Inferring paleosalinity trends using the chrysophyte cyst to diatom ratio in coastal shallow temperate/subtropical lagoons influenced by sea level changes

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Abstract Data on chrysophyte cyst to diatom ratios as an index to track Holocene paleosalinity changes are presented. Six sediment cores taken in four coastal systems influenced by Holocene sea level changes indicate that during the transition from marine/brackish to brackish/freshwater and freshwater conditions, increases in the cyst to diatom ratio were recorded. These data suggest that Holocene changes in paleosalinities in coastal aquatic systems may be tracked by using this simple index, however other factors (such as changes in nutrient levels) may complicate some interpretations. Nevertheless, data required to calculate this simple index are easy to obtain, and so relatively little effort is required to obtain some paleolimnological information on these two important algal groups.

Keywords Chrysophyte cysts · Diatoms · Salinity · Sea level change · Uruguay

Introduction

Since the publication of the chrysophyte cyst to diatom ratio (Smol 1985), researchers have used this simple index to track paleolimnological changes in trophic status in temperate lakes (e.g. Lotter et al. 1997, 1998; Karst and Smol 2000; Forrest et al. 2002; Paterson et al. 2004). Most of the papers dealing with this ratio report data from freshwater systems, as chrysophytes occur predominantly in freshwater oligotrophic poorly mineralized lakes (Smol 1985; Duff et al. 1995). For this reason, Smol (1985) proposed that in oligotrophic systems, cyst to diatom ratios often display relatively high values, whereas in meso–eutrophic systems ratios are often lower. In addition, chrysophytes are rarely found in marine environments (Duff et al. 1995). Because of this, taxonomic diversity in marine systems is thought to be low due to salinity stress (Rull and Vegas-Vilarrúbia 2000). Chrysophyte cysts have been investigated in marine/brackish and athalassic environments (Cumming et al. 1993; Rull and Vegas-Vilarrúbia 2000) on only a few occasions. Cumming et al. (1993) have already pointed out the paleolimnological potential of chrysophyte cysts as indicators of changes in inland lake salinity in cold north temperate regions. In temperate/subtropical regions, however, the paleolimnological use of chrysophytes as indicators of salinity changes has not yet been studied.

This paper presents paleolimnological data on the cyst to diatom ratio in four coastal water bodies from which six sediment cores were taken. The cores extend from 27,000 year BP to contemporary times, and encompass paleosalinity changes from

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marine/brackish to freshwater levels (García-Rodríguez et al. 2001, 2002a, b; 2004a, b, c; García-Rodríguez and Witkowski 2003; Bracco et al. 2005). In this paper it is shown that the ratio of chrysophyte cysts to diatoms provides interesting data on trends in this ratio that appear to be related to salinity.

The study area

The southern coast of Uruguay lies in a temperate/subtropical and humid region with a mean historical annual rainfall of 1,100 mm per year (García-Rodríguez et al. 2002b). The area contains a series of coastal shallow aquatic systems (Fig. 1) that originated about 7,000 year BP, after the first large Holocene marine transgression (Martin and Suguio 1992; Angulo and Lessa 1997; Angulo et al. 1999; Isla 1998). This transgression was a consequence of glacioeustatic processes, and there were no significant changes in tectonic/seismic activity in the eastern coast of South America during the late Pleistocene/Holocene (Martin and Suguio 1992; Espinosa et al. 2003). The coastal zone is dominated by grasslands, sand dunes and rocky shores. Detailed information on the limnology and paleolimnology of these coastal water bodies can be found in Conde et al. (1999, 2000, 2002), Conde and Sommaruga (1999), Jorcín (1999), Mazzeo et al. (2003), García-Rodríguez et al. (2001, 2002a, b, 2004a, b, c), García-Rodríguez and Witkowski (2003) and Bracco et al. (2005).

Materials and methods

Six piston cores were taken, one from Lake Blanca, two from Rocha Lagoon, two from Castillos Lagoon and one from Negra Lagoon (Fig. 1) in April/May 2000 with the aid of a 5-cm diameter piston corer. The length of the core ranged from almost 600 to 190 cm. After retrieval, the cores were immediately sealed and kept in the dark at 4°C, prior to laboratory analyses. Samples from each core were selected for both conventional and AMS radiocarbon dating. The conventional dating was performed on bulk sedimentary organic matter and on shells of *Heleobia australis* d'Orbigny and *Erodona mactroides* Daudin. The AMS ^{14}C was performed on bulk sedimentary organic matter. The samples were treated with 1% HCl, 1% NaOH and combustion to CO_2 was performed in a quartz tube with CuO and silver wool at 900°C. The CO_2 was reduced to graphite and the ^{14}C concentration was measured by comparing the simultaneously collected ^{14}C, ^{13}C and ^{12}C beams, with oxalic acid standard CO_2. Sediment age was calculated with a δ^{13}C correction for isotopic fractionation based on the ^{13}C/^{12}C ratio simultaneously with the ^{14}C/^{12}C ratio.

Sediment type was expressed as percentage of ϕ-units, which is a term used to group sediments into different types according to the size of the particles (Balsille and Tanner 1999; Wang and Ke 1997). The ϕ-units scale ranges from -12 (representing the biggest particles i.e. boulder), to 14 (representing the smallest particles i.e. very fine clay). Such a

Fig. 1 The study area. Black dots indicate coring stations
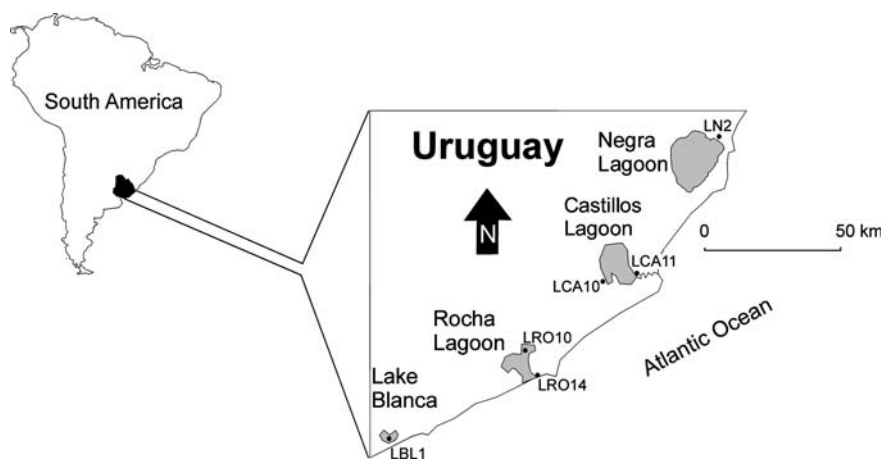
scale is computed with the equation $\phi=-\log_2$ (grain size, mm).

Total carbon (TC), total nitrogen (TN) and total phosphorus (TP) were determined according to the standard methods of the German Institute for Standardization (DIN: Deutsches Institut fuer Normung) and the International Standard Organization (ISO). TC and TN were measured with a vario-EL-CNS elemental analyzer (Elementar Analysesysteme GmbH, Jena, Germany). TP was measured according to DIN 38414 – S12 (1986). Organic matter and carbonate were determined by loss on ignition (Heiri et al. 2001).

About 230 slides were mounted in Naphrax® for diatom valves counting and identification at 1,250× magnification. A minimum of 250 valves was counted. Diatoms were identified and classified according to Metzeltin et al. (2005), Metzeltin and García-Rodríguez (2003), Lange-Bertalot (2001), Witkowski et al. (2000), Rumrich et al. (2000), Krammer (2000), Metzeltin and Lange-Bertalot (1998), and Frenguelli (1941, 1945). Chrysophyte cysts were simultaneously counted and expressed as the percentage ratio of their abundance to the total number of diatom valves and chrysophyte cysts (Smol 1985). A maximum of 421 chrysophyte cysts per slide was counted while some slides exhibited no cysts. Good preservation of both diatoms and chyrsophyte cysts was observed.

## Results and discussion

Castillos Lagoon

Core LCA10

This lagoon is separated from the Atlantic Ocean by a 10-km wide sand dune, but it connects to the sea via Valizas River. Salinity therefore ranges from 0 ‰ to 20 ‰ (Jorcín 1999). The system was characterized by terrestrial conditions until before 13,400 year BP (García-Rodríguez et al. 2004c). Once an aquatic system was established, marine/brackish conditions were inferred during the early Holocene until ~3000 year BP, when a brackish/freshwater stage was established. Since the lagoon presently connects to the ocean, it has never reached a full freshwater stage (Jorcín 1999).

The basal section of core LCA10 contained neither diatoms nor chrysophyte cysts. Between 190 cm and 110 cm, marine/brackish diatoms accounted for ~80% and brackish/freshwater and freshwater taxa accounted together for 20% (Fig. 2a). The cyst to diatom ratio exhibited a value close to 3%. Such a marine/brackish stage was established because the sea level was 5 m to 2 m above the present mean sea level (Martin and Suguio 1992; Angulo and Lessa 1997; Isla 1998; Angulo et al. 1999; García-Rodríguez et al. 2004c). During this stage, low relative abundances of freshwater diatoms, together with either lack of chrysophyte cysts (core LCA11) or a very low cyst to diatom ratios (core LCA10), were observed. This indicates salinity-stress conditions for the proliferation of freshwater microalgae (Rull and Vegas-Vilarrúbia 2000). Above 110 cm, marine/brackish diatoms decreased in abundance to values of ~40%, whereas brackish/freshwater and freshwater diatoms accounted together for ~50%. Maximum values for the cyst: diatom ratio were observed between 120 cm and 80 cm depth (Fig. 2a). This matches with the sea level fall inferred for ~5,000 year BP (Martin and Suguio 1992; Angulo and Lessa 1997; Angulo et al. 1999; García-Rodríguez et al. 2004c), which led to a decrease in salinity levels of the lagoon. As the salinity levels decreased from marine/brackish to brackish/freshwater levels, increases in cysts to diatoms ratios were recorded (Fig. 2a).

Core LCA11

From the basal section of core LCA11 to 330 cm, marine/brackish diatoms accounted for ~85% (Fig. 2b) and brackish/freshwater species displayed abundance values of ~8%, except for the peaks observed at 530, 430, 390 and 340 cm. Freshwater diatoms were only observed between 420 cm and 360 cm, but abundances values never exceeded 9%, and chrysophyte cysts were not observed (Fig. 2b). Such a marine/brackish stage was established because the sea level was 5 to 2 m higher than the present mean sea level (Martin and Suguio 1992; Angulo and Lessa 1997; Isla 1998; Angulo et al. 1999). This indicates salinity-stress conditions for the proliferation of freshwater microalgae (Rull and Vegas-Vilarrúbia 2000).

Fig. 2 Relative
abundances of freshwater,
brackish/freshwater and
marine/brackish diatoms as
well as cysts to diatoms
ratios versus depth. Black
boxes to the right of all six
plots indicate sediment age
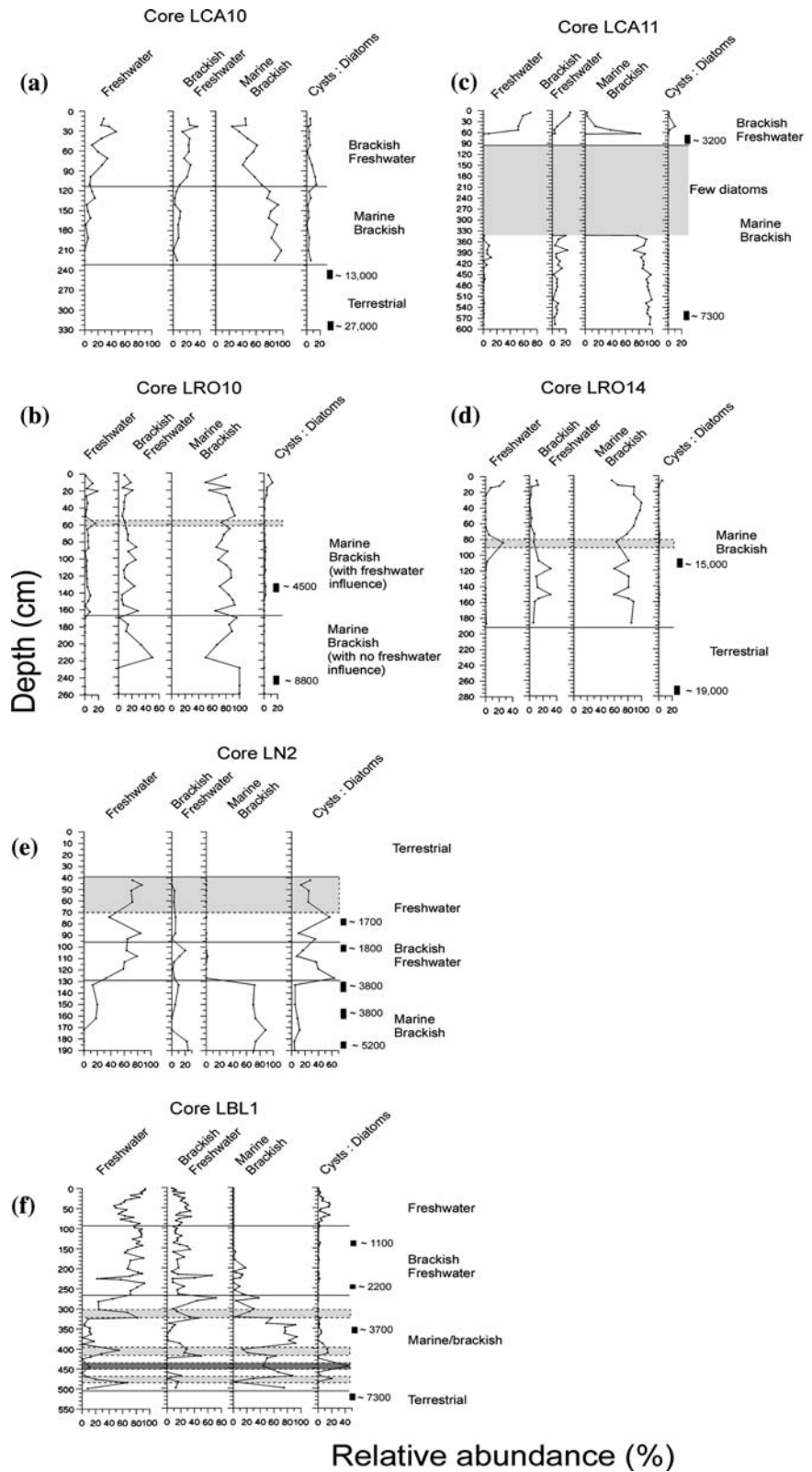
In the section 330–60 cm (depicted with grey in Fig. 2b), only about 50 diatom valves could be counted but most of the observed species were all marine/brackish indicators (García-Rodríguez et al. 2004c) and no chyrsophyte cysts were observed. The upper 60 cm of the core were dominated by brackish/ freshwater and freshwater taxa (Fig. 2b). Thus, only after the sea level fall observed after ∼4,000 year BP (Martin and Suguio 1992; Angulo and Lessa 1997; Angulo et al. 1999) both brackish/freshwater and freshwater diatoms were recorded. Marine/brackish diatoms showed a peak at 60 cm but then decreased towards the core surface. Only above 55 cm depth were high abundances of freshwater diatoms together with chrysophyte cysts observed (Fig. 2b), which again indicates that the ratio of chrysophyte cysts to diatoms may be a sensitive tool for inferring shifts in salinity.

Rocha Lagoon

Core LRO10

This lagoon is separated from the sea by a sand bar that opens naturally through a single mouth when the water level increases above ∼1.3 m, when wave action on the seaward side of the sandbar occurs (e.g. during storms), or a combination of both. Inter-communication with the ocean may occur several times per year. In addition, after freshwater discharges, marine intrusions take place (Conde and Sommaruga 1999). Thus, this water body is classified as a marine/brackish system, although freshwater pulses occur during the winter. Moreover, the water body never achieved a full brackish/freshwater stage during the Holocene (García-Rodríguez et al. 2004a). However, as indicated by diatoms, two major Holocene stages can be recognized (core LRO10, Fig. 2c). The first is a marine/brackish without freshwater influence, and the second, a marine/brackish but with freshwater influence. The boundary between the two stages can be set prior to 4,500 year BP (i.e. at 170 cm, Fig. 2c). Below 170 cm depth, marine brackish/diatoms accounted for ∼90% and brackish/freshwater taxa for ∼10% (Fig. 2c), except at 220 cm where brackish/freshwater species increased to about 40%. Even though at 220 cm there might have been a decrease in salinity, the system was not influenced by freshwater as no freshwater diatoms were detected (Fig. 2c).

Above 170 cm, marine/brackish diatoms accounted for 70%–80%, brackish/freshwater taxa accounted for 10%–20%, whereas freshwater diatoms accounted for 5% (Fig. 2c). In addition, the cyst to diatom ratio showed a slight increase to 2%. After the system began to experience freshwater inputs, the ratio of cysts to diatoms was sensitive to such changes. At 58 cm depth (indicated with grey in Fig. 2c), freshwater diatoms (with dominance of *Aulacoseira granulata*; García-Rodríguez et al. 2004a) increased in relative abundance values to ∼15%, but a concomitant increase in cyst to diatom ratio was not observed (Fig. 2c). Dominance of *A. granulata* suggests meso to eutrophic conditions (Krammer and Lange-Bertalot 1991; van Dam et al. 1994) which are not suitable for the proliferation or chrysophyte cysts (Smol 1985). In the top 20 cm of the sediment core, freshwater diatoms increased in relative abundances (Fig. 2c), and concomitant increases in the cyst to diatom ratios were recorded. The increase in freshwater diatoms and chrysophyte cysts within this section implies a decrease in salinity due to a decrease in sea level (Martin and Suguio 1992; Isla 1998).

Core LRO14

Core LRO14 extends from the late Pleistocene to the early Holocene (Fig. 2d, García-Rodríguez et al. 2004a). The basal section corresponds to the Chuy formation which was deposited during late Pleistocene (Sprechmann 1978). The lack of diatoms or chrysophyte cysts indicates a terrestrial system. After the establishment of an aquatic system, marine brackish/diatoms accounted for ∼90% and brackish/ freshwater species accounted for 10% in most samples (Fig. 2d). At 151 cm and 118 cm, increases in abundances of brackish/freshwater species and decreases in marine/brackish taxa were observed. Both freshwater diatoms and chrysophyte cysts accounted for less than 1% in this section. Although shifts in marine and marine/brackish taxa were registered at the above depths, changes in salinity might not have been significant as increases in freshwater diatom taxa were not observed.

Freshwater diatoms were not observed in the middle and the upper section of the core. In the middle section, freshwater diatoms accounted for 25%. Dominance of both *Aulacoseira granulata* and

Nitzschia denticula were observed. Since these two taxa are indicators of high trophic state (meso to eutrophic, Krammer and Lange-Bertalot 1991; van Dam et al. 1994), and since chrysophyte cysts often dominate in oligotrophic systems (Smol 1985), concomitant increases in cysts to diatoms ratios were not observed. In the upper section of the core (Fig. 2d), freshwater diatoms accounted for ∼27% of the relative abundances, and cyst to diatom ratio increased to ∼5%. In this case, increases in mesotrophic to eutrophic diatoms were not observed (García-Rodríguez et al. 2004a), and instead *Pinnularia latevittata* was the dominant diatom (a species commonly found in systems under a clear water phase in Uruguay; Metzeltin et al. 2005). This freshwater stage, within the upper 25 cm of core LRO14, which belongs to the early Holocene, is not representative of past environmental conditions (see García-Rodríguez et al. 2004a). However, the changes recorded in this interval indicate that the cyst to diatom ratio is still a sensitive tool to track changes in salinity in coastal systems.

Negra Lagoon

Core LN2

This lagoon is elevated 8 m above mean sea level. It is separated from the ocean by a 4-km wide sand bar and has no direct connection to the sea. Although it exhibits very small changes in salinity levels because of the marine spray influence, it is mostly a freshwater body (Conde and Sommaruga 1999). The lagoon showed marine conditions in the early Holocene, marine/brackish in the mid Holocene, and freshwater conditions were established during late Holocene. However, prior to the above stages (i.e. before 5,200 year BP, Fig. 2e), the system exhibited terrestrial conditions (Bracco et al. 2005). Once an aquatic system was established, marine/brackish diatoms accounted for at least ∼75% of the relative abundances (i.e. below 130 cm depth Fig. 2e). Brackish/freshwater species showed maximum percentages of ∼23% within the section 180–190 cm, and then decreased. Freshwater diatoms only occurred above 170 cm (Fig. 2e), and accounted for at most ∼20%. Cyst to diatoms ratios were always close to 5% below 130 cm, except for the 172 cm sample, where they reached a value of 10%. Only

after a brackish/freshwater system was established (after ∼3,800 year BP, just above 130 cm depth), because of a sea level fall (Martin and Suguio 1992; Angulo and Lessa 1997; Angulo et al. 1999; Bracco et al. 2005), sharp increases in both freshwater diatoms and chrysophyte cysts were observed (Fig. 2e).

Above 130 cm, marine brackish diatoms were almost absent, brackish/freshwater taxa accounted for ∼5%, and freshwater species showed a sharp increase (to ∼70%, Fig. 2e). Concomitant sharp increases (to ∼60%) in cyst to diatom ratios were recorded. At 108 cm depth, brackish/freshwater diatoms increased relative abundances to ∼20% and a concomitant decrease in cysts to diatoms ratio was observed (Fig. 2e). This suggests that changes in the ratios of chrysophyte cysts to diatoms are sensitive to salinity stress, as already indicated by Rull and Vegas-Vilarrúbia (2000).

A freshwater system was established above 95 cm depth. It is important to point out that Bracco et al. (2005) had set such a transition boundary at ∼65 cm depth in this core. However, the data shown in Fig. 2e indicate that this boundary could be set at 95 cm, as brackish/freshwater diatoms always accounted for 5%, and no marine/brackish taxa were observed above the 95 cm depth. During this stage, the cyst to diatom ratio reached a value of ∼60% at 75 cm, but then decreased to ∼30% in the sediment interval comprised between 70 cm and 40 cm (indicated with grey in Fig. 2e). Concomitant increases in the relative abundances of both *Aulacoseira granulata* and *Aulacoseira ambigua* were observed. Both *Aulacoseira* spp. are indicators of high trophic state (mesotrophic to eutrophic, Krammer and Lange-Bertalot 1991; van Dam et al. 1994). Since chrysophyte cysts are often dominant in oligotrophic systems (Smol 1985), they did not display a peak in this interval.

Lake Blanca

Core LBL1

Lake Blanca is elevated 4 m above mean sea level. It is a fresh waterbody from which drinking water is produced. The system showed several recent eutrophication episodes since the 1960s (García-Rodríguez et al. 2002b). The system exhibited marine/brackish conditions during the early Holocene, brackish/

freshwater during the mid Holocene and a full freshwater system was only established after ~1,000 year BP. However, prior to these aquatic stages, the system exhibited terrestrial conditions (García-Rodríguez et al. 2004b).

Below the 260 cm depth, the sediment core was dominated by marine/brackish and brackish/freshwater diatoms (Fig. 2f). However, during the marine/brackish stage, there were four episodes in which decreases in salinity were observed as increases in freshwater diatoms were recorded (one of them indicated with dark grey, and the other three with light grey; Fig. 2f). In the episode indicated with dark grey, a sharp increase in chrysophyte cysts (to ~45%) was observed. In this section, *Aulacoseira granulata*, an indicator of high trophic state (meso to eutrophic, Krammer and Lange-Bertalot 1991; van Dam et al. 1994) showed relative abundances of ~10% (García-Rodríguez et al. 2004b). The low percentages of *A. granulata*, together with high percentages of chrysophyte cysts, suggest a moderate trophic state. In contrast, in the other three episodes (those indicated with light grey in Fig. 2f), *A. granulata* accounted for 30%–60% of the relative abundances (García-Rodríguez et al. 2004b). Thus the system showed meso to eutrophic conditions. Since chrysophyte cysts are often dominant in oligotrophic systems (Smol 1985), they did not display sharp increases in relative abundances, as observed at 450 cm depth (depicted with dark grey in Fig. 2f). Nevertheless, the increases in the cyst to diatom ratio in all four sections depicted with grey indicate that such a ratio is sensitive to changes in paleosalinities.

In sediment the section from 260 cm to 93 cm, marine/brackish diatoms decreased in relative abundances (Fig. 2f), and brackish/freshwater species showed relative abundances of about 20%. Freshwater species increased and accounted for ~60% (Fig. 2f). The most abundant freshwater species in this section were *Aulacoseira granulata* and *Nitzschia denticula* (García-Rodríguez et al. 2004b), which are indicators of meso to eutrophic conditions (Krammer and Lange-Bertalot 1988; van Dam et al. 1994). During this stage, the cyst to diatom ratio was very low (Fig. 2f). García-Rodríguez et al. (2004b) inferred trophic states comparable to those observed during the past 30 years, during which time the lake was shown to be eutrophic. Such eutrophic conditions might have inhibited the proliferation of chrysophyte

cysts, as eutrophic conditions are not suitable for chrysophyte populations (Smol 1985).

After a freshwater body was established at 90 cm depth (García-Rodríguez et al. 2004b), concomitant increases in the cyst to diatom ratio were observed. However, there were two episodes where cysts to diatoms decreased (between 50 cm and 60 cm, and from 25 cm to the sediment surface; Fig. 2f). In the interval 50–60 cm, even though small increases in organic matter, TN and TP were observed (García-Rodríguez et al. 2004a), which might imply no major changes in trophic state, and chrysophyte cysts decreased. From 25 cm towards the core surface, sharp increases in organic matter, TN and TP were recorded (García-Rodríguez et al. 2004b). During this stage the lake was shown to be eutrophic. Since chrysophyte cysts are often dominant in oligotrophic systems (Smol 1985), they decreased in abundance.

Conclusions

The behaviour of chrysophyte cysts in relation to trophic state (expressed as cyst to diatom ratio) proposed by Smol (1985) for Canadian lakes, seems to hold for coastal shallow temperate/subtropical freshwater systems as well. That is, for the Holocene freshwater stages, the ratio of cysts to diatoms displayed maximum values during oligotrophic stages and minima during meso to eutrophic stages. In coastal systems influenced by Holocene sea level changes, as those reported in this paper, the ratio of cysts to diatoms might also be useful to track trends in paleosalinities. During the transition from marine/brackish to brackish/freshwater and freshwater conditions, increases in cyst to diatom ratio were recorded in all six sediment cores. Therefore, information on changes in paleosalinities can be obtained by using this simple ratio. As pointed out by Smol (1985), an operational advantage is that both diatoms and chrysophyte cysts can be identified and counted from the same microscope slide. Since both chrysophyte cysts and diatoms are very easy to identify as a group, researchers without expertise in taxonomy might be able to use such an index without any time consuming training on taxonomy.

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