fig. 7). The pre-mining concentrations of S are very high in Valkeinen compared to lakes in southern and central Finland (Fig. 4) (Meriläinen et al., 2010; Vähäkuopus et al., 2020; Mäkinen et al., 2023), even those with high background concentrations of sulphur and metals (Mäkinen et al., 2010). Mn, Ni, and Cu concentrations of Valkeinen correspond to the high background concentration lakes of Mäkinen et al. (2010), while Fe and Zn exhibit lower concentrations. The small-scale industrial activity in the Kotalahti area before mining may have led to increased erosion and metal mobility from the sulphide minerals in the bedrock in the area (Papunen & Koskinen, 1985; Turunen et al., 1960).

Active mining phase

The active mining phase of 1957–1987 at Kotalahti mine is clearly discernible in the geochemistry (Figs. 4, 5) and diatom assemblages (Fig. 6) of Valkeinen, incipiently from the depth of 19 cm and more clearly from 17 cm upwards. There are, however, no clear indications of a meromictic mixing regime in the lake during active mining based on the diatom assemblages and water sampling data (Table 2). Nevertheless, the diatom assemblage shift is likely driven by the S and metal loading and consequent changes in light and mixing conditions, as the lake still had low epilimnetic P concentration and electrical conductivity (EC) but a high mean Secchi depth of 5 m comparable to the heavily mine impacted lakes Orijärvi and Määrjärvi in SW Finland (Salonen et al., 2006; Tuovinen et al., 2012). The dominant diatom species *D. pseudostelligera* decreases sharply (Figs. 6, 7), and the assemblages become more reminiscent of the generally shallower and less human-impacted (i.e. holomictic) oligo-mesotrophic lakes in the region (Tammelin and Kauppila 2018). Changes in water quality thus seem to have given an advantage to heavier diatom

Table 2 Water quality measurements from Valkeinen (Finnish Environment Institute, 2023; Kehusmaa et al., 2023)

Date	Depth (m)	Temp (°C)	O ₂ (%)	P (µg/l)	Fe (µg/l)	pH	EC (mS/m)	Colour (mg/l Pt)
February 1973 ¹	1	1	85	9	n/a	6.6	5.6	23
	10	2.8	54	n/a	n/a	6.3	5.3	20
	11	2.9	55	12	71	6.4	5.6	20
October 1987 ²	1	7.1	n/a	10	40	7.0	54.5	30
February 1996 ²	1	0.9	52	13	<5	6.9	42.9	20
	6	3.3	50	13	<5	6.9	42.3	20
	10	3.6	44	n/a	n/a	6.8	43.2	20
	15	4.3	0	520	580	6.7	72.4	100
September 2008 ²	1	10.9	86	6	20	7.4	n/a	15
	6	10.8	84	8	20	7.4	n/a	15
	10	4.7	<2	n/a	n/a	n/a	n/a	n/a
	15	4.2	<2	390	710	6.9	n/a	70
October 2017 ²	2	6	79	270	<30	7.9	42.1	n/a
	9.5	4.9	3	194	<30	7.0	62.2	n/a
	10	4.5	3	465	390	6.8	62.6	n/a
	13	4.1	2	446	310	6.7	62.7	n/a

¹Max water depth at site of measurement 12 m

²Max water depth at site of measurement 16.1 m

species with higher light and nutrient requirements, allowing them to outcompete *D. pseudostelligera*. For example, the larger cyclotelloid *L. radiosa* has been shown to have higher growth rates in high light compared to small-celled stelligeroid species (Malik et al., 2017), whereas large-celled spring-blooming *Aulacoseira* species have been linked to stronger spring overturns (Rautio, 2000; Rühland et al., 2015). However, the growth rates of *D. pseudostelligera* may have also been affected by changes in the composition of the phytoplankton community in Valkeinen, as highlighted by Malik and Saros (2016), based on the shift in the C/D ratio trend during the active mining phase, possibly indicating more favourable conditions for chrysophytes. The diatom assemblage also shows increases in species such as *P. rossii* and *Achnanthisium minutissimum* (Kützing) Czarnecki 1994, which have been linked to metal pollution (Cattaneo et al., 2004; Salonen et al., 2006; Tuovinen et al., 2012).

In sediment geochemistry, the active mining is reflected in the increased concentrations of S and metals typical of acid mine drainage (AMD) (Fig. 4) (Blowes et al., 2014; Nordstrom et al., 2015). S is generally released from the oxidised sulphides exposed during the mining, the waste rock and tailings, as well as chemicals used in ore processing, and typically accumulates into lake sediments from the beginning of the mining (Salonen et al., 2006; Mäkinen et al., 2010; Nordstrom et al., 2015). S begins to increase immediately and steadily in the sediments of Valkeinen as well, reflecting the high S concentrations of the Kotalahti ore minerals, such as pyrrhotite (Fe_{1-x}S), pentlandite ($(\text{Fe},\text{Ni})_9\text{S}_8$), and chalcopyrite (CuFeS_2), and indicating rapid onset of sulphur and metal inputs to the lake from the mine site (Turunen et al., 1960; Papunen & Koskinen, 1985).

S is transported to the lake as soluble sulphate species, some of which may be adsorbed to Fe and Al oxyhydroxides either as surface runoff or in shallow groundwater. While sulphate loading may not always result in a corresponding increase in sediment S content, especially at the top of the sediment due to S cycling (e.g. Eimers et al., 2006; Holmer & Storkholm, 2001), a strong correlation has been found between sulphate supply and sulphate reduction in sediment in suitable conditions (Zhou et al., 2022). A part of the sulphate entering the lake may be incorporated in the plankton and be found in the seston in the basin. In the lake sediment, pore water, and the

immediately overlying water, sulphate reduction may occur and S can be incorporated in the sediment as Fe monosulphides that, although susceptible to oxidation, are fairly persistent in sediment and may also scavenge other metal species. Further diagenesis may gradually convert the monosulphides to pyrite which is an even more stable phase. During the active mining phase, conditions favourable for sulphate reduction likely existed a few centimetres inside the sediment at first, before conditions in the basin turned even more reducing. A part of both sulphate and the newly reduced S may transfer to the organic S pool (Holmer & Storkholm, 2001; Phillips et al., 2023). Some reduced S will be reoxidised in the oxic zone in the sediment and even under anoxic conditions and lost back in the overlying water. In anoxic conditions, roughly half of this reoxidised sulphide returns to the sulphide pool via thiosulphate (Jørgensen, 1990).

Ni and Co peak at the end of the mining, possibly indicating the flooding of the mine shafts and the end of tailings deposition and consequent oxidation and mobilisation of these metals into Valkeinen (Vestola & Mroueh, 2008; Räisänen et al., 2015). Cu concentrations fluctuate more during the active mining phase and increase modestly with less than twofold increases compared to pre-mining concentrations. This reflects the overall lower concentrations of Cu compared to Ni in the Kotalahti ore and tailings waste and the slower oxidation speed of the main Cu mineral, chalcopyrite, compared to the other sulphide ore minerals at Kotalahti (Papunen & Koskinen, 1985; Heikkinen et al., 2009; Lindsay et al., 2015; Räisänen et al., 2015).

Although elements derived from silicate mineral inputs remain relatively constant during the mining phase, there is a notable decrease in Ti and a slight decrease in Al (Fig. 4), which might suggest that erosion from the lake catchment area has decreased (Bertrand et al., 2024). However, as the concentrations are closed sum data, it is more likely that the increase in the concentrations of S and the trace elements associated with mining has “diluted” the share of minerogenic elements in the elemental composition of the sediment (Bertrand et al., 2024). This is also apparent in the ordination, where the diatom samples of the active mining phase are associated with higher sediment concentrations of S, Mn, As, and trace metals, and lower concentrations of minerogenic elements (Fig. 7). Additionally, the HNO_3 extraction method

used for the geochemical analysis is not intended to accomplish total decomposition of the sediment samples, and the dissolution of some refractory minerals, such as quartz, silicates, and titanium dioxide, from the samples may be incomplete (USEPA, 2007). The method also typically requires the addition of hydrochloric acid to better recover elements such as Al, Fe, and Mg. Differences in the exploited orebodies and evolving mining operations during the lifecycle of the Kotalahti mine might also partly explain the slight changes and fluctuations in the accumulation of silicate minerals to Valkeinen.

The behaviour of Fe and P suggests enhanced oxygen depletion during the active mining phase in Valkeinen, whereas no apparent signs of eutrophication were identified before the closure of the mine. The S/Fe ratio is high, indicating that the Fe is increasingly found in sulphides rather than as oxides or oxyhydroxides in the sediment (Rothe et al., 2015). The P concentrations are lower than before mining, suggesting that oxidised Fe fractions are no longer sufficient to bind P into the sediments, and possibly leading to P release from the sediments into the water column (Jilbert et al., 2020; Lanka et al., 2024). The lower sediment P concentrations of the active mining phase could, thus, be a result of post-depositional mobilisation, upwards migration, and lateral transport of P to shallower areas of the basin (Moyle & Boyle, 2021). According to Zhao et al. (2024), there is considerable heterogeneity in the P cycling of a lake: in shallow areas, internal loading is enhanced and varies more between seasons, whereas in deep and stratified basins internal P loading is restricted to the near-bottom water layer and has a limited impact on the nutrient cycle of the lake as a whole. If any internal loading took place in Lake Valkeinen during the active mining phase, it had to be limited to the deepest part of the lake based on the very low P concentrations recorded in the bottom water (Table 2).

Post-mining

The cessation of active mining at Kotalahti leads to notably different geochemistry in the sediments of Valkeinen, which, together with the biotic changes, most likely indicates the onset of meromixis in the lake. The tailings area was dried by ditching in the summer of 1987 and gradually covered afterwards with soils, till, plant debris, peat, and sediment

ditched from the nearby lake Oravilahti (Räisänen et al., 2015). The ditching probably increased the influx of electrolytes into Valkeinen, which is visible as increased EC in the surface water of the lake by October 1987 (Table 2). The shift in the redox conditions of the tailings area and an increase in both minerogenic and biogenic material likely explains the sharp increase in Fe and Ti, and a decrease in Mn, trace metals, and to a lesser degree S, in the sediments of Valkeinen following the closure of the mine (Fig. 4). These changes are also visible as a sudden drop in the element ratios of S/Fe and Mn/Fe (Fig. 5). Mn/Fe ratio is often used as a proxy of past lake water oxygenation because of the differing sensitivity of these elements to redox changes, whereby a lower Mn/Fe ratio is ideally thought to indicate reducing conditions (e.g. Makri et al. 2021). The interpretation of this proxy is, however, not straightforward if there is persistent bottom water anoxia or higher detrital input, both of which could also have influenced the accumulation of Mn and Fe in Valkeinen at this time.

The closing of the Kotalahti mine and subsequent salinisation is also apparent in the diatom assemblages of Valkeinen. *D. pseudostelligera* increases back to the pre-mining abundances and *P. rossii* and *L. radiosa* decrease, among others, consequently leading to a minimum in species richness in the studied samples. *Diatoma tenuis* appears in the 8 cm sample which corresponds to the year 1987 and the ditching at the tailings area. *D. tenuis* has been linked to elevated EC, together with small cyclotelloids and elongated pennate taxa (Tammelin et al., 2017). The amount of chrysophyte cysts also drops, and the 9 cm sample is also the last one with certain synurophyte algae (possibly *Mallomonas* sp.) present, which occur throughout the lower part of the sediment sequence, further pointing towards a drastic change in the ecological conditions of the lake. As a group, both chrysophytes and synurophytes are most diverse in slightly acidic waterbodies with low productivity and conductivity (Nicholls & Wujek, 2015; Siver, 2015; Korkkonen et al., 2020), and their sharp decrease or disappearance likely indicates a relatively quick shift towards a more electrolyte-rich water column after the closure of the mine, as the amount of chrysophytes is at its maximum during the end of the active mining phase (Fig. 6).

More recent attempts to manage the Kotalahti mine site are reflected in the uppermost samples of the

Valkeinen sediment sequence. The mine filled with water by 1994, after which the effluents have been treated with passive methods, including wetlands, a treatment plant for waters piped into the nearby lake Oravilahti, and the use of sulphate-reducing bacteria (SRB) in one of the underground mines. For the SRB treatment, organic amendments (pig manure) were added in the mine shaft in 1996–1997, and the process has successfully reduced the concentrations of metals and increased pH in the flooded mine (Vestola & Mroueh, 2008). These practices are also visible in the decreasing trace metal concentrations of Valkeinen, particularly in Co, Ni, and Zn (Fig. 4), and in the increasing K/Zn ratio (Fig. 5), which has been used to represent the ratio of minerogenic to industrial matter in sediment (Jilbert et al., 2020; Salminen et al., 2021). The source of the temporary increases in Zn and Cu, corresponding to the year 1998, could be the manure used in the organic amendments (Gourlez et al., 2024). S concentrations have not decreased as effectively and are still 3.5-fold in the two top samples (mean S 25500 mg kg⁻¹) compared to pre-mining samples (mean S 7383 mg kg⁻¹). This reflects the poor management of S and SO₄ from the mine wastes, as the environmental permits are more lenient with these substances compared to metals (ISAVI 2014). In recent decades, sewage sludge has also been used to cover the tailings area (ISAVI 2014). The addition of the sludge and the simultaneous decrease in S loading could have led to an increased availability of Fe oxides and oxyhydroxides able to bind P, explaining the increase in P concentrations in the topmost sediment samples (Fig. 4). These dynamics probably contribute to the current high P concentrations in the lake water, which were first seen as P-enriched bottom water by the 1990s and later followed by elevated epilimnetic P in the 2010s (Table 2, Kehusmaa et al. 2023).

Even though the diatom species richness and the amount of chrysophyte cysts increases in the most recent samples, the phytoplankton community does not revert to the pre-mining composition nor appear to find an equilibrium in the now meromictic water column (Fig. 7). The salinisation and subsequent eutrophication of the water column (Table 2) is reflected in the topmost samples of Valkeinen as an increase in fragilarioid species, such as *F. rumpens* and the *S. construens* complex, and a simultaneous

decrease in *D. pseudostelligera*. Small fragilarioids are cosmopolitan, opportunistic species, with a broad tolerance for, e.g. salinity and nutrients, which makes them competitive in unstable conditions (Weckström & Juggins, 2005), in contrast to cyclotelloid species which are generally thought to compete well in oligotrophic conditions (e.g. Saros & Anderson 2015) and tolerate metals poorly (Salonen et al., 2006; Tuovinen et al., 2012). Despite the high recent epilimnetic P concentration of Valkeinen (Table 2, Kehusmaa et al., 2023), the post-mining diatom assemblages differ from other currently eutrophic lakes in the region (Tammelin et al., 2017). The diatom assemblages thus seemed relatively unaffected by the onset of internal P loading, while epilimnetic P concentration remained low, but will likely show a more intensive response in the future, following the notable recent increase in epilimnetic P.

At present, Valkeinen is meromictic, with a chemocline at 8–10 m depth, and the EC and pH values have seemingly been relatively constant since the sampling of 1996, whereas P has increased (Table 2; Kauppila et al., 2017; Kehusmaa et al., 2023). The inflow from the mine still has elevated concentrations of substances such as S, SO₄, Ni, and Zn, and the lake is eutrophied in addition to being meromictic. Mn, Fe, and P exhibit elevated concentrations below the chemocline, suggesting higher solubility in the anoxic water or internal loading of these elements from the sediment. These findings indicate that the mine load is still impacting Valkeinen heavily, and even if the loading were to stop completely, the lake would not necessarily revert to holomixis in several decades (Kehusmaa et al., 2023).

Conclusions

We identified distinct pre-, active, and post-mining phases in the geochemistry and diatom assemblages of Valkeinen, a boreal lake receiving surface runoff from the closed Kotalahti Ni-Cu mine. Our results show that mines can affect the aquatic environment in complex and subtle ways, which makes comprehensive and long-term environmental monitoring and management vital to reduce the negative impacts of mining. Focusing on toxic metal concentrations and their management is not sufficient;

care must also be taken with minimising saline and eutrophying effluents from both active and legacy mine sites, particularly in areas with lakes or other small, fixed waterbodies. In addition, the biggest impacts might not occur during active mining but can instead happen after closure as changes take place, e.g. in the land use of the mine area, or in the redox conditions of tailings areas. In Valkeinen, the shift to meromixis seems to have happened during the closure of the mine several decades ago, but the eutrophication of the lake is a more recent phenomenon. Our study also reinforces the usefulness of palaeolimnological investigations of mine impacted lakes when monitoring data is lacking. For inferring changes in lake mixing regimes, we highlight the necessity of multiple proxies, as pinpointing the onset of meromixis from the sediment record of Valkeinen with certainty required both geochemical and ecological proxies.

Acknowledgements We thank Timo Saarinen, Arto Peltola, and Fukumoto Yu for their assistance in field work and Krister Dalhem and Sarianna Salminen for assistance in sample preparation. We also thank the anonymous reviewers for their valuable comments on the manuscript.

Author Contributions Tommi Kauppila, Karoliina Kehusmaa, Saija Saarni, Mira Tammelin, and Peter Österholm contributed to conceptualisation and methodology; Karoliina Kehusmaa and Mira Tammelin were involved in formal analysis and investigation and writing—original draft preparation; Tommi Kauppila, Karoliina Kehusmaa, Saija Saarni, Mira Tammelin, and Peter Österholm contributed to writing—review and editing; Tommi Kauppila and Karoliina Kehusmaa were involved in funding acquisition; and Tommi Kauppila, Saija Saarni, and Peter Österholm contributed to supervision.

Funding Open Access funding provided by University of Turku (including Turku University Central Hospital). The work of Karoliina Kehusmaa was supported by the K.H. Renlund Foundation and Maa- ja vesitekniiikan tuki ry.

Data availability The raw data supporting the conclusions of this manuscript will be made available by the corresponding author on reasonable request.

Declarations

Conflict of interests The authors declare no competing interests.

Ethical approval This is not applicable.

Consent to Participate This is not applicable.

Consent to Publish This is not applicable.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Appleby, P.G., G. Piliposyan, J. Weckström & G. Piliposian, 2023. Delayed inputs of hot ¹³⁷Cs and ²⁴¹Am particles from Chernobyl to sediments from three Finnish lakes: implications for sediment dating. *J Paleolimnol* 69, 293–303. <https://doi.org/10.1007/s10933-022-00273-6>
- Battarbee, R. W., V. J. Jones, R. J. Flower, N. G. Cameron, H. Bennion, L. Carvalho, & S. Juggins, 2001. Diatoms. In Smol, J. P., Birks, H. J. B. & Last, W. M. (eds.) *Tracking environmental change using lake sediments*, Vol. 3. Terrestrial, algal and siliceous indicators. Kluwer Academic Publisher, New York: 155–202
- Bennion, H., R. W. Battarbee, C. D. Sayer, G. L. Simpson & T. A. Davidson, 2011. Defining reference conditions and restoration targets for lake ecosystems using palaeolimnology: A synthesis. *Journal of Paleolimnology* 45: 533–544. <https://doi.org/10.1007/s10933-010-9419-3>.
- Bertrand, S., R. Tjallingii, M. E. Kylander, B. Wilhelm, S. J. Roberts, F. Arnaud, E. Brown & R. Bindler, 2024. Inorganic geochemistry of lake sediments: A review of analytical techniques and guidelines for data interpretation. *Earth-Science Reviews* 249: 104639. <https://doi.org/10.1016/j.earscirev.2023.104639>.
- Birks, H. J. B., 2010. Numerical methods for the analysis of diatom assemblage data. In Smol, J. P. & E. F. Stoermer (eds), *The Diatoms: Application for the Environmental and Earth Sciences* Cambridge University Press: 23–54.
- Birks, H. J. B. & J. M. Line, 1992. The use of rarefaction analysis for estimating palynological richness from Quaternary pollen-analytical data. *Holocene* 2: 1–10. <https://doi.org/10.1177/095968369200200101>.
- Blowes, D.W., C.J. Ptacek, J.L. Jambor, C.G. Weisener, D. Paktunc, W.D. Gould, & D.B. Johnson, 2014. The Geochemistry of Acid Mine Drainage. In Lollar, B.S., H.D. Holland, K.K. Turekian (eds), *Treatise on Geochemistry* (Second edition). Elsevier: 131–190. <https://doi.org/10.1016/B978-0-08-095975-7.00905-0>
- Boehrer, B., C. von Rohden, & M. Schultze, 2017. Physical Features of Meromictic Lakes: Stratification and Circulation. In Gulati, R. D., E. S. Zadereev, & A. G. Degermendzhi (eds) *Ecology of Meromictic Lakes*. Springer Cham. pp. 15–34.

- Boehrer, B. & M. Schultze, 2008. Stratification of Lakes. *Reviews of Geophysics* 46: 1–27. <https://doi.org/10.1029/2006RG000210.1>.INTRODUCTION.
- ter Braak, C. J. F., & P. Šmilauer, 2002. CANOCO reference manual and CanoDraw for Windows user's guide: software for canonical community ordination (version 4.5). Ithaca: Microcomputer Power
- Caraco, N. F., J. J. Cole & G. E. Likens, 1989. Evidence for sulphate-controlled phosphorus release from sediments of aquatic systems. *Nature* 341: 316–318. <https://doi.org/10.1038/341316a0>.
- Cattaneo, A., Y. Couillard, S. Wunsam & M. Courcelles, 2004. Diatom taxonomic and morphological changes as indicators of metal pollution and recovery in Lac Dufault (Québec, Canada). *Journal of Paleolimnology* 32: 163–175. <https://doi.org/10.1023/B:JOPL.0000029430.78278.a5>.
- Cunillera-Montcusí, D., M. Beklioglu, M. Cañedo-Argüelles, E. Jeppesen, R. Ptacnik, C. A. Amorim, S. E. Arnott, S. A. Berger, S. Brucet, H. A. Dugan, M. Gerhard, Z. Horváth, S. Langenheder, J. C. Nejtgaard, M. Reinikainen, M. Striebel, P. Urrutia-Cordero, C. F. Vad, E. Zadereev & M. Matias, 2022. Freshwater salinisation: a research agenda for a saltier world. *Trends in Ecology and Evolution* 37: 440–453. <https://doi.org/10.1016/j.tree.2021.12.005>.
- Duda, M. P., B. Sivarajah, K. M. Rühland, A. M. Paterson, J. L. Barrow, Y. Cheng, E. J. Favot, K. R. Hadley, R. I. Hall, K. E. Hargan, C. Nelligan, E. D. Reavie, R. E. Valleeau, P. Werner, C. Wilkins & J. P. Smol, 2023. Environmental optima for common diatoms from Ontario lakes along gradients of lakewater pH, total phosphorus concentration, and depth. *Journal of Paleolimnology* 70: 131–158. <https://doi.org/10.1007/s10933-023-00288-7>.
- Edlund, M. B., J. M. Ramstack Hobbs, A. J. Heathcote, D. R. Engstrom, J. E. Saros, K. E. Strock, W. O. Hobbs, N. A. Andresen & D. D. VanderMeulen, 2022. Physical characteristics of northern forested lakes predict sensitivity to climate change. *Hydrobiologia* 849: 2705–2729. <https://doi.org/10.1007/s10750-022-04887-9>.
- Eimers, M. C., A. M. Paterson, P. J. Dillon, S. L. Schiff, B. F. Cumming & R. I. Hall, 2006. Lake sediment core records of sulphur accumulation and sulphur isotopic composition in central Ontario, Canada lakes. *Journal of Paleolimnology* 35: 99–109. <https://doi.org/10.1007/s10933-005-7871-2>.
- Ek, A. S. & I. Renberg, 2001. Heavy metal pollution and lake acidity changes caused by one thousand years of copper mining at Falun, central Sweden. *Journal of Paleolimnology* 26: 89–107. <https://doi.org/10.1023/A:1011112020621>.
- European Commission, 2023. Proposal for a Regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020. Brussels, 16.3.2023. 67
- Finnish Environment Institute, 2014a. VALUE-Valuma-Aluejako (Ehdotus). VALUE – Valuma-Alueen Rajaustyökälu KM10. Unavailable as of 28 February 2025. <https://ckan.ymparisto.fi/dataset/value-selainpohjainen-valuma-alueiden-rajaustyokalu>.
- Finnish Environment Institute, 2014b. Corine Land Cover 2012. VALUE – Valuma-Alueen Rajaustyökälu KM10. Available at: <https://ckan.ymparisto.fi/dataset/corine-maanpeite-2012>.
- Finnish Environment Institute, 2023. Pintavesien tilan tietojärjestelmä, vedenlaatu – VESLA. Hertta information system 5.7. Available at: <https://www.syke.fi/en/environmental-data/maps-and-information-services/open-environmental-information-systems#status-of-surface-waters>.
- Finnish Meteorological Institute, 2021. Temperature and precipitation statistics from 1961 onwards. Available at: <https://en.ilmatieteenlaitos.fi/statistics-from-1961-onwards>.
- Fischer, S., G. Rosqvist, S. R. Chalov & J. Jarsjö, 2020. Disproportionate Water Quality Impacts from the Century-Old Nautanen Copper Mines. *Northern Sweden. Sustainability* 12: 1394. <https://doi.org/10.3390/su12041394>.
- Gourlez, E., F. Beline, J.-Y. Dourmad, A. R. Monteiro, F. Guizou, A. Le Bihan & F. de Quelen, 2024. The fate of Cu and Zn along the feed-animal-excreta-effluent continuum in swine systems according to feed and effluent treatment strategies. *Journal of Environmental Management* 354: 120299. <https://doi.org/10.1016/j.jenvman.2024.120299>.
- Guiry, M.D. & G.M. Guiry, 2025. AlgaeBase. World-wide electronic publication, University of Galway. <https://www.algaebase.org>, accessed on 17 November 2025.
- Hakala, A., 2004. Meromixis as a part of lake evolution - Observations and a revised classification of true meromictic lakes in Finland. *Boreal Environment Research* 9: 37–53.
- Hammer, Ø., D. A. T. Harper & P. D. Ryan, 2001. PAST: Paleontological Statistics Software Package for Education and Data Analysis. *Palaeontologia Electronica* 4: 1–9.
- Heikkinen, P. M., M. L. Räisänen & R. H. Johnson, 2009. Geochemical characterisation of seepage and drainage water quality from two sulphide mine tailings impoundments: Acid mine drainage versus neutral mine drainage. *Mine Water and the Environment* 28: 30–49. <https://doi.org/10.1007/s10230-008-0056-2>.
- Hill, M. O., 1973. Reciprocal Averaging: an eigenvector method of ordination. *Journal of Ecology* 61: 237–249.
- Hill, M. O. & H. G. Gauch Jr., 1980. Detrended Correspondence Analysis: An Improved Ordination Technique. *Veg-etatio* 42: 47–58.
- Holmer, M. & P. Storkholm, 2001. Sulphate reduction and sulphur cycling in lake sediments: a review. *Freshwater Biology* 46: 431–451.
- Hongve, D., 2002. Seasonal mixing and genesis of endogenic meromixis in small lakes in Southeast Norway. *Nordic Hydrology* 33: 189–206. <https://doi.org/10.2166/nh.2002.0022>.
- Houk, V., 2003. Atlas of freshwater centric diatoms with a brief key and descriptions. Part I. Melosiraceae, Orthoseiraceae, Paraliaceae and Aulacoseiraceae. *Czech Phycology Supplement*, Vol. 1. Czech Phycological Society, Olomouc

- IEA, 2021. The Role of Critical Minerals in Clean Energy Transitions. OECD Publishing, Paris. <https://doi.org/10.1787/262b91c-en>.
- ISAVI, 2014. Itä-Suomen Aluehallintovirasto. Päätös Nro 96/2014/1. Toimintansa lopettaneen Kotalahden kaivoksen ympäristöluvan muuttaminen, Leppävirta. Dnro ISAVI/94/04.08/2013. Julkipano 9.12.2014 [in Finnish]
- Jilbert, T., S. Jokinen, T. Saarinen, U. Mattus-Kumpunen, A. Simojoki, S. Saarni, S. Salminen, J. Niemistö & J. Horppila, 2020. Impacts of a deep reactive layer on sedimentary phosphorus dynamics in a boreal lake recovering from eutrophication. *Hydrobiologia* 847: 4401–4423. <https://doi.org/10.1007/s10750-020-04289-9>.
- Jørgensen, B. B., 1990. The sulfur cycle of freshwater sediments: role of thiosulfate. *Limnology and Oceanography* 35(6): 1329–1342.
- Juggins, S., 2007. C2 Version 1.5 User guide. Software for ecological and palaeoecological data analysis and visualisation. University of Newcastle, Newcastle upon Tyne, UK: 73.
- Kauppi, P., & M. Räisänen, 2015. Effluent Chemistry of Closed Sulfide Mine Tailings: Influence of Ore Type. In Agreeing on solutions for more sustainable mine water management – Proceedings of the 10th ICARD & IMWA Annual Conference. – electronic document (paper 181). Santiago, Chile (GECAMIN).
- Kauppi, T., J. Mäkinen, & L. Solismaa, 2017. Sediment And Pore Water Properties Across The Chemocline Of A Mine Water-Impacted Boreal Lake During Winter Stagnation And Autumn Overturn. In Wolkersdorfer, C., L. Sartz, M. Sillanpää & A. Häkkinen (eds) Proceedings of the IMWA 2017 Mine Water & Circular Economy (Vol D). 167 – 174. Lappeenranta, Finland (Lappeenranta University of Technology).
- Kaushal, S. S., G. E. Likens, M. L. Pace, J. E. Reimer, C. M. Maas, J. G. Galella, R. M. Utz, S. Duan, J. R. Kryger, A. M. Yaculak, W. L. Boger, N. W. Bailey, S. Haq, K. L. Wood, B. M. Wessel, C. E. Park, D. C. Collison, B. Y. aaqo, I. Aisin, T. M. Gedeon, S. K. Chaudhary, J. Widmer, C. R. Blackwood, C. M. Bolster, M. L. Devilbiss, D. L. Garrison, S. Halevi, G. Q. Kese, E. K. Quach, C. M. P. Rogelio, M. L. Tan, H. J. S. Wald & S. A. Woglo, 2021. Freshwater salinization syndrome: from emerging global problem to managing risks. *Biogeochemistry* 154: 255–292. <https://doi.org/10.1007/s10533-021-00784-w>.
- Kehusmaa, K., T. Kauppi, P. Österholm, J. Juntunen & S. Saarni, 2023. Properties and Stability of Mining-Induced Meromixis in Two Small Boreal Lakes in Eastern Finland. *Mine Water and the Environment* 42: 24–39. <https://doi.org/10.1007/s10230-023-00915-9>.
- Klaminder, J., P. Appleby, P. Crook & I. Renberg, 2012. Post-deposition diffusion of ^{137}Cs in lake sediment: Implications for radiocaesium dating. *Sedimentology* 59: 2259–2267. <https://doi.org/10.1111/j.1365-3091.2012.01343.x>.
- Korkonen, S., J. Weckström & A. Korhola, 2020. Biogeography and ecology of freshwater chrysophyte cysts in Finland. *Hydrobiologia* 847: 487–499. <https://doi.org/10.1007/s10750-019-04112-0>.
- Krammer, K. & H. Lange-Bertalot, 1986. Bacillariophyceae 1: Naviculaceae. In Ettl, H., J. Gerloff, H. Heyning & D. Mollenhauer (eds), Süßwasserflora von Mitteleuropa, Vol. 2. Gustav Fischer Verlag, Stuttgart: 867.
- Krammer, K. & H. Lange-Bertalot, 1988. Bacillariophyceae 2: Bacillariaceae, Epithemiaceae, Surirellaceae. In Ettl, H., J. Gerloff, H. Heyning & D. Mollenhauer (eds), Süßwasserflora von Mitteleuropa, Vol. 2. Gustav Fischer Verlag, Stuttgart: 596.
- Krammer, K. & H. Lange-Bertalot, 1991a. Bacillariophyceae 3: Centrales, Fragilariaceae, Eunotiaceae. In Ettl, H., G. Gärtner, J. Gerloff, H. Heyning & D. Mollenhauer (eds), Süßwasserflora von Mitteleuropa, Vol. 2. Gustav Fischer Verlag, Stuttgart: 576.
- Krammer, K. & H. Lange-Bertalot, 1991b. Bacillariophyceae 4: Achnanthaceae, Kritishe Ergänzungen zu Navicula (Lineolatae) und Gomphonema. In Ettl, H., J. Gerloff, H. Heyning & D. Mollenhauer (eds), Süßwasserflora von Mitteleuropa, Vol. 2. Gustav Fischer Verlag, Stuttgart: 536.
- Krammer, K., 1992. Pinnularia - eine Monographie der europäischen Taxa. Bibliotheca Diatomologica, Band 26. Berlin-Stuttgart: Gebrüder Borntraeger
- Lamers, L. P. M., S.-J. Falla, E. M. Samborska, I. A. R. van Dulken, G. vanHengstum & J. G. M. Roelofs, 2002. Factors controlling the extent of eutrophication and toxicity in sulfate-polluted freshwater wetlands. *Limnology and Oceanography* 47: 585–593. <https://doi.org/10.4319/lo.2002.47.2.0585>.
- Lange-Bertalot, H., & G. Moser, 1994. Brachysira - Monographie der Gattung. Bibliotheca Diatomologica, Band 29. Berlin-Stuttgart: Gebrüder Borntraeger
- Lanka, A., I. Dimante-Deimantovica, S. Saarni, N. Stivrins, W. Tylmann, I. Zawiska & S. Veski, 2024. Urbanization-driven Cladocera community shifts in the lake - a case study from Baltic region. *Europe. Anthropocene* 46: 100439. <https://doi.org/10.1016/j.ancene.2024.100439>.
- Lindsay, M. B. J., M. C. Moncur, J. G. Bain, J. L. Jambor, C. J. Ptacek & D. W. Blowes, 2015. Geochemical and mineralogical aspects of sulfide mine tailings. *Applied Geochemistry* 57: 157–177. <https://doi.org/10.1016/j.apgeochem.2015.01.009>.
- Mäkinen, J., T. Kauppi, K. Loukola-Ruskeeniemi, J. Mattila & J. Miettinen, 2010. Impacts of point source and diffuse metal and nutrient loading on three northern boreal lakes. *Journal of Geochemical Exploration* 104: 47–60. <https://doi.org/10.1016/j.gexplo.2009.11.007>.
- Mäkinen, J., M. Tammelin & T. Kauppi, 2023. Recent increase in sediment dry matter, carbon, and phosphorus accumulation in small boreal lakes with clayey catchments. *Anthropocene* 44: 100421. <https://doi.org/10.1016/j.ancene.2023.100421>.
- Makri, S., G. Wienhues, M. Bigalke, A. Gilli, F. Rey, W. Tinner, H. Vogel & M. Grosjean, 2021. Variations of sedimentary Fe and Mn fractions under changing lake mixing regimes, oxygenation and land surface processes during Late-glacial and Holocene times. *Science of the Total Environment* 755: 143418. <https://doi.org/10.1016/j.scitotenv.2020.143418>.
- Malik, H. I. & J. E. Saros, 2016. Effects of temperature, light and nutrients on five *Cyclotella sensu lato* taxa assessed with in situ experiments in arctic lakes. *Journal of*

- Plankton Research 38: 431–442. <https://doi.org/10.1093/plankt/fbw002>.
- Malik, H. I., R. M. Northington & J. E. Saros, 2017. Nutrient limitation status of Arctic lakes affects the responses of *Cyclotella* sensu lato diatom species to light: implications for distribution patterns. *Polar Biology* 40: 2445–2456. <https://doi.org/10.1007/s00300-017-2156-6>.
- Meriläinen, J. J., V. Kustula, A. Witick, E. Haltia-Hovi & T. Saarinen, 2010. Pollution history from 256 BC to AD 2005 inferred from the accumulation of elements in a varve record of Lake Korttajärvi in Finland. *Journal of Paleolimnology* 44: 531–545. <https://doi.org/10.1007/s10933-010-9435-3>.
- Moncur, M. C., C. J. Ptacek, D. W. Blowes & J. L. Jambor, 2006. Spatial variations in water composition at a northern Canadian lake impacted by mine drainage. *Applied Geochemistry* 21: 1799–1817. <https://doi.org/10.1016/j.apgeochem.2006.06.016>.
- Moncur, M. C., C. J. Ptacek, M. Hayashi, D. W. Blowes & S. J. Birks, 2014. Seasonal cycling and mass-loading of dissolved metals and sulfate discharging from an abandoned mine site in northern Canada. *Applied Geochemistry* 41: 176–188. <https://doi.org/10.1016/j.apgeochem.2013.12.007>.
- Moyle, M. & J. F. Boyle, 2021. A method for reconstructing past lake water phosphorus concentrations using sediment geochemical records. *Journal of Paleolimnology* 65: 461–478. <https://doi.org/10.1007/s10933-021-00174-0>.
- Nicholls, K. H., & D. E. Wujek, 2015. Chrysophyceae and Phaeothamniophyceae. In John D. Wehr, J. D., R. G. Sheath & J. P. Kociolek. (eds), *Freshwater Algae of North America: Ecology and Classification*, 2nd edition, Academic Press: 485–536. <https://doi.org/10.1016/B978-0-12-385876-4.00012-8>.
- Nordstrom, D. K., D. W. Blowes & C. J. Ptacek, 2015. Hydrogeochemistry and microbiology of mine drainage: An update. *Applied Geochemistry* 57: 3–16. <https://doi.org/10.1016/j.apgeochem.2015.02.008>.
- Ojala, A. E. K., T. P. Luoto & J. J. Virtasalo, 2017. Establishing a high-resolution surface sediment chronology with multiple dating methods – Testing ¹³⁷Cs determination with Nurmijärvi clastic-biogenic varves. *Quaternary Geochronology* 37: 32–41. <https://doi.org/10.1016/j.quageo.2016.10.005>.
- Papunen, H., & J. Koskinen, 1985. Geology of the Kotalahti nickel-copper ore. In Papunen H. & G. I. Gorbunov. (eds), *Nickel-copper deposits of the Baltic Shield and Scandinavian Caledonides*. Geological Survey of Finland, Bulletin 333. Geologian tutkimuskeskus, Espoo: 229–242.
- Parviainen, A., T. Kauppila & K. Loukola-Ruskeeniemi, 2012. Long-term lake sediment records and factors affecting the evolution of metal(loid) drainage from two mine sites (SW Finland). *Journal of Geochemical Exploration* 114: 46–56. <https://doi.org/10.1016/j.gexplo.2011.12.004>.
- Phillips, A. A., I. Ulloa, E. Hyde, J. Agnich, L. Sharpnack, K. G. O'Malley, S. M. Webb, K. M. Schreiner, C. S. Sheik, S. Katsev & M. R. Raven, 2023. Organic sulfur from source to sink in low-sulfate Lake Superior. *Limnology and Oceanography* 68: 2716–2732. <https://doi.org/10.1002/lno.12454>.
- Porter, S. D., 2008. *Algal Attributes: An Autecological Classification of Algal Taxa Collected by the National Water-Quality Assessment Program*: U.S. Geological Survey Data Series 329. U.S. Geological Survey, Reston, Virginia. <https://doi.org/10.3133/ds329>
- Ptacek, R., S. Diehl & S. Berger, 2003. Performance of sinking and nonsinking phytoplankton taxa in a gradient of mixing depths. *Limnology and Oceanography* 48: 1903–1912. <https://doi.org/10.4319/lo.2003.48.5.1903>.
- Puustinen, K., B. Saltikoff, & M. Tontti, 1995. Distribution and metallogenic types of nickel deposits in Finland. Geological Survey of Finland, Report of Investigation 132. Geologian tutkimuskeskus, Espoo: 38
- Puustinen, K., 2003. Suomen kaivosteollisuus ja mineraalisten raaka-aineiden tuotanto vuosina 1530–2001, historiallinen katsaus erityisesti tuotantolukujen valossa. *Arkistoraportti*, M. 578. Geologian tutkimuskeskus, Espoo. [in Finnish]
- Räsänen, M. L., A. Beucher, A. Tornivaara, & P. Kauppila, 2015. Suljettujen ja hylättyjen metallikaivosalueiden nykytila ja arvio jätealueiden ympäristöriskipotentialista. *Arkistoraportti* 46/2015. Geologian tutkimuskeskus, Kuopio: 129
- Rautio, M., 2000. Diatom and crustacean Zooplankton communities, their seasonal variability and representation in the sediments of subarctic Lake Saanajärvi. *Journal of Limnology* 59: 81–96. <https://doi.org/10.4081/jlimnol.2000.s1.81>.
- Renberg, I. & H. Hansson, 2008. The HTH sediment corer. *Journal of Paleolimnology* 40: 655–659. <https://doi.org/10.1007/s10933-007-9188-9>.
- Rothe, M., A. Kleeber, B. Grüneberg, K. Friese, M. Pérez-Mayo & M. Hupfer, 2015. Sedimentary sulphur:iron ratio indicates vivianite occurrence: A study from two contrasting freshwater systems. *PLoS ONE* 10: 1–18. <https://doi.org/10.1371/journal.pone.0143737>.
- Rühland, K. M., A. M. Paterson & J. P. Smol, 2015. Lake diatom responses to warming: reviewing the evidence. *Journal of Paleolimnology* 54: 1–35. <https://doi.org/10.1007/s10933-015-9837-3>.
- Salminen, S., M. Tammelin, T. Jilbert, Y. Fukumoto & S. Saarni, 2021. Human actions were responsible for both initiation and termination of varve preservation in Lake Vesijärvi, southern Finland. *Journal of Paleolimnology* 66: 207–227. <https://doi.org/10.1007/s10933-021-00200-1>.
- Salonen, V. P., N. Tuovinen & S. Valpola, 2006. History of mine drainage impact on Lake Orijärvi algal communities, SW Finland. *Journal of Paleolimnology* 35: 289–303. <https://doi.org/10.1007/s10933-005-0483-z>.
- Saros, J. E. & N. J. Anderson, 2015. The ecology of the planktonic diatom *Cyclotella* and its implications for global environmental change studies. *Biological Reviews* 90: 522–541. <https://doi.org/10.1111/brv.12120>.
- Schultze, M., B. Boehrer, K. Wendt-Potthoff, J. Sánchez-España, & D. Castendyk, 2017. Meromictic Pit Lakes: Case Studies from Spain, Germany and Canada and General Aspects of Management and Modelling. In Gulati, R. D., E. S. Zadereev, & A. G. Degermendzhi. (eds), *Ecology of Meromictic Lakes*. Springer Cham: 235–275. https://doi.org/10.1007/978-3-319-49143-1_9.

- Simola, H., & L. Arvola, 2005. Lakes of Northern Europe. In O'Sullivan, P. E., C.S. Reynolds. (eds), *The Lakes Handbook: Lake Restoration and Rehabilitation*, Vol. 2. Blackwell Publishing Ltd: 117–158. <https://doi.org/10.1002/9780470750506.ch5>.
- Sivarajah, B., J. B. Korosi, J. M. Blais & J. P. Smol, 2019. Multiple environmental variables influence diatom assemblages across an arsenic gradient in 33 subarctic lakes near abandoned gold mines. *Hydrobiologia* 841: 133–151. <https://doi.org/10.1007/s10750-019-04014-1>.
- Siver, P. A., 2015. Synurophyte Algae. In John D. Wehr, J. D., R. G. Sheath & J. P. Kociolek. (eds), *Freshwater Algae of North America: Ecology and Classification*. 2nd edition. Academic Press: 607–651. <https://doi.org/10.1016/B978-0-12-385876-4.00014-1>.
- Smol, J. P., 1985. The ratio of diatom frustules to chrysophytean statospores: A useful paleolimnological index. *Hydrobiologia* 123: 199–208. <https://doi.org/10.1007/BF00034378>.
- Smol, J. P., 2010. The power of the past: Using sediments to track the effects of multiple stressors on lake ecosystems. *Freshwater Biology* 55: 43–59. <https://doi.org/10.1111/j.1365-2427.2009.02373.x>.
- Smol, J. P., 2019. Under the radar: Long-term perspectives on ecological changes in lakes. *Proceedings of the Royal Society B: Biological Sciences* 286(1906): 20190834. <https://doi.org/10.1098/rspb.2019.0834>.
- Smol, J. P. & E. F. Stoermer, 2010. Applications and uses of diatoms: prologue. In Smol, J. P. & E. F. Stoermer (eds), *The Diatoms: Applications for the Environmental and Earth Sciences* Cambridge University Press: 3–7.
- Spaulding, S. A., M. G. Potapova, I. W. Bishop, S. S. Lee, T. S. Gasperak, E. Jovanoska, P. C. Furey & M. B. Edlund, 2021. Diatoms.org: supporting taxonomists, connecting communities. *Diatom Research* 36: 291–304. <https://doi.org/10.1080/0269249X.2021.2006790>.
- Spellerberg, I. F. & P. J. Fedor, 2003. A tribute to Claude-Shannon (1916–2001) and a plea for more rigorous use of species richness, species diversity and the “Shannon-Wiener” Index. *Global Ecology and Biogeography* 12: 177–179. <https://doi.org/10.1046/j.1466-822X.2003.00015.x>.
- Stenger-Kovács, C., V. B. Béres, K. Buczkó, K. Tapolczai, J. Padišák, G. B. Selmečzy & E. Lengyel, 2023. Diatom community response to inland water salinization: a review. *Hydrobiologia* 850: 4627–4663. <https://doi.org/10.1007/s10750-023-05167-w>.
- Tammelin, M. & T. Kauppila, 2018. Quaternary landforms and basin morphology control the natural eutrophy of boreal lakes and their sensitivity to anthropogenic forcing. *Frontiers in Ecology and Evolution* 6: 65. <https://doi.org/10.3389/fevo.2018.00065>.
- Tammelin, M., T. Kauppila & M. Viitasalo, 2017. Factors controlling recent diatom assemblages across a steep local nutrient gradient in central-eastern Finland. *Hydrobiologia* 799: 309–325. <https://doi.org/10.1007/s10750-017-3229-9>.
- Tornivaara, A., M. L. Räisänen, & H. Kovalainen, 2018. Suljetujen ja hylättyjen kaivosten kaivannaisjätealueiden jatkokartoitus (KAJAK II). Ympäristöministeriön julkaisuja 2020:16. Ympäristöministeriö, Helsinki: 157 [in Finnish, abstract in English]
- Tuovinen, N., K. Weckström & V. P. Salonen, 2012. Impact of mine drainage on diatom communities of Orijärvi and Määrjärvi, lakes in SW Finland. *Boreal Environment Research* 17: 437–446.
- Turunen, E., J. Koskinen, E. Pihko & T. Lukkarinen, 1960. Outokumpu Oy:n Kotalahden Kaivos. *Vuoriteollisuus* 2: 32–50.
- USEPA, 2007. Method 3015A: Microwave Assisted Acid Digestion of Aqueous Samples and Extracts. Revision 1, February 2007. Final Update IV to the Third Edition of the Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, EPA publication SW-846. Washington, D.C. 30
- Vähäkuopus, T., T. Kauppila, J. Mäkinen, A. E. K. Ojala & S. E. Valpola, 2020. Sedimentation patterns of multiple finnish lakes reveal the main environmental stressors and the role of peat extraction in lake sedimentation. *Geosciences* 10: 1–32. <https://doi.org/10.3390/geosciences10080313>.
- Vasara, H., J. Pokki, B. Långbacka, & M. Kivinen, 2023. Kaivosalan toimialaraportti. TEM toimialaraportit 2023:4. Työ- ja elinkeinoministeriö, Helsinki: 125. [in Finnish, abstract in English]
- Vestola, E., & U. M. Mrueh, 2008. Sulfaatinpelkistyksen hyödyntäminen happamien kaivosvesien käsittelyssä. Opas louhoskäsittelyn hallintaan. VTT Tiedotteita - Research Notes 2422. Espoo: 58
- Weckström, K. & S. Juggins, 2005. Coastal diatom-environment relationships from the Gulf of Finland, Baltic Sea. *Journal of Phycology* 42: 21–35. <https://doi.org/10.1111/j.1529-8817.2005.00166.x>.
- Werner, P. & J. P. Smol, 2005. Diatom-environmental relationships and nutrient transfer functions from contrasting shallow and deep limestone lakes in Ontario, Canada. *Hydrobiologia* 533: 145–173. <https://doi.org/10.1007/s10750-004-2409-6>.
- Wetzel, R. G., 2001. *Limnology: lake and river ecosystems*, Academic Press, San Diego:
- Winder, M., J. E. Reuter & S. G. Schladow, 2009. Lake warming favours small-sized planktonic diatom species. *Proceedings of the Royal Society B: Biological Sciences* 276: 427–435. <https://doi.org/10.1098/rspb.2008.1200>.
- Zhao, S., M. Hermans, J. Niemistö, J. Vesterinen & T. Jilbert, 2024. Stratification controls the magnitude of in-lake phosphorus cycling: insights from a morphologically complex eutrophic lake. *Hydrobiologia* 852: 359–376. <https://doi.org/10.1007/s10750-024-05701-4>.
- Zhou, C., Y. Peng, L. Chen, M. Yu, M. Zhou, R. Xu, L. Zhang, S. Zhang, X. Xu, L. Zhang & G. Wang, 2022. Rapidly increasing sulphate concentration: a hidden promoter of eutrophication in shallow lakes. *Biogeosciences Discussions* 2022: 1–28. <https://doi.org/10.5194/bg-19-4351-2022>.
- Zolitschka, B., P. Francus, A. E. K. Ojala & A. Schimmelmann, 2015. Varves in lake sediments - a review. *Quaternary Science Reviews* 117: 1–41. <https://doi.org/10.1016/j.quascirev.2015.03.019>.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.