



Diatom and biogeochemical changes during recent centuries in a small boreal lake: deciphering the influence of large volcanic eruptions

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ABSTRACT

Volcanic eruptions can have severe societal and environmental impacts as shown by ash dispersal and sulphur emissions from recent Icelandic eruptions. However, ice-core sulphur records demonstrate that these events were minor as compared to eruptions of much larger magnitude in recent centuries, with severe implications for past society documented in historical records. Biological and chemical evidence of these events can be found in highly resolved varved sediment records. Such records can provide insight into the responses and resilience of lake ecosystems and surrounding catchments following widespread atmospheric perturbations brought about by large volcanic eruptions. In this study we analysed varved sediments spanning the period 1641–1931 CE from Lake Kassjön, a small boreal lake in northern Sweden. We aimed at assessing the potential impacts of the Icelandic eruption of Laki 1783–1784 and the Indonesian eruption of Tambora (1815), based on diatom analysis in combination with organic and inorganic geochemical analyses at sub-decadal resolution. To provide site-specific process understanding, we also assessed the impacts of an intensive ditching operation, which is known to have occurred in 1900–1902 CE. While no significant responses to the eruption of Tambora were identified, our findings indicate enhanced weathering of minerals in the catchment following the eruption of Laki and changes in nutrient dynamics reflected by multiple decades of succession in the diatom assemblage. In timing with Laki, we found an immediate and sustained increase in the concentrations of *Aulacoseira tenella*. Increased delivery of terrestrial organic matter to the lake and altered nutrient dynamics persisted for around half a century following the eruption of Laki, coinciding with elevated diatom productivity. With consideration of available land-use records, we identify a series of mechanisms as potentially responsible for the immediate responses of the diatom assemblage as well as the more long-lasting effects on the aquatic environment mediated by catchment processes.

1. Introduction

Volcanic eruptions are important contributors of sulphur dioxide (SO_2) emission to the atmosphere with an estimated global discharge of 23 Tg (10^{12}g) SO_2/yr between 2005 and 2015 (Carn et al., 2017). Sulphur deposition and ash dispersal from volcanic activity can have severe impacts on ecosystems as well as on human health and society. The largest effusive Icelandic eruption in recent years, Bárðarbunga-Veiðivötn (Holuhraun) in 2014–15, emitted 11 Tg of SO_2 over six months and caused a persistent deterioration of air quality and affected the chemistry of snow and rainfall around Iceland (Galeczka

et al., 2016; Ilyinskaya et al., 2017; Stefánsson et al., 2017), but periodic impacts on air quality were also detected as far as 2750 km away (Schmidt et al., 2015). While Holuhraun released the equivalent of six months of global volcanic SO_2 emissions based on 2005–2015 measurements (Carn et al., 2017), this is a minor amount compared to historical events of much larger magnitude (Sigl et al., 2015). Two of the largest eruptions documented in the past three centuries; Laki, 1783–84 CE (Iceland) and Tambora, 1815 CE (Indonesia), had far greater consequences. With an estimated discharge of 122 Tg of SO_2 from the former (Thordarson and Self, 2003) and 80 Tg from the latter (Oppenheimer, 2003; Wirakusumah and Rachmat, 2017), these events

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were associated with major losses of livestock, crop failure, famine, and climatic perturbations ultimately contributing to tens of thousands of human deaths (Oppenheimer, 2003; Thordarson and Self, 2003).

While the societal impacts of past major eruptions are well documented in historical records, the environmental impacts must be studied retroactively, such as through geochemical and biological analyses of natural archives, for example, peatlands, lake-sediment records and ice cores (Abbott and Davies, 2012; Van Daele et al., 2014; Watson et al., 2016). Perhaps the strongest indicator of past volcanic events is the presence of tephra; volcanic material ejected during an eruption (Thorarinsson, 1944; Kittleman, 1979). Such material can travel large distances and be recovered hundreds of kilometres away from the source (Scollo et al., 2013). Tephra and cryptotephra are abundant in natural archives in Sweden, and Late Quaternary tephrochronology is well defined and has been discussed in detail by Wastegård (2005). When tephra is absent, which is common at distances far from the eruption zone, environmental changes associated with volcanic events may be inferred from biological and chemical analyses of lake sediments (Mills et al., 2017).

The ecological impacts of a volcanic event depend heavily on the type and duration of its disturbance. An eruption can influence local lake ecosystems for many years after the initial event, until nutrient dynamics and geochemical processes in their catchments stabilise (Carrillo and Díaz-Villanueva, 2021). Such disruptive potential can be extended to lakes at greater distances because volcanic aerosols and tephra can travel hundreds of kilometres away from the eruption centre (Payne and Egan, 2019). For example, the 1783–84 eruption of Laki brought acidic fog and associated damage of vegetation to many places in Europe (Grattan, 1998), and the eruption of Tambora in 1815 was associated with significant cooling (“the year without summer”) in both North America and Europe (Raible et al., 2016). Despite the documented effects of these events on past societies and terrestrial ecosystems (predominantly concerning agriculture), the potential biogeochemical responses of distant lake ecosystems to these two eruptions are still poorly documented.

To assess the responses of a lake ecosystem and its catchment to volcanism-related disturbance, such as acid deposition and climatic perturbations, a multi-proxy study of lake sediments at high-temporal resolution is desirable. Geochemical fingerprinting is standard in tephrochronological studies, where the elemental composition of a tephra deposit serves to identify the volcanic source of the layer in question (De Maisonneuve and Bergal-Kuvikas, 2020). Measurements of sulphur (S), chlorine (Cl), and fluorine (F) in tephra samples allowed Thordarson et al. (1996) to quantify degassing and atmospheric loading after the eruption of Laki, although this was limited to Iceland. Corresponding geochemical evidence of biotic and abiotic responses of lake ecosystems distant from the source of an eruption, especially in the absence of tephra, is scarce. In addition, geochemical proxies are also sensitive to changes in land use and climate (Anderson, 2014), which justifies the use of biological proxies, such as diatoms, as complementary sources of evidence of the effects of distant volcanic eruptions. Diatoms are globally distributed aquatic microorganisms, which are highly responsive to physical, chemical and biological shifts in lake ecosystems (Reavie and Edlund, 2010). Diatoms may respond rapidly to volcanic acid deposition due to their sensitivity to changes in their environment, including water pH (DeNicola, 2000; Payne and Egan, 2019). In previous studies, diatoms have been used to unravel the influence of volcanism at different spatial scales, and responses of diatom communities to tephra deposition have been frequently reported (Cruces et al., 2006; Andrén et al., 2015). Even in the absence of tephra, acid deposition following the eruption of Laki 1783–84 has been associated with increased nutrient cycling and blooming of opportunistic diatom species in a sub-arctic peatland in northern Sweden (Kokfelt et al., 2016). An attempt at identifying such effects on a lake ecosystem in southern Sweden was presented by Silvester et al. (2025).

In this study we analysed varved sediments from Kassjön, a small

boreal lake in northern Sweden, which has annually laminated (varved) sediments following lake formation c. 6350 cal yr BP until ditching operations in 1902 CE disrupted varve formation (Anderson et al., 1994, 1995). We analysed the sediment record from 1641 to 1931 with the objective of assessing the potential ecological impacts of the two large and historically well-documented eruptions of Laki 1783–84 and Tambora 1815. The precise chronology afforded by varves provide an opportunity to assess these specific time periods. A challenge for our question is that previous research had shown changes in the diatom community following the initiation of agriculture at Kassjön from c. 1200 CE (Anderson et al., 1995). The fine-grained, relatively nutrient-rich soils in Kassjön’s catchment that contributed to the necessary conditions for varve formation in the lake (Renberg, 1981) were also soil conditions attractive for agriculture. To address our objective of teasing out potential effects of these historic eruptions, we applied the highest temporal resolution of sub-sampling as was practically possible, with three main aims. Our first aim was to characterise the biogeochemical dynamics of the lake and its catchment and assess the stability of the diatom assemblage prior to the eruption of Laki in 1783–84. Our second aim was to identify and characterise any potential responses of the diatom community coinciding with the two eruptions. Finally, we intended to evaluate the persistence of, and the recovery from, any observable disturbance to the diatom community identified in the period of interest.

Based on available historical evidence and modelling studies (Stevenson et al., 2003; Schmidt et al., 2010), we hypothesised that S deposition following the eruption of Laki in 1783–84: 1) damaged vegetation in the catchment leading to an increase in the supply of organic matter and nutrients to the lake; 2) increased the rate of mineral weathering and facilitated the leaching of mobile elements from catchment soils to the lake; and 3) altered the physicochemical conditions of lake waters with immediate consequences for the biota of the lower-trophic levels, including diatoms. We also hypothesised that a signal of the eruption of Tambora in 1815, if present in the record, would reflect hydroclimatic conditions in the Northern Hemisphere following the eruption and that its potential impacts may be dependent on the severity and persistence of any disturbance attributed to Laki and the subsequent state of recovery of the lake and its catchment. To address these hypotheses, we applied a combination of diatom and geochemical analyses to contiguous sediment samples at predominantly sub-decadal resolution with the chronological control offered by varved sediments.

2. Study site and land-use history

Kassjön (63° 55' N, 20° 01' E) is a dimictic lake situated at 84 m a.s.l in Umeå municipality, Västerbotten, Sweden (Fig. 1). It has a maximum depth of 12.5 m, a relatively small volume of 1.24 Mm³, a surface area of 0.22 km², and a catchment area of 6.19 km². The lake has three main inlets – on the western, northern and northeastern sides (the latter naturally one stream, but after ditching two adjacent streams), and a well-defined outlet at the southern end. The catchment is dominated by clayey and silty deposits from the Ancylus Lake stage of the Baltic Basin, particularly on the western and northern sides of the lake and a thin strip along the eastern shore, followed by till on the eastern side of the catchment with some outcrops on the western edge of the catchment. Peat also occurs along the northeastern inlet stream.

Kassjön contains over 5 m of varved sediments at water depths greater than 10 m (Anderson et al., 1994, 1995), dating to its origin around 6350 cal. BP as a result of isolation following isostatic uplift (Petterson, 1999). Varves are continuous from the formation of the lake until 1900–02 CE, when a major ditching operation was performed in the nearby farmland, leaving a distinctive clay layer in the sediment record (Anderson et al., 1994). Ice covers the lake for 6–7 months during normal winters and annual sediment deposition reflects a typical boreal setting. Snowmelt in spring delivers minerogenic matter, which forms a light spring lamina. Organic matter and biogenic silica are deposited

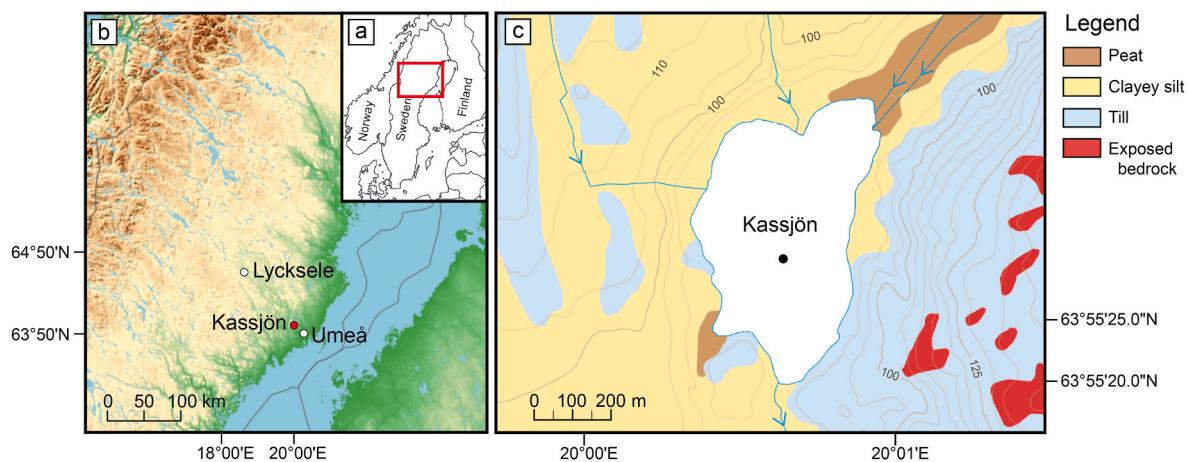


Fig. 1. Location of Kassjön in Sweden, showing **a.** the regional setting, **b.** elevation map generated through OpenTopoMap (OpenTopoMap, n.d., CC BY-SA, using data from OpenStreetMap Contributors, n.d., CC BY-SA), and **c.** map of Quaternary deposits from the Geological Survey of Sweden, with a black circle showing the coring location in the deepest part of the lake. See Anderson et al. (1995) for the bathymetry of the basin.

during the summer and autumn months. Fine-grained organic matter settles out of suspension during the ice-cover season, forming a dark winter lamina. The result is a mixed clastic-biogenic varve type, with a sharp winter-spring boundary (Zolitschka et al., 2015).

Pollen analyses indicate that cultivation in the catchment was established from c. 1200 CE (Segerström, 1990; Anderson et al., 1995) as reflected by gradual increases in apophytes (native plants favoured by human disturbance, such as sorrel (*Rumex*) and Poaceae) and anthropochores (cultivated plants, such as rye and barley), as well as a distinct increase in the planktonic diatom accumulation rate in the deep sediments (Anderson et al., 1995). Apophytes more than doubled after c. 1790 CE, which paralleled a rapid increase in population in the parish of Umeå (Palm, 2000), which included the village of Kassjö, from 3800 in 1751 CE to 5850 in 1780 CE and 8500 in 1805 CE. Importantly, livestock, which probably increased correspondingly in numbers, were not grazed in the infields surrounding the home farms nor on the meadows, which provided valuable fodder, but were typically grazed in the surrounding forest during the summer (Eriksson et al., 2021).

The oldest historical maps from the digital archives of Lantmäteriet (2024) covering the Kassjön area are from 1690 and 1785 CE (detailed in Table S1). The 1690 map shows well-established farming surrounding the lake, with enclosed infields along the western and northern sides of the lake and enclosed meadows along the eastern side of the lake. The surrounding forest was held in common by the village of Kassjö. The more specific detail in the 1690 map shows four farmhouses and enclosed cultivated soils within the infields. The land use indicated in these two maps coincides with the distribution of quaternary deposits, where the infields are on the clayey-silty deposits, as are the meadows along the eastern shore as outlined in the 1690 map. In the 1785 map, the distinction is somewhat expanded meadows on the eastern side of the lake and particularly further up along the northeastern inlet stream. A land reform map from 1803 details the partitioned land use of the five farms, all bordering the western side of the lake. This map indicates some expansion in land use, particularly in the northern part of the catchment. Maps produced in 1851–52 show further partitioning of allotments, almost double the number of buildings and early draining efforts in the northern vicinity of the lake.

3. Materials and methods

3.1. Core treatment, varve counting and subsampling

A 79-cm sediment sequence was obtained in March 2019 at a water depth of 12.06 m, using a freeze corer (Renberg and Hansson, 2010). The core was kept frozen during transport and was stored in a freezer

room during cleaning, imaging, and subsampling. The frozen core was photographed using a $2 \times$ macro lens with a polarising filter to enable detailed documentation under stable conditions.

Varve counting using images of the core was then conducted by two observers, using the 1900–02 CE clay horizon as a reference point (Fig. S1). Varve counting below this horizon yielded a solid agreement between the independent counts of the two observers, with a maximum uncertainty of ± 1 varve in the interval of 1712–1931 CE and ± 3 varves in the interval of 1641–1712 CE. Absolute and cumulative uncertainties of the varve counts were calculated based on the difference in the number of varves counted at frequent intervals. Based on the varve counts, the sediment record analysed in this study covers the period of 1641–1931 CE. All dates hereafter refer to the current era (CE).

Sampling was performed using a ceramic scalpel under frozen conditions. Samples were taken according to clearly discernible varve boundaries to the unaided eye and the sample resolution is therefore variable. The sampling followed the boundaries between the darker winter laminae and the lighter spring laminae. For example, a sample spanning the years 1779–1785 contains sediments deposited from the onset of the spring lamina formation in 1779, to and including the dark winter lamina of 1784–85. Table S2 shows the sample boundaries in further detail and associated age uncertainties. Within the interval of 21–40 cm depth, 46 contiguous samples were obtained, covering the period of 1641–1931, yielding an average sample span of 6 years (rounded), with a range of 2–14 years. Aliquots for various analyses were collected from each sample following freeze drying and homogenisation.

3.2. Diatom analysis

Aliquots of 15 mg of dry material from each of the 46 samples were treated with HCl and H₂O₂ for digestion of calcium carbonates and organic matter, respectively, using the water bath method (Renberg, 1990). To quantify the concentration of diatom frustules, a known concentration of divinylbenzene (DVB) microspheres was added to each sample, following digestion. Diatom concentrations are presented as the number of diatom frustules per gram of dry sediment weight (frustules gdw⁻¹). Microscope slides for diatom analysis were produced using Naphrax mountant. At least 500 diatom valves per slide were counted at a magnification $\times 1000$, and contemporary resources including Nakov et al. (2015), Lange-Bertalot et al. (2017) and Heudre et al. (2021) were consulted for species identification. Chrysophycean stomatocysts were counted in addition to diatoms. In total, 238 diatom species belonging to 69 genera were identified. Scanning electron microscopy (SEM) was used to confirm the identification of species within the genus *Aulacoseira*

Thwaites and small species, including those within the order *Achnanthes* Silva.

For all samples, a minimum diatom counting efficiency of 84.4 % (average = 87.1 %, $\sigma = 1.5$) was achieved (Pappas and Stoermer, 1996). Rare species comprising less than 1 % of the assemblage accounted for a maximum of 13.5 % of the total in all samples (average = 8.7 %, $\sigma = 2.4$). Excluding rare species, the minimum counting efficiency achieved was 90.8 % (average = 92.1 %, $\sigma = 0.7$). Observed species richness was compared with rarefied species richness to inspect for biases related to observation efforts, and species accumulation rate was calculated to ensure a sufficient number of observations were made (Fig. S2).

3.3. Geochemical analyses

To identify changes in elemental composition, semi-quantitative X-ray Fluorescence (XRF) measurements were obtained using a Bruker S1 Titan handheld instrument at the Department of Ecology and Environmental Science, Umeå University, using at least 200 mg of dry material per sample. XRF measurements of oxides were converted to elemental concentrations for further analysis. Trace elements and elements with large uncertainties based on regular duplicates were excluded from further analysis.

We consider titanium [Ti], a stable component in clays and minerals, as representative of detrital input from the catchment and use it as a constraining variable in elemental ratios for comparison with the proportion of other elements including aluminium [Al], iron [Fe], potassium [K], sulphur [S], silicon [Si] and phosphorus [P] (Demory et al., 2005; Metcalfe et al., 2010; Boës et al., 2011). The K/Al ratio is assessed as an indicator of erosion and chemical weathering, because K is more susceptible to chemical weathering than Al in clay minerals (Burnett et al., 2011). In addition to BSi content, used to assess the biogenic component of silica in the sediments (Conley and Schelske, 2001), the Si/Ti ratio and the Si/Al ratios are assessed as proxies of biogenic and siliciclastic input (Peinerud et al., 2001). The Zr/Rb ratio is used as a qualitative proxy for grain-size variations (Kylander et al., 2011).

Contents of total carbon (TC), total organic carbon (TOC) and total nitrogen (TN) contents were determined using a Costech ECS4010 elemental analyser at the department of Geology, Lund University. For TOC content determination, a minimum of 5 mg of dry material per sample was packed into Ag capsules, followed by wrapping in Sn capsules and decalcification via iterative application of 50 μ l of HCl in a fume hood until nil effect. Elemental TOC/TN ratios were converted to atomic ratios by multiplication with 1.167.

Biogenic silica (BSi) content was determined using the method described by Conley and Schelske (2001). A 1 % solution of Na₂CO₃ was used for sample digestion in a shaking water bath and extractions were taken after 3, 4 and 5 h, with frequent duplicates. Extractions were neutralised with HCl before cooling. Ammonium molybdate was added to quantify dissolved silicon (dSi) content via spectrophotometric measurement of molybdate blue using a Smartchem 200 (AMS System) wet chemical analyser. BSi concentrations were determined by the intercept of a least-squares regression of dSi data.

3.4. Data treatment and numerical analysis

3.4.1. Biogeochemistry

To assess the factors characterising the changes in sediment properties across samples, TOC, TN and BSi contents as well as elemental data from XRF measurements were standardised and included in a principal component-based factor analysis using varimax rotation to maximise the variance of loadings within each factor, using IBM SPSS Statistics 29 (IBM Corp, 2022). Variables were iteratively removed if the sum of squared factor loadings was less than 0.5.

3.4.2. Diatoms

Hill's N2 diversity (effective number of species) of the diatom

assemblage was estimated based on equal-coverage for robust comparison between samples (Roswell et al., 2021), using the R package MeanRarity (Roswell and Dushoff, 2020). To assess the temporal changes, a stratigraphically constrained incremental sum of squares (CONISS) clustering of Hellinger-transformed diatom concentration data was performed using the R package Rioja (Juggins, 2019), based on the Euclidean distances between samples. The number of significant clusters was determined using the broken stick model, although a larger number of clusters are used to define diatom zones for practical interpretation. The relative proportion of diatom frustules to chrysophycean stomatocysts was calculated following Smol (1985). To assess changes in diatom community structure, tychoplanktonic species were treated with planktonic species in the calculation of both the relative proportion of planktonic to benthic diatoms and the relative proportion of planktonic centric to planktonic pennate diatoms.

3.4.3. Diatom-based pH reconstruction

Two diatom-inferred pH (DI-pH) reconstructions were produced using the program C2 (Juggins, 2007). A 167-lake training dataset from the Surface Water Acidity Programme (SWAP) (Battarbee and Renberg, 1990), encompassing England, Scotland, Wales, Sweden and Norway, was used to produce the 'SWAP' reconstruction, and a 100-lake training dataset from northern Sweden was used to produce the 'Arctic' reconstruction (Bigler and Hall, 2002). Both reconstructions use species codes according to the European Diatom Database Initiative (EDDI) (Battarbee et al., 2001). The contemporary nomenclature of each of the 238 observed species was cross-referenced with nomenclature used by the EDDI database for harmonisation. *Aulacoseira pusilla* (Meister) Tuji & Houki was pragmatically aggregated with *Aulacoseira subarctica* (Müller) Haworth on the basis that the former was described after both transfer functions were developed and their combined proportions in this study similarly reflect the proportions of *A. subarctica* in a previous study of varved sediments from the same lake (Anderson et al., 1995). The average sample coverage, or the proportion of the diatom community present in the transfer function and actively included in the reconstruction, is 79.9 % ($\sigma = 4.4$) in the SWAP reconstruction and 78.9 % ($\sigma = 4.6$) in the Arctic reconstruction. Both reconstructions were performed using weighted-averaging partial least squares (WA-PLS) regression, with 10,000 bootstrap iterations to assess model stability. The average uncertainty of DI-pH is 0.08 pH units ($\sigma = 0.01$) in the SWAP reconstruction and 0.11 pH units ($\sigma = 0.01$) in the Arctic reconstruction.

4. Results and interpretation

4.1. Sediment composition

The sediments contain BSi and TOC contents in the ranges of 3.1–18.4 % and 2.2–11.5 %, respectively. XRF measurements of Si range between 16.9 and 22.3 %. Aluminosilicate clays are represented by Fe (4.8–7.8 %) and Al (1.6–3 %), and partly by Si, which is also related to BSi content. XRF measurements of Ti and K show generally similar trends compared with the record of sediment accumulation rates presented by Brännvall et al. (1999), as shown in Fig. S2. Together with Al, both K (0.6–1.2 %) and Ca (0.7–1 %) have a predominantly minerogenic origin, closely following the trend of Ti (0.3–0.5 %).

Variations in sediment composition are primarily attributed to changes in the proportions of minerogenic material, organic matter, and biogenic silica. The factor analysis of biogeochemical data (Fig. 3) explains 77 % of the variance in the first (FA1: 52 %) and second factors (FA2: 25 %). Variables separated on the FA1 axis represent differences between samples with greater BSi and TOC contents (negative values) and greater minerogenic content (positive values). Variables separated on the FA2 axis represent differences between samples with greater content of total Si (and to a lesser extent minerogenic matter; negative values), and elements that are typically more mobile and those

commonly associated with changes in the water column and redox conditions (Fe, S, Mn, P), in addition to TOC content (positive values). Total Si is oriented almost perpendicularly to BSi content and positively on the FA1 axis, indicating that the factor analysis robustly differentiates between the indiscriminate (semi-quantitative XRF) measurements of total Si and the biogenic fraction of Si (quantitative measurements).

Many of the oldest samples are positioned centrally on FA1 and positively on FA2, indicating a greater association with organic material. Multiple samples from the mid-1700's are positioned negatively on both axes, indicating a greater association with BSi content (negative FA1 values) and a weaker association with both minerogenic components (which are positioned positively on FA1) and organic components (positioned positively on FA2). The position of samples from the late 1700's rises along FA2, reflecting an increasing association with organic components. Samples from the early 1800's decline along both FA1 and FA2, partly reflecting a decline in clastic input concurrent with an increase in BSi content. Samples with the greatest FA1 scores are associated with the ditching operation in 1900–02 and reflect an incremental decline in minerogenic content as sediment input stabilised in the following years.

The sample containing sediments encompassing the eruption of Laki (labelled 1779 in Fig. 3 and covering the years 1779–85) is positioned neutrally along both axes and the following sample (labelled 1785 and covering the years 1785–92) is aligned closer to organic components (negatively along FA1 and positively along FA2). The sample containing sediments encompassing the eruption of Tambora (labelled 1808 and covering the years 1808–1816) is positioned negatively along FA1, neutrally along FA2 and near a cluster of samples from the early 1800's with a stronger association with BSi content versus both organic and minerogenic components.

4.1.1. Biogenic silica and total organic carbon contents

Prior to the ditching in 1900–02, BSi and TOC contents are in the ranges of 8.2–18.4 % and 4.5–11.5 %, respectively. In the pre-Laki period (1641–1779) BSi content increases gradually within the range of 8.2–13.1 %, coinciding with a generally declining trend in TOC content, which has greater variability in the range of 5.4–11.2 %. The most pronounced increase in TOC content, of 70 %, occurs between 1779–85 (6.75 %) and 1785–92 (11.5 %), coinciding with a 27 % increase in BSi content (to 12.4 %). BSi content continues to increase beyond 1792, to its second highest proportion in 1820–27 (17.6 %), a 79 % increase versus 1779–85 (9.8 %). Following a transient decrease around 1835, BSi content rises to its maximum proportion in 1845–47 (18.4 %). TOC content remains high after its initial increase (1779–1792) until a marked decline after 1845–47, remaining in the range of 4.54–5.98 % until 1900. BSi content decreases substantially after 1845–47, followed by relatively stable values in the range of 9.8–11.4 % until 1900. Both BSi and TOC contents fall to their lowest proportions of 3.1 % and 2.2 %, respectively, in sediments associated with the ditching in 1900–02. This is followed by a steady increase in both BSi and TOC contents to 9.2 % and 5.25 %, respectively, to 1931 (end of the record).

Both the Si/Ti ratio (Fig. 4) and the Si/Al ratio are commonly used as a proxy to distinguish between biogenic and siliciclastic input (Peinerud et al., 2001). Both the Si/Ti ratio and Si/Al ratios are strongly correlated with BSi content (Fig. 4 inset; $R^2 = 0.83$ and 0.81, respectively), demonstrating their reliability as a proxy for changes in BSi content in these sediments (Balascio et al., 2011; Kylander et al., 2011; Melles et al., 2012).

4.1.2. Detrital input

Variations in Ti content closely follow the fluctuations in sedimentation rate determined by Brännvall et al. (1999), demonstrating the consistency of the varve record (Fig. S3). Prior to 1900, Ti ranges between 0.3 and 0.38 % and fluctuates in timing and contrasts with the contents of BSi and TOC, showing an initial decline between 1779 and

1792 followed by a sharp increase after 1852, to 0.38 % (Fig. 2). Ti indicates stable and consistent detrital input in the late 1800's. The ditching in 1900–02 coincides with a 30 % increase in Ti to its maximum value of 0.48 %. The proportions of Al, Ca and K are closely aligned with the proportions of Ti throughout the record. Accordingly, the ditching is associated with significant increases in Al (from 2.2 to 3.0 %), Ca (from 0.9 to 1.0 %), and K (from 0.9 to 1.2 %), representing their maximum proportions throughout the record. In the 28 years following the ditching operation, Al, Ca, K, and Ti decline, recovering to proportions comparable to those of the late 1800's.

4.2. Diatom assemblage

A total of 238 species belonging to 69 genera were identified, of which 17 species exceed a relative abundance of 3 % in at least one sample (Fig. 5). A minimum of 62 % of the assemblage consists of planktonic and tychoplanktonic species (average = 78 %, $\sigma = 8.8 \%$). The mean proportion of benthic species is 21 % ($\sigma = 5 \%$). The tychoplanktonic species *Tabellaria flocculosa* (Roth) Kützing is the dominant species in most samples. There is a negative relationship between the relative proportions of *T. flocculosa* and both the relative proportions of planktonic centric species and Hill's N2 diversity index. The proportion of *T. flocculosa* relative to centric species (mostly consisting of *Aulacoseira*) explains most of the changes in the relative proportions of planktonic centric and planktonic pinnate diatoms as few exclusively planktonic pinnate species were present, of which, only *Asterionella formosa* Hassal is dominant (exceeding a threshold of 3 %).

CONISS clustering revealed five consecutive periods of distinct community composition. The first branch of separation determined by CONISS separates the period before and after 1779 (Fig. 5), which corresponds to the two significant clusters identified by the broken stick model and coincides with the sharp increase in *Aulacoseira tenella* (Nygaard) Simonsen 1979 and the relative decline in *T. flocculosa* (Fig. 5). The second branch of separation falls at 1738 coinciding with the first occurrence of *Lindavia rossii* (Håkansson) Nakov et al. (2015), the third branch of separation falls at 1845 and the fourth branch of separation falls at 1665 and is distinguished by a sharp increase in the relative abundance of *Aulacoseira pusilla* (Meister) Tuji & Houki. The community composition of the resulting diatom zones (DZ 1–5) are summarised below together with a brief description of changes in total diatom concentration, BSi content and diatom-inferred pH.

4.2.1. DZ-1 (1641–1665)

The diatom community is dominated by *T. flocculosa* (15–25 %) and *A. alpigena* (10–13 %), with minor contributions (<10 %) of *Aulacoseira ambiguia* (Grunow) Simonsen and *Stauroforma exiguum* (Lange-Bertalot) Flower, Jones & Round. The proportions of planktonic centric and planktonic pinnate diatoms are nearly equal. The proportion of benthic species ranges between 25 and 31 % and the Hill's N2 diversity index declines from 19 to 11. BSi content (averaging 8 %) and diatom-inferred pH (SWAP ~6.2, Arctic ~6.4) are stable. Diatom concentrations decline significantly from an initial value of over 180×10^6 frustules gdw^{-1} (around 1645) to 50×10^6 frustules gdw^{-1} around 1653. The relative proportion of diatoms to chrysophytes exceeds 90 %.

4.2.2. DZ-2 (1665–1738)

Tabellaria flocculosa continues to dominate overall, surpassed only by *A. pusilla* between 1665 and 1684. There is a notable contribution of *Discostella stelligera* (Cleve & Grunow) Houk & Klee around 1665–1673 in timing with the initial increase of *A. pusilla*. The proportion of planktonic centric diatoms declines from 75 % to 50 % in timing with a relative increase of *T. flocculosa* and a decline of *A. pusilla*. Hill's N2 diversity index ranges from 7 to 11. While the BSi content remains stable in the range of 8.2–13.1 %, the total diatom concentration declines more than 80 % from its initial peak of over 210×10^6 frustules gdw^{-1} around 1670 to 35×10^6 frustules gdw^{-1} around 1718, in timing with declining

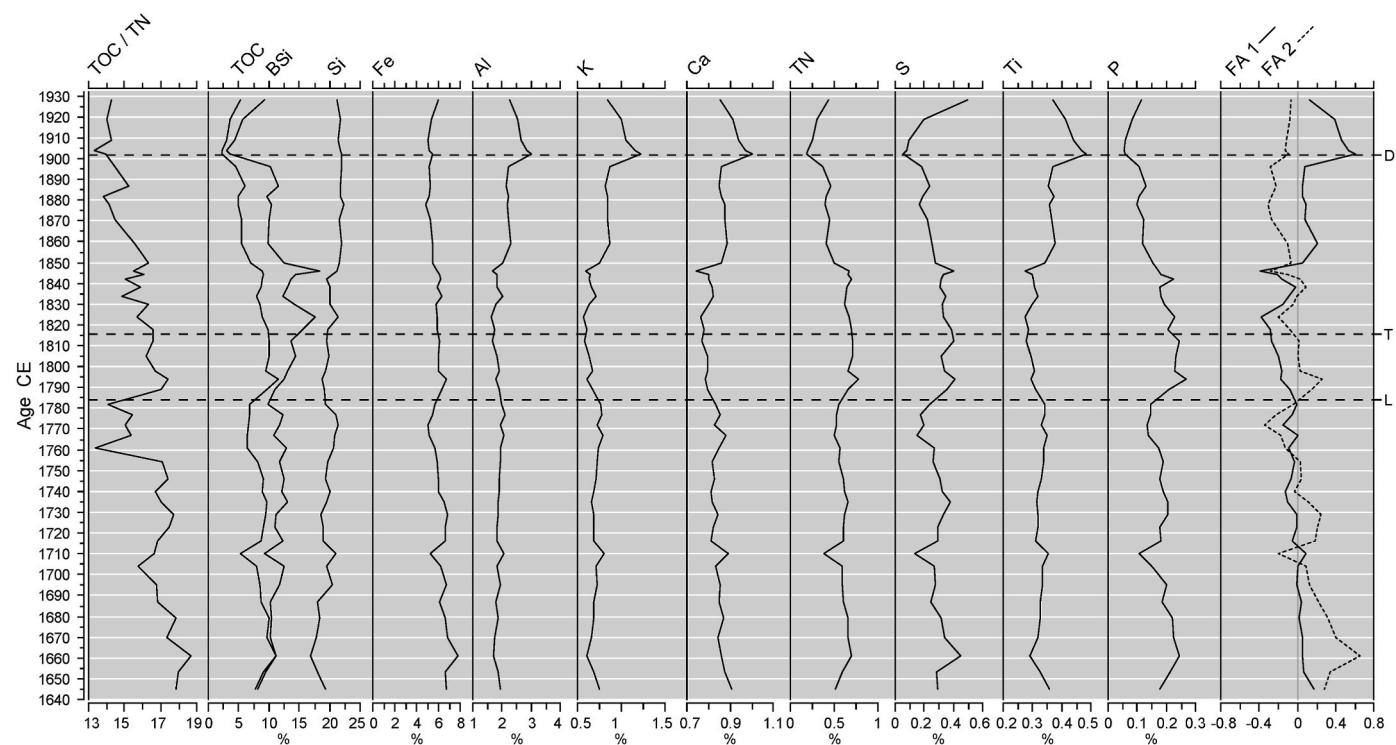


Fig. 2. Biogeochemical data plotted against sediment age (y-axis) based on varve counts. Dashed horizontal lines indicate the eruptions of Laki (L), Tambora (T) and the ditching operation (D) and are labelled on the right. Note that although different analyses were used to determine TOC content (quantitative data), BSi content (quantitative data) and Si (semi-quantitative XRF data), they are overlayed (not stacked) in a single plot to ease interpretation. From left to right: atomic TOC/TN ratio, TOC content plotted together with BSi content and Si (XRF), TN content, XRF-based elemental counts with proportions above 0.2 % (Fe, Al, K, Ca, S, Ti and P), and sample scores of the first two factors of the factor analysis (Fig. 3).

contributions of *A. pusilla* and *D. stelligera*, and accordingly, the proportion of planktonic centric diatoms. Diatom-inferred pH decreases to 6.0 (SWAP) and 6.3 (Arctic) from 1684, in timing with a decline of 8 % in the proportion of diatoms to chrysophytes, and DI-pH then stabilises at 6.3 (SWAP) and 6.5 (Arctic).

4.2.3. DZ-3 (1738–1779)

This zone remains dominated by *T. flocculosa* and species of *Aulacoseira* and represents the most stable period in terms of BSi contents, diatom concentrations and community structure. The first occurrence of *L. rossii* is recorded from 1738 with a maximum abundance of 15 % in DZ-3. The proportion of planktonic centrics remains around 40–50 %, whereas Hill's N2 index declines slightly to the range of 4–7. Following on from DZ-2, BSi contents remains stable and there is an increase of approximately 50 % in diatom concentrations, reflecting the decline in *T. flocculosa* and the increase in smaller species of *Aulacoseira*. DZ-3 contains the longest period of discrepancy between the two pH reconstructions despite both remaining within the range of around 6.0–6.5. The proportion of diatoms to chrysophytes increases slightly versus DZ-3, exceeding 90 %.

4.2.4. DZ-4 (1779–1845)

Tabellaria flocculosa initially declines by 56 %, to 17 %, coinciding with a significant increase in the relative abundance of *A. tenella*, which was low in abundance in previous zones, to a proportion of 21 %. This zone is dominated by species of *Aulacoseira*, with large contributions of *A. tenella* and *A. pusilla*. *Tabellaria flocculosa* trends lower overall compared to DZ-3, with notable declines around 1779–85, 1792–1801 and 1832–40, and some stability between 1808 and 1832 at proportions of 25–30 %. The proportion of planktonic centric diatoms fluctuates in the range of 50–60 %, closely following variations in the proportion of *Aulacoseira* species, predominantly *A. tenella* and *A. pusilla*, relative to those of *T. flocculosa*. Hill's N2 index varies from 6 to 14 with greater

values corresponding to larger contributions of benthic species. A 31 % increase in BSi content, to 14.4 %, occurs between 1779 and 1827. This coincides with an increase in total diatom concentration, initially to 193×10^6 frustules gdw^{-1} by 1808 before stabilising around 140×10^6 frustules gdw^{-1} . The SWAP pH reconstruction declines from around 6.15 (1774–79; in DZ-3) to 6.05 in 1779–85, in timing with a decline in the Arctic pH reconstruction from 6.41 (1774–79; in DZ-3) to 6.31 (1779–85), and both reconstructions then remain in the range of 6.0–6.6. Elevated total diatom concentration occurs from 1801–08, when the proportion of diatoms to chrysophytes declines to around 80 %.

4.2.5. DZ-5 (1845–1931)

This zone is dominated by *T. flocculosa*, *A. pusilla* and *A. tenella* with notable contributions of *A. formosa*, *D. stelligera* and *L. rossii*. The proportion of planktonic centric diatoms increases, reflecting the gradual decline in *T. flocculosa*. Total diatom concentration and BSi content sharply decline in timing with the ditching operation, to their minima of 26×10^6 frustules gdw^{-1} and 3 %, respectively. Between 1901 and 1932, total diatom concentration and BSi content increase, reaching 80×10^6 frustules gdw^{-1} and 10 %, respectively. Both DI-pH reconstructions follow similar trends, fluctuating between 6.2 and 6.6 prior to the ditching operation and following an initial decline after the ditching operation, recovering to 6.4–6.7 by 1924–31. The minimum proportion of diatoms to chrysophytes, of 76 %, occurs at 1913–24 (Fig. 5).

4.3. Diatom productivity and selected biogeochemical data

Between 1641 and 1779 (DZ-1 to DZ-3) there is a discrepancy between diatom concentration and BSi content (Fig. 6). While BSi content is stable around 10 % (± 3), total diatom concentration ranges between 40×10^6 and 220×10^6 frustules gdw^{-1} (Fig. 6). The concentration of

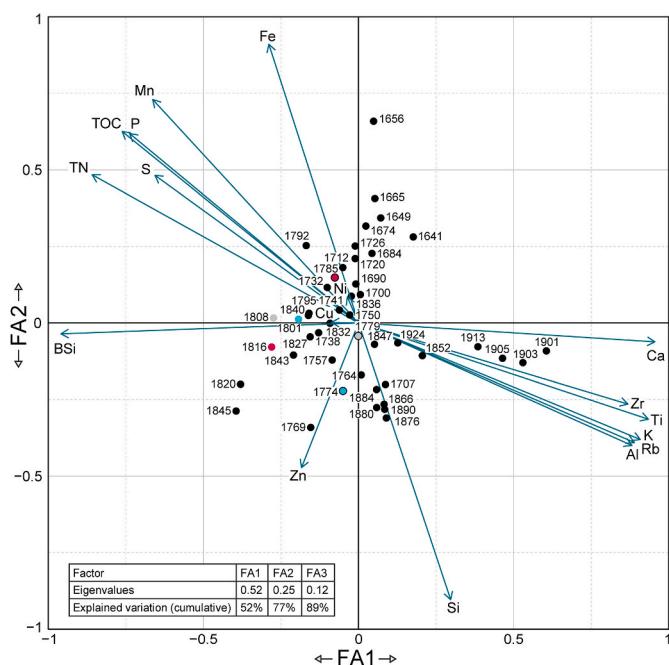


Fig. 3. Biplot of the first and second factors of a varimax-rotated factor analysis of standardised biogeochemical data, including: TOC, TN and BSi contents as well as multiple variables from XRF data (Al, Ca, Cu, Fe, K, Mn, Ni, P, Rb, S, Si, Ti, Zn and Zr). Geochemical variables are represented by arrows and samples by points. Coloured points indicate samples containing sediments deposited in the years before (blue), encompassing (grey) and following (red) the eruptions of Laki 1783–84 (encircled in black) and Tambora 1815. Sample labels represent the oldest varve age of each sample. FA1 (x-axis) explains 52 % of the variance and FA2 (y-axis) explains 25 % of the variance. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

benthic diatoms ranges from 6×10^6 to 56×10^6 frustules gdw^{-1} and generally follows the changes in the total diatom concentration. The latter parameter is largely driven by the productivity of tychoplanktonic and planktonic species, which range between 20×10^6 and 120×10^6 frustules gdw^{-1} . Total diatom concentration increases rapidly between

1785 (91×10^6 frustules gdw^{-1}) and 1808 (183×10^6 frustules gdw^{-1}), which coincides with increases in TOC/TN, S/Ti, Fe/Ti and P/Ti ratios. From 1779 to the top of the record, BSi content, total diatom concentrations and the P/Ti ratio share generally similar trends.

Together with TOC content, the Fe/Ti, S/Ti, and P/Ti ratios share generally similar trends throughout the record. There are strong negative correlations between the K/Al ratio and the Fe/Ti ratio ($R = -0.77$), S/Ti ($R = -0.86$), and P/Ti ($R = -0.86$). Changes in the K/Al ratio generally follow those of the K/Ti ratio. As K/Al ratios decline, the proportions of S, Fe, and P increase relative to Ti. Prior to 1785, relatively high K/Al ratios indicate generally stable weathering and erosion conditions albeit with brief declines around 1656–65 and 1732–38. The most profound change in the K/Al ratio occurs after 1785 in the form of a sharp decline from 0.38 to 0.35. This is followed by a gradual increase in the K/Al ratio to its maximum value of 0.4 following the ditching in 1900–02. In agreement with BSi and TOC contents, as well as detrital components, K/Al ratios return to values corresponding to those prior to the ditching, declining to 0.37 at the end of the record (1931).

5. Discussion

5.1. Diatom assemblage composition and imprint of land use

The species in the assemblage are typical of a boreal setting. Co-occurrence of the dominant species recorded here, including *T. flocculosa*, various species of *Aulacoseira*, *A. formosa*, *L. rossii* and *D. stellaris*, has been reported in boreal lakes in Canada (Karmakar et al., 2015; Shinneman et al., 2016) and elsewhere in Fennoscandia (Weckström et al., 1997a, 1997b; Rosén et al., 2000; Bigler and Hall, 2002; Sienkiewicz, 2005). Multiple *Aulacoseira* species were observed, although in slightly greater abundance than in the previous study of the Kassjön diatom record, and *A. formosa* in lower abundance (Anderson et al., 1995). The consistently high proportion of planktonic and tychoplanktonic species was expected, given the underrepresentation of benthic species in sediments at greater water depths as documented by Anderson et al. (1994).

As Anderson et al. (1995) observed, the overall effect of intensified land use in the catchment of Kassjön, beginning in the 1200's, but particularly from the 1600's, was to increase nutrient supply to the lake, with resulting changes in the diatom assemblage. However, the historical maps from 1690, 1785, and 1803 do not indicate any major

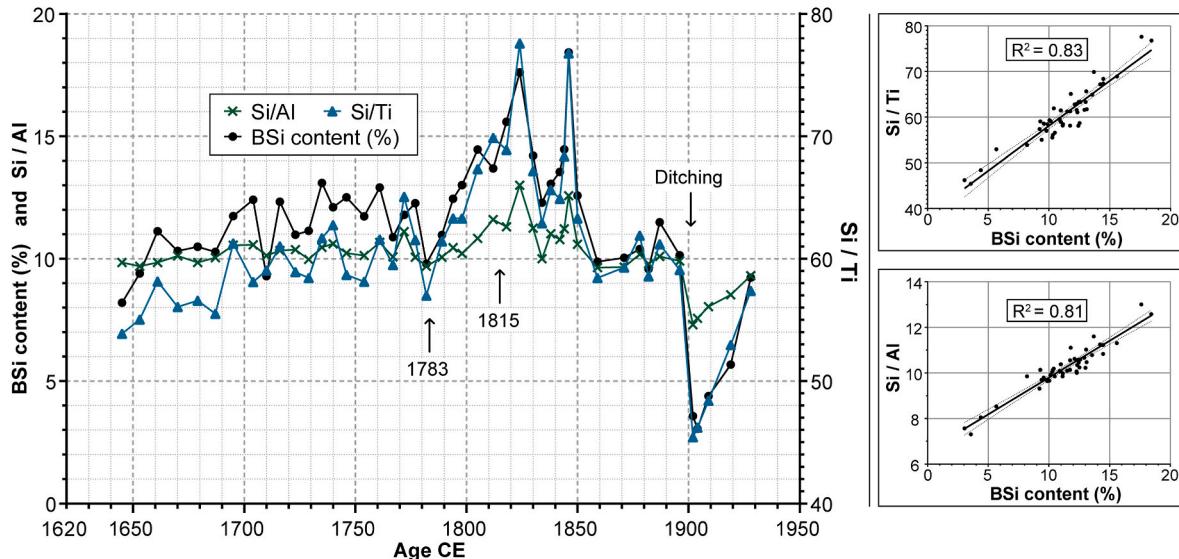


Fig. 4. Temporal trends in biogenic silica (BSi) content plotted together with Si/Al and Si/Ti ratios based on XRF-data covering the period from 1641 to 1931. Samples are plotted based on their median varve dates. Shown on the right are two simple linear regressions between BSi content and the Si/Ti ratio (top; $R^2 = 0.83$) and Si/Al ratio (bottom; $R^2 = 0.81$) showing standard deviations (dotted lines).

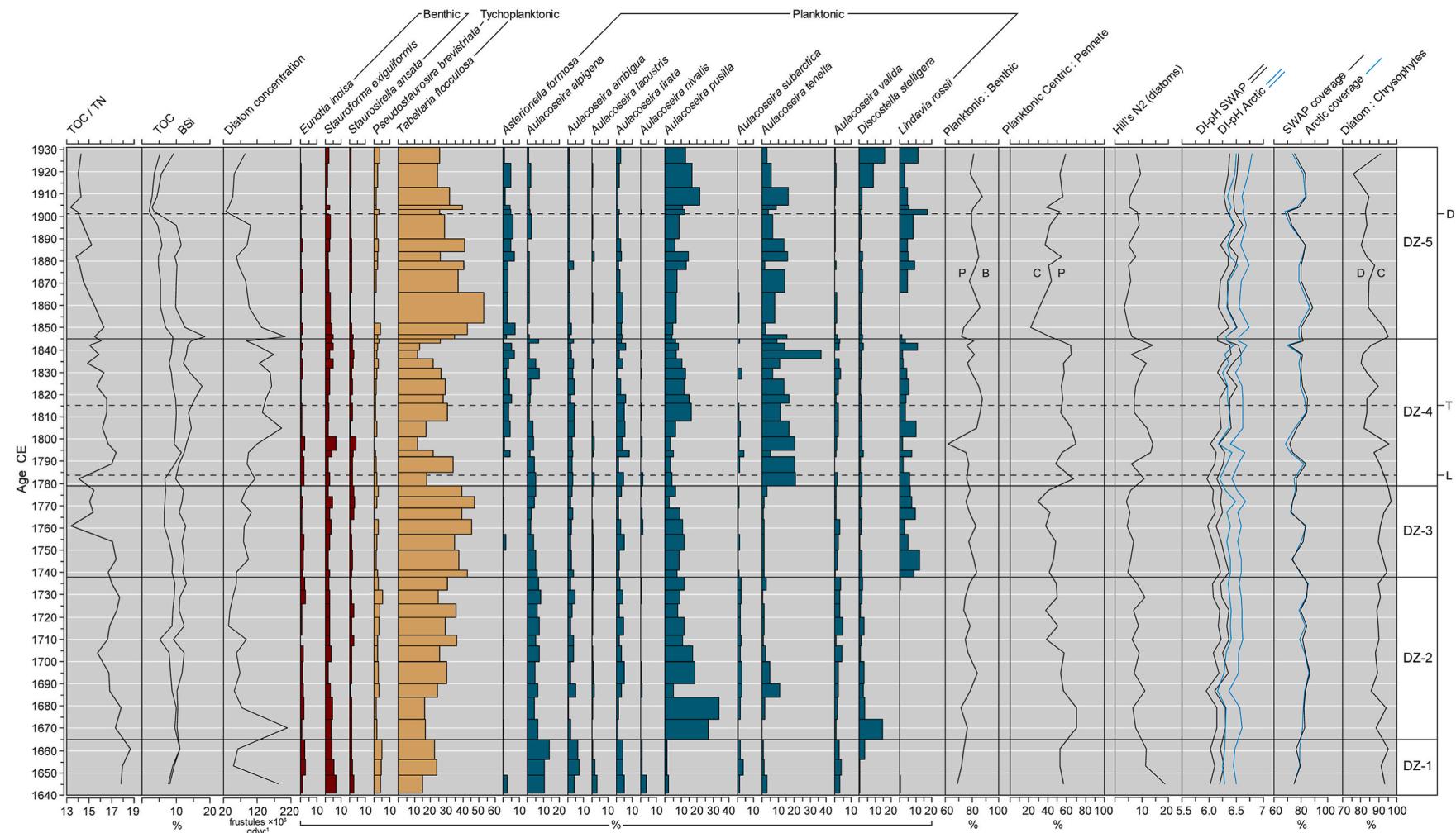


Fig. 5. Diatom stratigraphy and selected geochemical variables. All variables are plotted against sediment age according to varve counts. Horizontal lines mark the boundaries between diatom zones DZ1–DZ5 based on CONISS. Dashed horizontal lines mark the dates of the eruptions of Laki (L), Tambora (T) and the ditching operation (D). Left to right: atomic TOC/TN ratio, TOC and biogenic silica (BSi) contents, total diatom concentration, the relative proportion of dominant diatoms ($\geq 3\%$ in at least one sample), the relative proportion of planktonic (and tychoplanktonic) and benthic diatoms, the relative proportion of centric to pennate diatoms within the planktonic (and tychoplanktonic) fraction of the assemblage, equal coverage-based Hill's N2, diatom-inferred pH showing upper and lower envelopes of the SWAP (black) and the Arctic (blue) reconstructions, the proportion of the assemblage covered by each reconstruction (coverage) and the relative proportion of diatom frustules to chrysophyte cysts. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

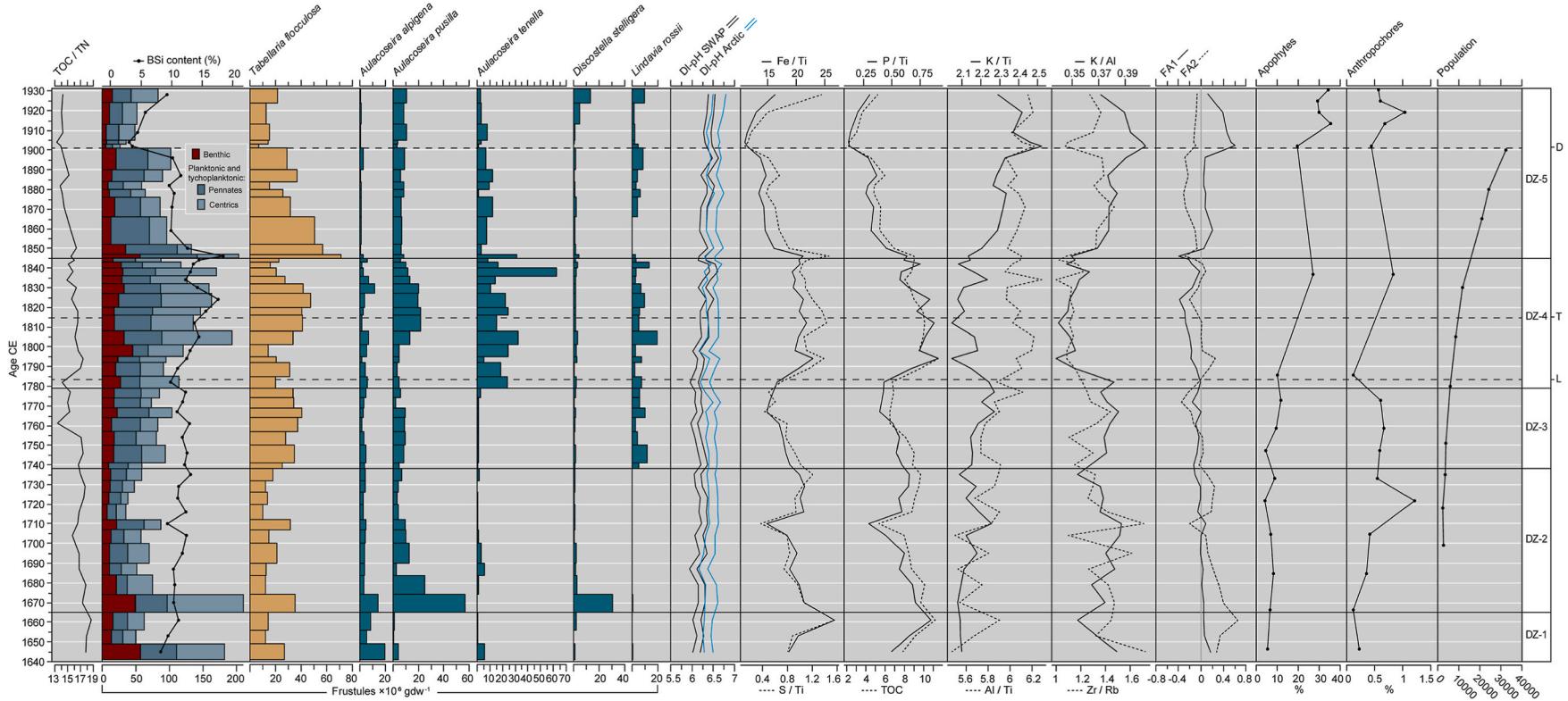


Fig. 6. Diatom concentration data and biogeochemical proxies. All variables are plotted against sediment age according to varve counts. Horizontal lines mark the boundaries between diatom zones DZ1–DZ5 based on CONISS. Dashed horizontal lines mark the dates of the eruptions of Laki (L), Tambora (T) and the ditching operation (D). From left to right: atomic TOC/TN ratio, stacked bar plot of diatom frustules per gram (dry weight) of sediment in each sample (lower x-axis), grouped according to benthic, tychoplanktonic and planktonic species with overlain line plot showing biogenic silica (BSi) content (upper x-axis), diatom frustules per gram (dry weight) of sediment for dominant species (with a threshold of a minimum relative proportion of 5 %), diatom-inferred pH based on the SWAP and Arctic reconstructions showing upper and lower boundaries, TOC content and multiple XRF-based elemental ratios plotted on upper (black lines) and lower (dashed black lines) axes, and the first and second factor scores of samples based of the factor analysis (Fig. 3). Also shown are pollen percentages (Apophytes and Anthropochores) redrawn from Anderson et al. (1995) and the population of the parish of Umeå (which encompasses the village of Kassjö) adapted from Palm (2000). Note that the stacked bar plot showing the concentrations of specific diatom groups has a different scale than the plots of individual species (which share the same scale).

subsequent changes in the spatial pattern of land use and show similar boundaries for the agricultural land, with the main difference being an expansion of meadows along the northeastern inlet stream after 1690. Cultivated fields occupied approximately the same areas on the western and northwestern side of the lake, with a buffer of meadows between these fields and the lake.

Pollen data (Anderson et al., 1995) and the historical maps from 1690 onwards indicate that agriculture and its influence on the diatom assemblage was well established before the period studied here, 1641–1931. For example, *T. flocculosa* is present in significant proportions throughout our record. This species is considered to be acidophilous (Battarbee, 1984) and is frequently found in oligotrophic waters in temperate and subarctic regions (Rühland et al., 2003; Cantoni et al., 2012), and is known to respond positively to increases in nutrient concentrations, especially P, in oligotrophic lakes (Klee and Schmidt, 1987; Marchetto et al., 2004; Dokulil and Teubner, 2005). Many species of *Aulacoseira* are cosmopolitan and occur under a broad range of nutrient and climatic conditions (Leira, 2005; Bicudo et al., 2016; Garzon and Saros, 2022). The second most dominant species throughout most of the record is *A. pusilla*, which has been associated with low nutrient availability, although light availability appears to be a more crucial factor (Garzon and Saros, 2022; Van de Vyver et al., 2022), as for *T. flocculosa*.

5.2. Responses to the ditching operation in 1900–02

As shown by our data, and providing valuable process understanding, the ditching operation in 1900–02 led to substantial changes in both diatom composition and geochemical characteristics of the sediments. The increases in Ti, Al, and K reflect enhanced delivery of detrital mineral matter (Fig. 4) and the decline in the Zr/Rb ratio reflects a general dominance of clay-sized particle input to the lake (Fig. 6). Throughout the record, changes in the K/Al and Zr/Rb ratios are well aligned, although they clearly deviate in response to the ditching (Fig. 6). The declining Zr/Rb ratio is largely due to a relative decline in Zr, reflecting the enhanced delivery of clay minerals. While small mineral particles are generally more susceptible to chemical weathering because of their large surface area-to-volume ratio, the general alignment of the K/Ti and Al/Ti ratios suggests that the increases in the K/Al ratio represents greater proportions of relatively unweathered mineral matter in the sediments, probably originating from deeper layers of the catchment overburden with little prior exposure (Kauppila and Salonen, 1997).

The decline in BSi content of the sediments in response to the ditching is partly explained by the relative increase in detrital input, with the proportion of total Si remaining stable (Fig. 4). However, there was also a clear change in the diatom assemblage composition in response to the ditching, including subsequent increases in the relative proportions of *A. pusilla* and *A. tenella* (Fig. 5). Aligning with the observations of Anderson et al. (1995), the total diatom concentration decreased markedly, which reflects reduced productivity, in addition to the dilution effect related to increased detrital input (Fig. 6). Anthropogenic disturbance to catchment soils and increased fluvial erosion are frequently associated with increased delivery of nutrients and allochthonous organic matter to lakes (Meyers and Teranes, 2002; Yang et al., 2020). In contrast, the increased detrital input recorded here in response to the ditching was accompanied by a decline in the proportion of allochthonous organic matter in the sediments, as indicated by lowered TOC/TN ratios (Fig. 4). A possible explanation to this anomalous response is that algal groups not covered in our analyses were favoured by elevated nutrient supply. However, a noteworthy conclusion is that the ditching did not result in increased supply of terrestrial organic matter to the lake.

Garzon and Saros (2022) demonstrated that *A. pusilla* is a versatile oligotrophic species and their findings suggest that nutrient additions may not stimulate its growth if light availability is already optimal. A

decline in allochthonous organic matter would plausibly have resulted in reduced dissolved organic carbon (DOC) concentration of the lake water, consequently increasing light penetration to the benefit of *A. pusilla*. As the geochemical parameters began to return to levels corresponding to those before the ditching, the proportion of *A. pusilla* declined and both *D. stelligera* and *L. rossii* increased. *Discostella stelligera* is competitive under reduced light availability, particularly in relation to increased DOC concentration (Brown et al., 2017). *Lindavia rossii* is commonly observed together with multiple species of *Aulacoseira* and *D. stelligera* (Genkal and Chekryzheva, 2016) and is frequently considered as part of a complex (*L. comta* complex) with *Lindavia comensis* (Saros and Anderson, 2015). The succession in the diatom assemblage therefore probably reflects the influence of changes in both nutrient dynamics and light availability in the years following the ditching.

Interestingly, the decline in *Aulacoseira* (both *A. tenella* and *A. pusilla*) and the increase in Cyclotelloid species (*D. stelligera* and *L. rossii*) represent changes in the diatom assemblage resembling those documented in response to increasing temperatures in the Northern Hemisphere (Rühland et al., 2008). This highlights the complexities of interpretations in relation to human activity, particularly at shorter timescales, as the shift in diatom assemblage composition recorded here undoubtedly reflects human-induced catchment disturbance.

5.3. Potential impacts of the eruptions of Laki 1783–84 and Tambora 1815

The consistent dominance of *T. flocculosa*, *A. pusilla* and *L. rossii* in DZ-3, spanning the period of 1738–79, represents a relatively stable reference period for comparison with diatom changes potentially associated with the eruption of Laki (Fig. 5). The sediment composition and geochemical characteristics also indicate generally stable lacustrine conditions during this period, although declining TOC content and TOC/TN ratios indicate a reduction in the delivery of allochthonous organic matter from around 1755.

From 1779, *A. tenella* rose to dominant proportions of around 20 % following low proportions of less than 5 % from the late 1600's. This substantial increase in the concentration of *A. tenella* and the decline in *T. flocculosa* mark a significant and lasting change in the diatom community (Fig. 5), which is represented by the two significant clusters determined by the broken stick model (corresponding to the first branch of separation into the periods before and after 1779). It should be noted that the lowermost sample of zone DZ-3 spans the years 1779–1785, which encompasses the duration of the Laki 1783–84 eruption, considering the uncertainty of our varve-based chronology of ± 1 year at this stage. *Aulacoseira tenella* is a widely distributed planktonic species which is commonly found in oligotrophic-mesotrophic waters. A recent study by Wengrat et al. (2019) reported its decline in mesotrophic tropical reservoirs exposed to eutrophication. *Aulacoseira tenella* has been reported with a pH optimum of 6.17 in western Quebec (Philibert and Prairie, 2002), 6.57 in tropical reservoirs in Brazil (Bicudo et al., 2016), 6.67 in the northeastern United States (Camburn and Charles, 2000), and has been reported to tolerate circumneutral to mildly acidic conditions in Fennoscandian lakes (Eloranta, 1986; Weckström et al., 1997a). The findings of these studies suggest that *A. tenella* prefers mildly acidic conditions within the pH range of the reconstructions applied here. The sharp increase in *A. tenella* from 1779 lends support to our hypothesis of a decline in pH resulting from acid deposition following the eruption of Laki, despite neither pH reconstruction showing a decline in pH exceeding 0.4 units, which would meet the modern threshold of acidification according to Fölster et al. (2007).

While only minor components of the dominant assemblage, both *E. incisa* and *S. exiguaformis* increased slightly in abundance for around a decade following the eruption of Laki. Strong resilience to acidification by *E. incisa* has been documented (Jones et al., 1989), and the SWAP included the species among indicator species, with a pH optimum of 5.0 (Stevenson et al., 1991), although the Arctic training set did not find a

significant correlation with pH (Bigler and Hall, 2002). *Stauroforma exiguumiformis* has a pH optimum of 5.7 (Flower et al., 1996) and is frequently associated with periods of lowered pH (Buczkó et al., 2012). The increase in benthic diatom concentration (Fig. 6) and acid-tolerant benthic species may represent a minor lag effect of acid deposition on benthic diatom productivity.

The decline in the concentration of *T. flocculosa* in DZ-4 (Fig. 6) is less pronounced than that of its relative abundance (Fig. 5), although this decline is still contrary to what might be expected following a decline in pH, as hypothesised, given its acidophilous status (Battarbee, 1984). However, as shown by Siver et al. (2003), enhanced bacterial sulphate reduction in response to acid deposition may lead to increased lake-water alkalinity sufficient to negate some of the effects of acid deposition on algal communities. Supporting the findings of Caraco et al. (1989), Siver et al. (2003) also suggest that enhanced sequestration of Fe resulting from sulphate reduction can lead to increased P availability, a process that may have influenced the changes in diatom assemblage composition at this stage, as well as the increase in BSi content and total diatom concentration within DZ-4 (Figs. 5 and 6).

Contrary to the development following the ditching operation in 1900–02, elevated TOC/TN ratios recorded following the Laki eruption indicate increased delivery of terrestrial organic matter to the lake (Fig. 2). While the increases in TOC and BSi contents following Laki reflect partly the relative decline in detrital input, as indicated by the decreases in Ti, Al, and K from 1779 (Fig. 2), the elevated delivery of allochthonous organic matter may explain the increase in nutrients, including P. However, the increases in Fe/Ti and S/Ti ratios (Fig. 6) could point to enhanced Fe sulphide sequestration, potentially increasing the availability of P in the water column (Siver et al., 2003). Although multiple processes are involved, the release of carbon from catchment soils can be suppressed by high levels of soil acidity (Evans et al., 2008; Ekström et al., 2011). This suggests that the initial increase in the TOC/TN ratio following Laki was potentially associated more with the direct effects of damage to catchment vegetation by acid deposition than the corresponding effects on catchment soils.

The most substantial shift in sediment geochemistry prior to the ditching occurred between 1779 and 1795 (Fig. 2). A substantial decline in the K/Al ratio was recorded after 1785, following the decline in the concentration of *T. flocculosa* and the initial increase in *A. tenella* from 1779 (Fig. 6). The decline in the K/Al ratio may be related to increased chemical weathering of minerals, or a decline in detrital input. Unlike the years following the ditching, the alignment between the K/Al and Zr/Rb ratios does not suggest a shift in sediment source or grain size following the Laki eruption. While the K/Ti and Al/Ti ratios are generally well aligned throughout most of the record, there is a clear deviation between the two ratios after the eruption of Laki, yielding substantially lowered K/Al ratios (Fig. 6). This rapid and long-lasting change suggests that more weathered mineral matter was delivered to the lake, potentially reflecting the effects of acid deposition in the catchment.

Our data show that variations in the proportion of Si in the sediments are heavily influenced by changes in BSi content (Fig. 3). The disproportionate increase in BSi content relative to total Si over multiple decades following the eruption of Laki, during a period of relatively stable detrital input (Fig. 4), indicates an increase in diatom productivity, potentially in response to increased nutrient availability following acid deposition, as discussed above. A period of high diatom productivity following eutrophication can result in reduced dissolved silica concentrations (Conley et al., 1993). The increase in BSi content relative to Si in the decades following Laki (Fig. 4) potentially indicates that a greater proportion of the available dissolved silica (dSi) was utilised by diatoms. Both *T. flocculosa* and *A. tenella* perform well in waters with low Si availability (Van de Vyver et al., 2022). Despite little being known about its division rates, with a cell volume of ~1/3 of that of *T. flocculosa* (Wolfe, 2003), *A. tenella* probably had an advantage from 1779, under a potential reduction in dSi availability. An earlier period of increases in

A. pusilla and *D. stelligera* of similar magnitude was recorded at about 1665, although the different preferences of these species (as outlined above) compared to those of *A. tenella* suggest that other, unknown drivers were at play in this brief interval.

The influence of grazing pressures on diatom productivity and assemblage composition are also likely to be affected by acid deposition. Common grazers, including macroinvertebrates and small detritivores, are known to be sensitive to acidification (Muniz, 1990), consistent with zooplankton (Havens et al., 1993). A negative response of grazers to the initial effects of acid deposition following Laki may have resulted in reduced grazing pressure during the period of elevated diatom productivity (Fig. 5). Ross and Arnott (2022) demonstrated the importance of Ca availability for zooplankton populations during the recovery from acidification. Although speculative, a potential reduction in Ca availability associated with the decline in Ca coinciding with the general decline in detrital input after 1785 (Fig. 4) may have contributed to a lasting reduction in grazing pressure.

A succession of changes in the structure of the diatom assemblage following Laki indicates persistent disturbance and altered conditions of the aquatic ecosystem during a period of about 60 years, details of which coincide with the TOC/N ratio dynamics and the trends in K/Ti, Al/Ti and K/Al ratios discussed above (DZ-4; Fig. 6). The immediate lacustrine response at 1779–85, favouring *A. tenella* at the expense of *T. flocculosa*, was probably induced by direct impacts of acid deposition on the lake water, providing further evidence of the responsiveness of opportunistic diatom species to the Laki 1783–84 eruption in Scandinavia (Kokfelt et al., 2016). In contrast the catchment-mediated responses recorded by the above geochemical parameters peaked about a decade later. Thereafter, from 1802, increases in *T. flocculosa* and *A. pusilla*, coinciding with a slight decline in *A. tenella*, potentially indicate partial recovery of the aquatic environment to pre-Laki conditions. As mentioned, both *T. flocculosa* and *A. pusilla* are favoured by enhanced light penetration, and both perform well under low-nutrient conditions. Hence, these species may have responded positively to decreased delivery of terrestrial organic matter, as indicated by the slight decrease in TOC/TN ratio at this stage (Fig. 6). A gradual increase in BSi content in the sediments relative to total Si, which mostly remained stable, potentially reflects enhanced uptake of silica from the water column and reduced dSi availability, consistent with the increased abundance of *A. pusilla*. Eventually, around 1845, following further decreases in the delivery of terrestrial organic matter and the associated elements Fe, S and P, the lake ecosystem seems to have reverted largely back to pre-Laki conditions.

As evidenced by pollen data obtained from the varved sediments of Kassjön by Segerström (1990) and illustrated in Anderson et al. (1995), apophytes and anthropochores were present well before the eruption of Laki (Fig. 6), demonstrating that small-scale grazing and agriculture were established in the lake catchment, consistent with the map from 1690 (Table S1). However, the absence of any clear increases in these pollen types, rather the opposite, in the late 1700's suggests that the sedimentary responses coinciding with the volcanic event were not caused by increased land-use intensity. On the contrary, the subsequent land reform led to intensified agricultural activity during the first half of the 19th century as evidenced by later historical maps and population data (Fig. 6). This later development may have led to successively elevated delivery of weathered mineral matter and related alkalisation, which precludes a detailed and unambiguous assessment of the longevity of the inferred volcanic imprint on the lake ecosystem. Nevertheless, our records from Kassjön show clear and sustained responses to the Laki eruption. This differs markedly from corresponding data obtained from the sediments of Lake Odensjön in southern Sweden where only weak indications were recorded, probably because of the resilience of its relatively alkaline water (Silvester et al., 2025).

While the concentration of *T. flocculosa* returned to pre-Laki levels by 1808 (Fig. 6), changes in the diatom assemblage at the timing of Tambora were mostly continuations of the trends initiated prior to the event,

with no major shifts directly following the eruption (Fig. 5). The records of BSi content and total diatom concentration indicate relatively stable and rising productivity during the decade following the eruption. Likewise, no significant changes in the TOC/TN ratio, TOC content, nor in the proportions of elements potentially reflecting nutrient dynamics were recorded between 1815 and 1825 (Fig. 6). Hence, the eruption of Tambora in 1815 does not seem to have affected the aquatic ecosystem of Kassjön, at least not to the extent that it was captured by our analytical approach. This indicates that boreal lake ecosystems may be less sensitive to transient cooling episodes regionally, like the ones recorded and simulated in response to Tambora 1815 and the preceding eruption of unknown provenance in 1808–09 (Raible et al., 2016), than to eruptions depositing massive amounts of sulphur to the catchments, such as Laki 1783–84.

5.4. General process reflections

Our results provide insight into the sensitivity and resilience of boreal lake waters to acidification in general, and particularly what might be expected when a volcanic event of a magnitude and character resembling the eruption of Laki in 1783–84 takes place in the future (cf. Sigl et al., 2015). In addition, although the prior environmental conditions, forcing mechanisms and duration times differ greatly, the lake ecosystem responses recorded here, can be compared with the impacts of the late 20th century industrial acidification of Fennoscandian soils and freshwaters, as well as their subsequent recovery, as demonstrated by numerous studies (e.g. Vuorenmaa and Forsius, 2008; Futter et al., 2014). Indeed, these two developments may share some important similarities in terms of mineral weathering, carbon and nutrient cycling in soils and water, as well as recovery rates, parameters that are partly related to the generally poor acid neutralising capacity of bedrock and overburden in the region (Akselsson et al., 2013). Corresponding responses and recovery trajectories of lacustrine diatom assemblages have been recorded (Dixit et al., 2002; Battarbee et al., 2014; Diamond et al., 2022), although sometimes affected by liming programmes and other mitigation efforts (Norberg et al., 2008).

6. Conclusions

The objective of this study was to attempt to identify and characterise any potential ecological impacts of the eruptions of Laki 1783–84 and Tambora 1815. We applied two diatom-based pH reconstructions based on transfer functions and found there was a general agreement between them throughout the record, although no significant acidification of the lake water was indicated. No significant changes in diatom assemblage composition or sediment geochemistry were recorded in timing with the eruption of Tambora. On the contrary, we identified substantial changes in the diatom community directly following the eruption of Laki. An initial pulse of terrestrial organic matter input to the lake in response to the disturbance of catchment vegetation was followed by an extended period of elevated supply of chemically weathered mineral matter and nutrients, including P, which led to generally increased diatom productivity during a period of about 60 years.

Agricultural expansion is known to have occurred during the relatively recent period of interest in this study. However, although available land-use records are poorly resolved, we can conclude that the major expansion phase took place in the early 1800's, while no substantial agricultural reforms affected the catchment during the previous decades. Therefore, the rapid responses revealed by our highly resolved diatom and geochemical data, initiated in the sample dating to 1779–85, can be plausibly attributed to direct environmental effects of the eruption of Laki. Although confounding effects of local land-use changes cannot be excluded, the subsequent development inferred from our records indicates sustained impacts on the lacustrine ecosystem during several decades. Our study demonstrates that sampling of varved sediments with high temporal resolution can reveal

short-term dynamics that are not reflected by standard palaeolimnological approaches.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quascirev.2025.109608>.

Data availability

Data are included in the manuscript and supplementary information. Data are also available from the corresponding author upon reasonable request.

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