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Paleolimnological evidence for atmospheric pollution, climate and catchment-related changes in alpine chrysophyte stomatocyst assemblages (Tatra, Slovakia)

by

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with 5 figures and 3 tables

Abstract: A stratigraphic study of spheroidal carbonaceous fly-ash particles (SCP) in a sediment core section from high mountain lake Nižné Térianske Pleso (1941 m a.s.l., High Tatra mountains), spanning the last ~150 years, revealed a rapid increase in SCP starting 1935–1940 AD. This increase coincided with a rise in ferrimagnetic, paramagnetic and canted antiferromagnetic mineral concentrations indicating atmospheric deposition of pollutants. Statistical analyses revealed that the sub-fossil stomatocyst assemblages from Nižné Térianske Pleso were significantly related to SCP, mineral magnetics, air temperature and diatom-inferred pH. Significant changes in the stomatocyst assemblages coincided with changes in SCP and magnetic mineral concentrations. Our study suggests that atmospheric pollution, climate and catchment-related changes caused major changes in the stomatocyst assemblages.

Key words: chrysophyte stomatocysts, C/D ratio, spheroidal carbonaceous fly-ash particles, SCP, mineral magnetics, atmospheric pollution, climate, land-water interactions, acid-base balance

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Introduction

Chrysophytes (classes Chrysophyceae and Synurophyceae) produce siliceous resting stages (stomato- and or simply cysts). Cyst assemblages have been shown to respond to the acid-base balance, conductivity, nutrients and temperature (Facher & Schmidt 1996, Duff et al. 1997, Lotter et al. 1997, Smol & Cumming 2000, Battarbee et al. 2002, Pla et al. 2003). They are probably affected by atmospheric pollution (Betts-Piper et al. 2004, Kamenik et al. 2005), and respond to land-use changes (Wilkinson et al. 1999, Kamenik et al. 2001a). Cysts are resistant, abundant and diverse in lake sediments, and have been used to reconstruct past environmental conditions (see Zeeb & Smol (2001) for a comprehensive review on their use in paleolimnology). High cyst abundance in lake sediments coincided with climate amelioration (Brancelj et al. 2002). The ratio of cysts to diatoms (C/D ratio) has been proposed as a quick and easy measure for climate changes (Smol 1983, 1985, Zeeb & Smol 1993, Lotter et al. 1997).

In this paper we use paleolimnological methods to study potential effects of atmospheric pollution, climate and catchment-related changes on the C/D ratio and the cyst assemblages from alpine Lake Nižné Terianske Pleso. Spheroidal carbonaceous fly-ash particles (SCP) form an unambiguous record of atmospheric deposition of industrial pollutants in lake sediment records, because there are no natural SCP sources (Rose et al. 1999). Their spatial distribution is similar to those of other fossil-fuel derived pollutants such as sulfur or organic pollutants (Broman et al. 1990, Rose & Juggins 1994). SCP are inert to changes in water and sediment chemistry and consequently the sediment record is robust and reliable (Rose et al. 1999). Mineral magnetics are indicators of atmospheric pollution, erosion and weathering in lake sediments; in contrast to SCP they might be affected by post-depositional changes ( diagene- sis) (Thompson & Oldfield 1986). Diatoms are reliable indicators of changes in the acid-base balance; they have been used to reconstruct pH (Battarbee et al. 2001).

Alpine lakes (i.e., lakes above the treeline) are suitable for studying the effects of (i) atmospheric pollution, because they are less influenced by direct human disturbance and more vulnerable to inputs than lowland lakes (Sommarg- Wa-grath et al. 1997, Rose et al. 1999), and (ii) climate, because meteorological forcing is more direct and catchment (soil and vegetation) responses are less important than in lowland lakes (Psenner & Schmid 1992, Catalán et al. 2002).

Study site

Nižné Terianske Pleso (49°10'N 20°00'E, 1941 m a.s.l.) is located in the High Tatra (Slovakia). Biotite-rich granite and tonalite dominate the catchment (1.1 km²). Half of the steep catchment is covered by alpine meadows. Nižné Terianske Pleso is 46 m deep, with a mean depth of 18 m. Its surface area is 4.8 ha. It has one permanent in- and outflow (Šporaka et al. 2002). It is oligotrophic (total phosphorus = 1.0 μg L⁻¹, dissolved organic carbon = 0.9 mg L⁻¹, conductivity = 21 μS cm⁻¹) and, unlike other Tatra lakes, not acidified (pH = 6.5, alkalinity = 77 μeq L⁻¹) (The MOLAR Water Chemistry Group 1999). In comparison to other Slovakian mountain lakes Nižné Terianske Pleso has experienced lower atmospheric deposition of industrial pollutants, probably due to small-scale differences in meteorology (Rose et al. 1999). Nižné Terianske Pleso is part of the Eurasian continental climate zone with lowest/ highest monthly mean air-temperatures in February/March (−10 °C) and July/August (+9 °C), respectively (Agusti-Panareda & Thompson 2002). Minimum and maximum precipitation occur January to April and June/July, respectively. Annual precipitation is ca. 1300 mm (Šporaka et al. 2002). Maximum summer surface-temperatures are 8 to 9 °C. Nižné Te- rianske Pleso is ice-covered from October to June (Pott et al. 1999). Phytoplankton biomass, which is dominated by Chrysophyceae and dinoflagellates, peaks during the ice-free period.
Bitrichia, Dinobryon, Ochromonas, Chrysococcus, Chrysoyloks, Chromulina, Kephyrion, Kephyriopsis and Mallomonas are important Chrysophyte genera (Fott et al. 1999).

Material and Methods

Sediment core analyses

A 30 cm long sediment core (TERI96/7) was taken during the open water period 1996 from the deepest area of Niżné Terianske Pleso using a Glew gravity corer (Glew et al. 2001), and cut in 2 mm slices. The core was dated with $^{210}\text{Pb}$, $^{226}\text{Ra}$ and $^{137}\text{Cs}$ using a piecewise CRS (constant rate of $^{210}\text{Pb}$ supply) model, resulting in sedimentation rates of 0.010 g cm$^{-2}$ y$^{-1}$ and 0.0041 g cm$^{-2}$ y$^{-1}$ for the periods 1884–1949 AD and 1949–1996 AD, respectively. Prior to 1884 AD the sedimentation rate was estimated to be 0.0034 g cm$^{-2}$ y$^{-1}$ (Appleby 2000), and this value has been used to extend the chronology back to the mid 19th century, when total sedimentary $^{210}\text{Pb}$ activity of the supporting $^{226}\text{Ra}$ reached equilibrium.

TERI96/7 was analyzed for SCP, mineral magnetics, diatoms (including diatom-inferred pH; minimum counts: 500 valves per sample), and chrysophyte cysts (minimum counts: 200 cysts per sample), following methods described in Kamenik et al. (2000), Šorka et al. (2002) and Kamenik & Schmidt (this volume). We characterized mineral magnetics by (i) mass-specific terms (low field susceptibility ($\chi_{\text{low}}$), ferrimagnetic susceptibility ($\chi_{\text{ferrm}}$), paramagnetic susceptibility ($\chi_{\text{high}}$), saturation remanence ($M_r$), saturation magnetization ($M_s$), saturation remanent magnetization (SIRM), soft (~20 mT) remanence (soft IRM) and hard (~300 mT) remanence (HIRM), and (ii) by magnetic percentages (% HIRM, % soft IRM, % $\chi_{\text{high}}, % \chi_{\text{ferrm}}$).

Identification of cysts was based on Duff et al. (1995), Facher & Schmidt (1996), Coradeghini & Vigna (2001), Hansen (2001), Pla (2001), Wilkinson et al. (2001), Cabala (2002, 2003a and b), and other references listed in Kamenik (2001). Numbering of cyst types (ST) was in accordance with Facher & Schmidt (1996) (ST 17–ST 92) and Kamenik et al. (in press) (ST 144–ST 152). References are presented in Table 1. ST 17 combined PEARL # 50, Table 1. Cyst types from Niżné Terianske Pleso that are known from literature, their numbers according to Facher and Schmidt (1996) (ST 17–ST 92) and Kamenik et al. (in press) (ST 144–ST 152), and their corresponding PEARL numbers (Duff et al. 1995, Wilkinson et al. 2001). Other references were included, when PEARL descriptions were not available.

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PEARL # 52 (Duff et al. 1995), no 9, no 17 (Facher and Schmidt 1996) and ST # 19 (Kamenik et al. 2001a). ST # 19 (Kamenik et al. 2001a) was assigned to ST 17 due to corrected size measurements. Cyst types without a collar and ornamentation were grouped according to pore morphology and size (regular pore: 3.3–4.7 μm; conical pore: 3.1–4.5 μm and 4.5–6.6 μm; swollen pseudoannulus: 4.7–4.9 μm). This grouping was based on results from Kamenik (2001).

New cyst types or types that could not be identified with certainty (ST 164–ST 169) were described following the ISWG guidelines (Cronberg & Sandgren 1986) using the terminology of Duff et al. (1995) and Wilkinson et al. (2001). The SEM descriptions were based on 4–36 specimens:

(A) Stomatocysts without ornamentations

Biological affinity: unknown
Picture-file number: F3620
Locality: TER196/7, 2.2–2.4 cm
SEM description: This smooth, spherical cyst (diameter: 4.9–7.4 μm) has a simple, conical collar (basal diameter: 2.2–3.0 μm, apical diameter: 1.8–2.7 μm, collar height: 0.3–0.4 μm). The rounded outer collar margin, the straight inner collar margin and the sloping annulus were often corroded. The collar then appeared to have an acute apex with a gently sloping inner margin. The diameter of the conical pore is 0.4–0.6 μm.


Ecology: ST 164 occurred at low numbers (<5%). It was positively correlated with air temperatures prior to or during ice-out, suggesting that ice-out dates are of major importance for this cyst type.

ST 165. Kamenik, C. & R. Schmidt, scanning electron micrograph B.
Biological affinity: unknown
Picture-file number: F1592
Locality: TER196/7, 0.6–0.8 cm
SEM description: This morphotype was split into two size classes: 5.7–8.0 μm (ST 165) and 7.9–9.0 μm (no 23, Facher and Schmidt 1996). ST 165 is spherical without ornamentation. The low conical collar (apical diameter: 1.5–2.7 μm, collar height: 0.1–0.7 μm) has a very gradual outer margin. The apex is usually acute. Some specimens, however, were found with a partly thickened, rounded apex. The inner collar margin is steep. A planar, flat to gently sloping annulus surrounds the regular to slightly conical pore (pore diameter: 0.4–1.0 μm). A convex siliceous plug was often found covering the pore and the annulus.

References: Kamenik et al. (2001a) assigned this cyst type to no 23 (Facher and Schmidt 1996). They suggested a high morphological variability within this cyst type, grouping ST 165 with ST # 114 formae A–D. This variability was, however, only found in Lake Gossenköllesee. We therefore separate ST 165 from ST # 114. Van der Vijver and Beyens (1997) described this cyst type as # 34 with a smaller size range (6.6–6.7 μm). Pla (2001) referred to it as S393 with a size of 7.2 μm.

Ecology: This cyst occurred at low numbers (<5%). It was positively correlated with SCP concentrations. It may have a high tolerance to atmospheric pollutants, and/or it may be favored by a pollution-related increase in nutrients or decrease in pH. It showed a negative response to diatom-inferred pH.
Paleolimnological evidence for atmospheric pollution

(B) Stomatocysts with ornamentations

**ST 166.** Kamenik, C. & R. Schmidt, scanning electron micrograph C.

Biological affinity: unknown
Picture-file number: F3617
Locality: TER196/7, 2.2–2.4 cm

SEM description: This spherical to oblate cyst (cyst diameter: 7.2–10.5 µm) is ornamented with widely and irregularly scattered scabrae. A ring of scabrae (diameter: 1.8–2.6 µm) can form a collar-like structure. The regular pore (pore diameter: 1.0–1.2 µm) has a flat, planar pseudoannulus (inner diameter: 0.5–0.6 µm).

References: This cyst probably represents a new cyst type.

Ecology: ST 166 was found at low numbers (<5%). Its abundance was highest in the lower part (> 15.6 cm) of TER196/7, and correlated with changes in mineral magnetics. Its decline towards the top was possibly related to a decrease in pH and/or changes in the catchment which were coupled with erosion or weathering. ST 166 showed a negative response to diatom-inferred pH.

**ST 167.** Kamenik, C. & R. Schmidt, scanning electron micrograph D.

Biological affinity: unknown
Picture-file number: F3998
Locality: TER196/7, 1.4–1.6 cm

SEM description: ST 167 is spherical (cyst diameter: 3.0–4.7 µm) with straight, widely spaced and randomly oriented ridges (length: 0.5–1.3 µm, height: <0.1–0.2 µm). The low conical to cylindrical collar (basal diameter: 0.6–1.4 µm) has a flattened or slightly rounded apex (apical diameter: 0.4–1.3 µm, collar height: <0.1–0.3 µm). The pore diameter of the regular pore is 0.2–0.6 µm.

References: Lotter et al. (2000) and Lotter et al. (2002) referred to this cyst type as no 8, but did not describe it.

Ecology: ST 167 was primarily found in the upper part (< 13.0 cm) of TER196/7. Its abundance correlated with changes in mineral magnetics. Its increase towards the top was possibly related to changes in the catchment which were coupled with erosion or weathering. ST 167 was positively correlated with SCP concentrations. It may have a high tolerance to atmospheric pollutants, and/or it may be favored by a pollution-related increase in nutrients or decrease in pH. It showed a negative response to diatom-inferred pH. It was negatively correlated with air temperatures prior to or during ice-out, suggesting that ice-out dates are of major importance for this cyst type. It is possibly produced by a species living in or under the ice, which is favored by low pH and temperatures.

**ST 168.** Kamenik, C. & R. Schmidt, scanning electron micrograph E.

Biological affinity: unknown
Picture-file number: F3714
Locality: TER196/7, 1.4–1.6 cm

SEM description: ST 168 is spherical (cyst diameter: 3.1–3.8 µm) and ornamented with one circulum (max. height: 1.1 µm), which often changes direction down to the posterior pole. The high, cylindrical to obconical collar has an acute apex (basal diameter: 0.4–0.8 µm, apical diameter: 0.5–1.0 µm). The collar was often broken. Its height was < 1.1 µm. The diameter of the regular pore is 0.3–0.4 µm.

References: This cyst resembles S325 in Pla (2001) which is, however, bigger, and stomatocyst 380 in Wilkinson et al (2001). The circulum of 308 (Wilkinson et al. 2001) is equato-
rial-located, whereas the circulum of ST 168, like on S325 in Pla (2001), changes direction down to the posterior pole.

Ecology: This cyst type was found at low numbers (<5%) throughout TERI96/7. We could not determine ecological preferences.

**ST 169.** Kamenik, C. & R. Schmidt, scanning electron micrograph F.

Biological affinity: unknown

Picture-file number: F3907

Locality: TERI96/7, 0.2–0.4 cm

SEM description: This spherical cyst (cyst diameter: 12.9–16.3 µm) is densely ornamented with randomly oriented fossae. We often found deep concave depressions, which can form a regular reticulum, and widely and irregularly spaced baculate spines. ST 169 lacks a collar. The conical pore has an outer diameter of 1.1–1.3 µm and an inner diameter of 0.6–0.7 µm.

References: The ornamentation of PEARL # 100 (Duff et al. 1995) is comparable with the ornamentation of ST 169. ST 169 is, however, bigger.

Ecology: ST 169 was found at low number (<5%) primarily in the upper core section (<1.8 cm). It was positively correlated with SCP concentrations. It may have a high tolerance to atmospheric pollutants, and/or it may be favored by a pollution-related increase in nutrients or decrease in pH.

**Air-temperature reconstructions**

Instrumental climate data from Nižné Terianske Pleso that are sufficiently long for a comparison with sediment core data do not exist; however, recent monitoring were carried out between July and October 1997, and these provide a means of validating climatic hindcasts. Monthly mean air temperatures were reconstructed from 1781 to 1997 AD following methods described in Agustí-Panareda & Thompson (2002). The reconstructions were based on twenty homogenized lowland records. Spatial interpolations were made based on a multiple regression approach supplemented by radiosonde air-temperature data. According to leave-one-out cross-validation the errors associated with the transfer functions varied between about 0.6 °C in June to 1.4 °C in February. We used mean April–October air temperatures (i) because winter air temperatures have little influence on ice-out dates or water temperatures (Livingstone 1997, Livingstone & Lotter 1998), and (ii) because of the lower transfer-function errors during summer months. We calculated bi-monthly means because they had probably the largest influence on ice-out dates (Livingstone 1997), a variable which is of major interest when studying stomatocyst ecology (Kamenik et al. 2001a). Finally, we averaged the temperature reconstructions corresponding to the time period each sediment core sample represented back to 1852 AD, when total sedimentary $^{210}$Pb activity of the supporting $^{226}$Ra reached equilibrium. These averaged bi-monthly mean air temperature reconstructions ($T_{April/May}$–$T_{Sept/Oct}$) were compared with sediment core data.

**Numerical methods**

We used Principal Components Analysis (PCA) for summarizing correlations among the proxies and the reconstructed air temperatures and for visualizing changes among these variables in time (ter Braak & Šmilauer 2002). Variables were centered and standardized. The significance of PC axes was assessed with the broken-stick model (Jackson 1993). We tested the significance of bivariate correlations among the environmental variables taking into account multiple testing ($P_{adj}$, Hochberg 1988).
We established significant zones in the diatom and cyst stratigraphy with the optimal sum of the squares partitioning method (Birks & Gordon 1985), as implemented in the computer program ZONE (Lotter & Juggins 1991), and the broken-stick model (Bennett 1996). We summarized similarities among cyst assemblages from different zones with non-metric multidimensional scaling (MDS), based on a Bray-Curtis similarity matrix (Clarke & Warwick 1994).

Following Športka et al. (2002) we used linear models to assess the significance of environmental variables for the cysts: (i) We ran a series of (partial) redundancy analyses (RDA) using the environmental variable of interest as the only explanatory variable (and sample age as
covariable); the significance of environmental variables was tested with 9999 unrestricted Monte Carlo permutations (ter Braak and Šmilauer 2002). The strength of each variable was assessed by its ability to maximize the dispersion of the species scores which was expressed as the ratio of the eigenvalues of the first constrained to the second unconstrained ordination axis \( \lambda_1/\lambda_2 \) (ter Braak & Juggins 1993). (ii) The response of individual cyst types to environmental variables was assessed by generalized linear models (GLM) using maximum likelihood with a Poisson error structure and a logarithmic link function (ter Braak and Šmilauer 2002).

**Results**

**Environmental variables**

The main feature was a distinct rise in SCP and the magnetic variables SIRM, soft IRM, \( M_{rs} \), \( M_s \), HIRM, \( \chi_{low} \), \( \chi_{ferri} \) and to lesser extents \( \chi_{high} \) in the upper 1.8 cm (post-1937 ± 2 AD); % soft IRM and % \( \chi_{ferri} \) showed a considerable increase above 1.8 cm in contrast to declining trends for % HIRM and % \( \chi_{high} \) starting at ca. 5 cm (Fig. 1). Below 5 cm changes in the magnetic variables, such as a small rise in \( \chi_{low} \) and \( \chi_{ferri} \) at 7.5–10 cm, or a zone of low SIRM, soft IRM and HIRM with broad peak in \( \chi_{high} \) at 15–20 cm, were small. Changes at 1.8 cm coincided with a small decrease in diatom-inferred pH. Another decrease in diatom-inferred pH occurred between 7.8 and 9.6 cm.

Four PCAs summarized correlations among the environmental variables, focusing (1) on the dated period (upper 4.8 cm, 1852 ± 12–1996 AD) and (2) on the non-dated period (below 4.8 cm, prior to 1852 ± 12 AD). They either included (a) all variables or (b) all samples (Fig. 2):

(1a) The first PCA was based on 14 samples and 16 environmental variables. The first two PC axes were significant (broken stick model). PC axis 1 was highest correlated with SCP and the magnetic variables SIRM, soft IRM, \( M_{rs} \), \( M_s \), \( \chi_{low} \) and \( \chi_{ferri} \). These variables were significantly correlated with each other (\( P_{adj} < 0.05 \)). Furthermore, PC axis 1 was correlated with diatom-inferred pH, \( T_{May/June} \) and \( T_{June/July} \). PC axis 2 was correlated with \( T_{April/May} \), \( T_{July/Aug} \), \( T_{Aug/Sept} \) and \( T_{Sept/Oct} \). Diatom-inferred pH was significantly correlated with \( M_{rs} \); \( T_{June/July} \) was significantly correlated with SCP (\( P_{adj} < 0.05 \)).

(1b) The second PCA was based on all 24 samples above 4.8 cm and on 14 environmental variables. Results resembled those from (1a) except for SCP and diatom-inferred pH which were not available for all samples. \( T_{June/July} \) was significantly correlated with SCP, \( M_{rs} \), \( M_s \), SIRM and soft IRM (\( P_{adj} < 0.05 \)).

(2a) The third PCA was based on nine samples below 4.8 cm, on the magnetic variables and diatom-inferred pH. Three PC axes were significant (broken stick model). Axes 1 and 2 were correlated with magnetic variables. Axis 3 was correlated with diatom-inferred pH.

(2b) The fourth PCA was based on 121 samples below 4.8 cm and on the eight magnetic variables. The first PC axis was significant (broken stick model). It was highest correlated with \( M_s \), \( \chi_{low} \), \( \chi_{ferri} \), SIRM and soft IRM. \( \chi_{high} \) was significantly correlated with \( \chi_{low} \); \( M_{rs} \) was significantly correlated with HIRM and \( M_s \); the remaining six magnetic variables were significantly correlated with each other (\( P_{adj} < 0.05 \)).

**General characteristics of the stomatocysts**

We found 25 cyst types with an abundance > 3% and occurrences in at least two samples (Fig. 3). The number of cyst types per sample (N) increased from 12 at 29.8 cm to 21 at 2.2 cm
Fig. 1. Selected magnetic variables (thin lines denote percentages) and diatom-inferred pH from the sediment core TER196/7. Superimposed on the magnetic variables are the spheroidal carbonaceous flyash particle (SCP) concentrations (white circles) having a peak around 1980 AD. Above 5 cm magnetic variables and SCP indicate atmospheric deposition of pollutants. Below 5 cm magnetic variables indicate erosion and/or weathering. The horizontal line and the gray area indicate significant changes in the chrysophyte stomatocyst assemblages (Fig. 3).

(1928 ± 3 AD); it dropped to 12 at 1.6 cm (1943 ± 2 AD) and reached 20 in the uppermost core section (Fig. 4). The effective number of cyst types per sample (N2, Hill 1973) fluctuated around eight; it decreased at 12.8 cm and 1.6 cm (1943 ± 2 AD) (Fig. 4). ST 17 dominated during times of low N and N2 (Fig. 3). The ratio of cysts to diatoms (C/D ratio) fluctuated around 0.14. It peaked at 1.4 cm (1949 ± 2 AD). The C/D ratio was negatively correlated with N (P < 0.05).

According to optimal partitioning and the broken stick model, there were two significant changes in the stomatocyst assemblages. The first occurred between 15.6 and 13.0 cm before the drop in N2; the second occurred at 1.8 cm (1937 ± 2 AD) before a drop in N and N2 and a peak in the C/D ratio (Fig. 4). It coincided with a significant change in the diatom assemblages.

Non-metric multidimensional scaling (stress = 0.15) showed that the cyst assemblages below 15.6 cm (zone I) clearly differed from the ones above 1.8 cm (zone III). Cyst assemblages in zone II (1.8–13.0 cm) were intermediate (Fig. 5). PCA showed the same result. PC axis 1 separated zones I–III. ST 144, ST 147, ST 148, ST 162, ST 166 decreased from the lower to
Fig. 2. Four PCAs summarize correlations among the environmental variables and visualize changes among these variables in time. They focus (1) on the dated period (upper 4.8 cm, 1852 ± 12–1996 AD) and (2) on the non-dated period (below 4.8 cm, prior to 1852 ± 12 AD). They either included (a) all variables or (b) all samples. Sample age and the C/D ratio are passive variables; they do not influence the PCA. Sample scores are scaled (factor = 0.4). Sample names correspond to sediment depth (cm). SCP and magnetic variables (SIRM, soft IRM, M_s, \( \chi_{low} \), \( \chi_{form} \), \( \chi_{high} \), M_r and HIRM) indicate atmospheric deposition of pollutants after 1852 ± 12 AD with a strong increase ca. 1940 AD. Prior to 1852 ± 12 AD the magnetic variables indicate erosion and/or weathering. Triangles, circles and squares correspond to cyst zones I, II and III, respectively. Lines connect adjacent samples. Samples in the transition from cyst zone I to zone II (between 13.0 and 15.6 cm, Fig. 3) are not drawn.

the upper part of the core; smooth cysts with a regular pore and a size 3.3–4.7 μm. ST 17, ST 79, ST 84, ST 149, ST 152, ST 167 and ST 169 increased from the lower to the upper part of the core (Fig. 3). ST 79, ST 84, ST 149 and ST 167 were rare in zone I.

Relationships between environmental variables and stomatocysts

N and N2 were negatively correlated with \( T_{Aug/Sept} \); the C/D ratio was positively correlated with \( T_{Aug/Sept} \) and \( T_{Sept/Oct} \) (P < 0.05).

Studying relations between environmental variables and the cyst assemblages we focused on (1) the dated period (upper 4.8 cm, 1852 ± 12–1996 AD), and (2) on the non-dated period (below 4.8 cm, prior to 1852 ± 12 AD):
Fig. 3. Cyst stratigraphy in the sediment core TERR167. References to known cysts are presented in Table 1 (ST 17–ST 163). New cyst types or types that could not be identified with certainty (ST 164–ST 169) were described following the ISWG guidelines (Cronberg & Sandgren 1986) using the terminology of Duff et al. (1995) and Wilkinson et al. (2001) (see scanning electron micrographs). The horizontal line and the gray area indicate significant changes in the chrysophyte stomatocyst assemblages, separating cyst zones I–III. Cyst types are ordered along their PC axis 1 scores, illustrating changes between zones I–III. Cyst assemblages in zone I clearly differ from those in zone III (Fig. 5). The time axis indicates the core sequence dated by $^{210}$Pb, $^{226}$Ra and $^{137}$Cs.

Fig. 4. Number of cyst types per sample (N), effective number of cyst types per sample (Hill's N2) and the ratio of cysts to diatoms (C/D ratio). The horizontal line and the gray area indicate significant changes in the chrysophyte stomatocyst assemblages (Fig. 3). N and N2 are mainly driven by the dominant ST 17 (Fig. 3). The C/D ratio has been proposed as a quick and easy estimate of climate. In Nižné Terianske Pleso it correlates with $T_{Aug/Sept}$ and $T_{Sept/Oct}$. 
The significant change of the cyst assemblages at 1.8 cm coincided with a marked increase in SCP and all magnetic variables, and a small decrease in diatom-inferred pH towards the top (Fig. 1). Redundancy analyses, based on 14 samples, revealed that among the 16 tested environmental variables SIRM, soft IRM and SCP singly explained a significant amount of variation in the cyst assemblages, taking into account multiple testing (P_{adj} < 0.05). Among the six climate variables T_{May/June} and T_{June/July} singly explained a significant amount of variation in the cyst assemblages (P < 0.05; Table 2). After we removed effects of sample age (by defining it as a covariable) SCP and T_{June/July} still explained a significant amount of variation in the cyst assemblages (P < 0.05; Table 2). Significant responses of cyst types to SCP and air temperature are shown in Table 3. The numbers of significant responses (P < 0.05) were highest for SCP, T_{May/June} and T_{June/July}.

The significant change of the cyst assemblages prior to 1852 ± 12 AD coincided with a small increase in the magnetic variables HIRM, M_{s}, SIRM and soft IRM, and a small decrease in \( \chi_{\text{high}} \) towards the top. Redundancy analyses, based on 10 samples, revealed that among the nine tested environmental variables M_{s} and SIRM singly explained a significant amount of variation in the cyst assemblages (P < 0.05, Table 2). GLMs revealed that ST 147, ST 148, ST 151 and ST 166 showed a negative response to both M_{s} and SIRM, whereas smooth cysts with a regular pore and a size 3.3–4.7 \( \mu \)m showed a positive response to the two variables (P < 0.05). ST 144, ST 161 and ST 162 showed a negative response to SIRM, and smooth cysts with a conical pore and a size 3.1–4.5 \( \mu \)m, ST 17, ST 149 and ST 167 showed a positive response to this variable (P < 0.05).

Finally, redundancy analyses revealed that diatom-inferred pH singly explained a significant amount of variation (18.1 %, \( \lambda_{1}/\lambda_{2} = 0.79 \), P < 0.001) when considering the entire core. Fourteen cyst types significantly responded to diatom-inferred pH (P < 0.05): Smooth cysts with a conical pore and a size 3.1–4.5 \( \mu \)m, ST 79, ST 84, ST 92, ST 149, ST 152, ST 165, ST 167 and ST 169 showed a negative response. ST 144, ST 147, ST 148, ST 162 and ST 166 showed a positive response.

**Table 2.** Significant (P < 0.05) marginal effects (i.e., amount of variation in the cyst assemblages explained by the variable when used as the only environmental variable) focusing on (A) the dated period and (B) the non-dated period. Asterisks in (A) indicate variables having significant effects after removing effects of sample age. The ratio \( \lambda_{1}/\lambda_{2} \) (i.e., the ratio of the eigenvalues of the first constrained to the second unconstrained ordination axis, given in brackets) is a measure of the relative importance of the environmental variable for the cyst assemblages. It is 0.79 for diatom-inferred pH (whole core).

<table>
<thead>
<tr>
<th></th>
<th>(A) 1852 ± 12–1996 AD</th>
<th>(B) prior to 1852 ± 12 AD</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIRM</td>
<td>20.2% (0.80)</td>
<td>25.3% (0.96)</td>
</tr>
<tr>
<td>SCP</td>
<td>20.1%* (0.77)</td>
<td>Not available</td>
</tr>
<tr>
<td>Soft IRM</td>
<td>20.0% (0.78)</td>
<td>Not significant</td>
</tr>
<tr>
<td>low</td>
<td>18.7% (0.75)</td>
<td>Not significant</td>
</tr>
<tr>
<td>M_{s}</td>
<td>18.5% (0.72)</td>
<td>30.5% (1.33)</td>
</tr>
<tr>
<td>( \chi_{\text{ferri}} )</td>
<td>18.3% (0.74)</td>
<td>Not significant</td>
</tr>
<tr>
<td>M_{ts}</td>
<td>16.7% (0.63)</td>
<td>Not significant</td>
</tr>
<tr>
<td>T_{June/July}</td>
<td>15.9%* (0.55)</td>
<td>Not available</td>
</tr>
<tr>
<td>T_{May/June}</td>
<td>15.3% (0.58)</td>
<td>Not available</td>
</tr>
</tbody>
</table>
Table 3. Significant positive (pos) and negative (neg) responses of cyst types to SCP concentrations, indicating atmospheric deposition of pollutants, and air temperatures (GLM, P < 0.05).

<table>
<thead>
<tr>
<th>SCP</th>
<th>$T_{April/May}$</th>
<th>$T_{May/June}$</th>
<th>$T_{June/July}$</th>
<th>$T_{July/Aug}$</th>
<th>$T_{Aug/Sept}$</th>
<th>$T_{Sept/Oct}$</th>
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<tr>
<td>Smooth, regular pore (3.3–4.7 μm)</td>
<td>---</td>
<td>---</td>
<td>---</td>
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<td>pos</td>
<td>pos</td>
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<tr>
<td>Smooth, conical pore (3.1–4.5 μm)</td>
<td>---</td>
<td>pos</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>pos</td>
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<tr>
<td>Smooth, conical pore (4.5–6.6 μm)</td>
<td>neg</td>
<td>---</td>
<td>pos</td>
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<td>---</td>
</tr>
<tr>
<td>ST 17</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>pos</td>
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</tr>
<tr>
<td>ST 79</td>
<td>pos</td>
<td>---</td>
<td>---</td>
<td>---</td>
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</tr>
<tr>
<td>ST 144</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>neg</td>
<td>neg</td>
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</tr>
<tr>
<td>ST 147</td>
<td>neg</td>
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<td>---</td>
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<tr>
<td>ST 150</td>
<td>pos</td>
<td>---</td>
<td>---</td>
<td>neg</td>
<td>neg</td>
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<tr>
<td>ST 151</td>
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<tr>
<td>ST 165</td>
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<tr>
<td>ST 167</td>
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<td>7</td>
<td>6</td>
<td>4</td>
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</table>

Discussion

Environmental variables

The start of the SCP record suggests contamination from the Industrial Revolution; the distinct rise at 1.8 cm (Fig. 1) indicates an increase in atmospheric pollution starting ca. 1940 AD and coinciding with increased industrial output during the Second World War (Sporka et al. 2002). Historical SO$_2$ emission models (Mylonas 1993) resemble the SCP profile from Nižná Terianske Plešo (Rose et al. 1999). A similar rise in magnetic variables (Fig. 1) indicates an increase in ferrimagnetic, paramagnetic and canted antiferromagnetic mineral concentrations. This increase is most likely caused by atmospheric pollution particles. The twenty to thirty-fold increases in soft IRM and $\chi_{\text{ferr}}$ in comparison to the two to threefold increases in paramagnetic minerals is consistent with a new source of ferrimagnetic minerals (probably atmospheric pollutants) rather than an increase in all minerals through erosion. Bacterial magnetosomes would not be expected to produce a rise in values of HIRM or $\chi_{\text{high}}$. Hence, the curve trajectories of $\% \chi_{\text{ferr}}$, $\% \chi_{\text{high}}$, % HIRM and % soft IRM (Fig. 1) suggest that the proportion of relatively coarse-grained ferrimagnetic minerals from fossil fuel sources was rising at the expense of finer grained bacterial magnetosomes and iron-bearing minerals from eroded catchment sources (Thompson & Oldfield 1986, Dearing 1999). There is no evidence for diagenic formation of ferrimagnetic iron-sulfide greigite; (i) a low SIRM: $\chi_{\text{low}}$ ratio suggests that greigite is not a dominant mineral; (ii) there are no spikes in the ferrimagnetic concentrations which are typical of greigite bands; and (iii) the increases in ferrimagnetic concentrations in the upper 2 cm parallel HIRM that does not measure iron sulfides.
Dissolution had probably also little effects. All the samples have non-zero concentrations of magnetic minerals. The covariance between SCP and upper raises in ferrimagnetic concentrations is consistent with an external (atmospheric) source of ferrimagnetic minerals.

Atmospheric deposition of pollutants indicated by SCP and magnetic minerals correlated with $T_{June/July}$ (Fig. 2). $T_{June/July}$ drives ice-out dates (Livingstone 1997). Atmospheric deposition may be affected by ice-out dates or other climate-related variables, e.g., the convective transport of boundary air to high-altitude sites (Lugauer et al. 1998). Other air temperatures, however, had little effect on atmospheric depositions (Fig. 2).

Atmospheric pollution causes acid deposition (Psenner & Catalan 1994). In Nižné Terianske Pleso this is indicated by a clear recent (after ca. 1950 AD) increase of sedimentary sulfur and nitrogen concentrations (Lami et al. 2000). Acid deposition had probably little impact on the acid-base balance of the buffered Lake Nižné Terianske Pleso. Diatom-inferred pH dropped by only 0.1.

Prior to the dated period (below 4.8 cm, prior to 1852 ± 12 AD) we have no evidence for atmospheric pollution. Changes in the mineral magnetics, such as a small rise in $\chi_{low}$ and $\chi_{tberry}$ at 7.5–10.0 cm or a zone of low SIRM, soft IRM and HIRM with a broad peak in $\chi_{high}$ at 15–20 cm (Fig. 1), might suggest erosion of non-ferrimagnetic clay minerals or mineral dissolution and iron precipitation.

**General characteristics of the stomatocysts**

The number of cyst types found in Nižné Terianske Pleso lies within the range of 11–39 cyst types found in other Alpine lake sediment cores (Lotter et al. 2000, Kamenik et al. 2001a, Brancelj et al. 2002, Kamenik et al. in press). These sediment cores were studied by the same analyst using similar methods. Results are therefore comparable. The cyst flora of Nižné Terianske Pleso is dominated by small types without ornamentation and collar and by ST 17 (Fig. 3). These cyst types are probably produced by several species (Duff et al. 1995). The dominance of unornamented cysts has been frequently observed in clear-water, oligotrophic lakes, and has been thought to be characteristic for arctic environments (Wilkinson et al. 1997, Stewart et al. 2000, Betts-Piper et al. 2004).

**Stomatocysts and atmospheric pollution**

The most obvious environmental change, related to atmospheric pollution, coincided with a significant change in the cyst assemblages (Fig. 1). RDA suggested that the cyst assemblages were significantly affected by atmospheric deposition (Table 2). Currently we do not know how atmospheric deposition might have affected the cysts. Atmospheric pollutants, such as metals or persistent organics, can cause shifts in cyst assemblages (Betts-Piper et al. 2004, Kamenik et al. 2005). Cysts with a positive response to SCP (Table 3) may have higher tolerances to atmospheric pollutants (Smol 2002). The small pH-decline during the dated period (1852 ± 12–1996 AD), most likely caused by acid deposition, had only little effects on the cyst assemblages according to RDA. Atmospheric nitrogen, however, can also be an important nutrient (Skjelkvåle & Wright 1998). Sedimentary carbon, nitrogen and pigment concentrations in another sediment core from Nižné Terianske Pleso (TER196/6) indicated increased primary production during the last ca. 50 years (Lami et al. 2000). Kamenik et al. (2001a) showed that cyst assemblages responded to nutrient changes in an alpine lake. Changes of diatom abundances in the top 3 cm were probably influenced by trophic changes (Sporka et al. 2002). Nutrients and primary production alone cannot, however, explain the unique cyst assemblages found in the upper core section (zone III, Fig. 5), because sedimentary pigment concentrations were high also in old sediment layers (Lami et al. 2000).
Stomatocysts and climate

Air temperatures most likely affected selected cyst types (Table 3). Air temperatures prior to or during ice-out seemed to have the highest impact on the cyst assemblages, suggesting that ice-out dates are of major importance for cysts in mountain lakes. This corresponds to other studies from Niżně Terianske Pleso (Šporka et al. 2002) and the Alps (Kamenik et al. 2001a, Lotter et al. 2002). Cyst types negatively responding to $T_{\text{May/June}}$ and $T_{\text{June/July}}$ may be produced by species living in or under the ice. Smooth cysts with a conical pore and a size 3.1–4.5 µm positively responded to air temperatures driving (i) ice-out dates ($T_{\text{April/May}}$), (ii) summer water temperatures ($T_{\text{Aug/Sept}}$) and (iii) ice-on dates ($T_{\text{Sept/Oct}}$). They are probably produced by several species that occur during different times of the year.

The ratio of cysts to diatoms (C/D ratio) has been proposed as a quick and easy estimate of ice-out in arctic regions (Smol 1983). In Niżně Terianske Pleso the C/D ratio increased with $T_{\text{Aug/Sept}}$ and $T_{\text{Sept/Oct}}$, opposing the hypothesis from arctic environments that it increases with extended ice cover and cold climate. The increase can be attributed to the dominant ST 17, probably formed by *Chromulina* sp. (Nygaard 1956). *Chromulina* sp. dominated the total phytoplankton biomass of Niżně Terianske Pleso in September 1997 when $T_{\text{Aug/Sept}}$ was 7.7 °C. It was less abundant in September 1996 when $T_{\text{Aug/Sept}}$ was 4.3 °C (Fott et al. 1999, Agustí-Panareda & Thompson 2002).

Stomatocysts and the catchment

Prior to 1852 ± 12 AD our environmental information is limited. Nevertheless, our data suggest that the significant change in the cyst assemblages between 15.6 and 13.0 cm was related to changes in the catchment. The composition of the magnetic variables differed between zones I and II (Fig. 2), indicating changes in weathering and/or erosion. Catchment characteristics influence the water chemistry of mountain lakes (Kamenik et al. 2001b) which drives cyst assemblages (Facher and Schmidt 1996, Duff et al. 1997, Pla et al. 2003). Changes in the catchment have been shown to significantly affect paleoindicators in mountain lakes (Lotter & Birks 2003). In Niżně Terianske Pleso episodes of rapid sediment accumulation, probably from intermittent input from the catchment or the margins of the lake, occurred fairly regular (Šporka et al. 2002).
Stomatocysts and pH

Chrysophyete cysts are well known to be driven by changes in pH (e.g., Facher and Schmidt 1996, Duff et al. 1997, Pla et al. 2003). In Nižná Terianske Pleso other environmental factors seem to be equally or more important than pH, as indicated by the ratio $\lambda_1/\lambda_2$ (Table 2). None of the significant changes in the cyst assemblages coincided with the pronounced drop in diatom-inferred pH (Fig. 1); however, diatom-inferred pH explained a significant amount of variation in the cyst assemblages, and a high number of cyst types were related to diatom-inferred pH.

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