Diatom preservation: differential preservation of sedimentary diatoms in two saline lakes

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The integrity of all sedimentary diatom assemblages is influenced to some degree by taphonomic processes. Recognising these processes with regard to preservation pathways for diatom assemblages and for individual species can be instructive for interpreting sediment core diatom records. Diatoms deposited in saline lakes are usually particularly exposed to both chemical and physical processes that promote poor preservation. Aspects of diatom preservation are explored in two markedly different saline lakes (one in North America and one in Egypt) and observations are used to make some initial inferences about diatom preservation. By applying dissolution indices to evaluate differences in valve preservation states between assemblages and between species in an objective manner, sedimentation processes and valve characteristics are indicated important implications for interpreting sedimentary diatom records. It is further argued that, by taking account of diatom dissolution states, both qualitative and quantitative inferences about past environments can be extended.

Keywords: Diatom, dissolution, preservation, biogenic silica, ultrastructure, saline lake, sedimentation, taphonomy, climate change

Abbreviations: **DDI** – Diatom dissolution index,

Introduction

Assuring the integrity of sedimentary diatom records in aquatic sediments, either freshwater or saline/marine, is a prime concern if qualitative or quantitative information contained in the fossil assemblages is to be used for palaeo-environmental reconstructions. Yet in aquatic environments, diatom communities are subject to a variety of environmental processes before, during and after incorporation into sediments that can highly modify resultant sedimentary assemblages. Such modifications can influence the effectiveness of palaeo-environmental reconstruction methods. The value of recognising the influences of processes involved in the transformation of organismal remains into fossils was recognised by the palaeontologist I. A. Efremov over 60 years ago. He used the term 'taphonomy' to

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describe the transformation processes (EFREMOV 1940). Some specific taphonomic criteria that are particularly relevant to diatoms were discussed by CAMERON (1995) where the issue of representativity of fossil diatom assemblages is dealt with in some detail. The 'faithfulness' of sedimentary records can be assessed in a number of ways that include comparisons with archived material and with source communities as well as by using diatom preservation experiments and indices (BARKER 1992, RYVES et al. 2001).

Taphonomy is an issue for diatom valves in both modern and sedimentary environments as well as for archival and other diatom procedures. In the environment, prior to and during the accumulation of diatom valves in sediments, breakage and dissolution can cause differential preservation. Indeed, these processes are not mutually exclusive but are often closely correlated (e.g. STRAUB 1993, RYVES et al. 2006). Excessive valve breakage is typical of high energy environments (BEYENS and DENYS 1982) but also results from grazing effects (TURNER 1991) and, after deposition, by compaction and drying of sediments (FLOWER 1993). Diatom dissolution will always occur when diatom remains are exposed to water with low (below saturation) concentration of dissolved silica. On a longer time scale, diatoms incorporated into sediment can undergo diagenesis involving the crystallization or mineral replacement of the diatom silica (WILLIAMS and CRERAR 1985, BARKER et al. 1994, LENG and BARKER 2006).

The literature describes a variety of specific processes and conditions that are known to affect diatom dissolution. In many cases, it is the pH, salt concentration and temperature of surrounding media (LEWIN 1961, LAWSON et al. 1978, HURD and BIRDWHISTELL 1983, BARKER et al. 1994, BIDLE et al. 2002, RYVES et al. 2006) that are particularly important in influencing valve dissolution. Water permanence, depth and meromixis (REED 1998, RYVES et al. 2006) can affect preservation, as can diatom sedimentation or sinking rates in the water column (CONLEY and SCHELSKE 1989, SHIMADA et al. 2003, BATTARBEE et al. 2005). Sediment texture, grazing and (bio) turbation (HECKY and KILHAM 1973, TURNER 1991, FLOWER 1993) are all influential external factors. Diatom structure and surface area (LEWIN 1961, FLOWER 1993, RYVES et al. 2001) and diatom concentration (BRADSHAW et al. 2005, SWANN and MACKAY 2006) together with bacterial action (PATRICK and HOLDING 1985, BIDLE and AZAM 1999) all have further implications for diatom preservation.

This paper examines some common features of diatom dissolution and evaluates sedimentary diatom sequences from two different lakes where current salinity is relatively low (Spiritwood Lake, USA) and relatively high (Lake Qarun, Egypt). By taking a direct approach to investigating preservation *in situ* we hope to refine interpretation techniques for the occurrence and abundance of poorly preserved sedimentary diatom sequences. Rather than taking an experimental approach (e.g. LEWIN 1961, BARKER et al. 1994, RYVES et al. 2001), characteristics of particular diatom facies are investigated by using objective methods of dissolution assessment.

Assessing diatom dissolution

There are two principal ways of tackling preservation problems in sediment cores. Firstly, the various diatom dissolution studies described above can be consulted and used to infer possible causes of poor preservation. To aid this approach the results of many studies addressing diatom preservation are summarized in table 1 so that principal processes or conditions that are known to favour good or poor diatom valve preservation (either in the

Tab. 1. A simple check-list of some factors known to influence diatom preservation in modern aquatic environments and in sediments (see text for relevant references).

Process/environmental characteristic	Preservation	
	Poor	Good
pH	High	Low
Conductivity (high base cations)	High	Low
Water depth (and permanence)	Shallow (ephemeral)	Deep (permanent)
Sinking rate (in water)	Low	High
Sediment accumulation rate	Low	High
Sediment texture	Coarse	Fine
Grazing and bioturbation (including bacteria)	High	Low
Diatom structure	Delicate	Robust
Diatom concentration	Low	High
Temperature	High	Low

water column or in surficial sediments) are identified. This simple checklist of preservation characteristics and conditions is derived mainly from experimental studies, observations on sinking material and from sediment profiles. So, although table 1 indicates some of the main processes and conditions that affect diatom preservation, it does not take into account the interactions between dissolution processes. Hence, its value for interpreting lake sediment records from any specific site is limited. Any particular lake will display strongly differing patterns of preservation through time where past process interactions and phasing are unknown.

A second approach that is more objective is based on measuring the quality of specific assemblages by applying a quantitative method of assessment. Dissolution indices (e.g. RYVES et al. 2001, 2006) can be used to compare proportions of part dissolved and undissolved (pristine) valves and there are essentially two simple ways to do this. One, the F index (FLOWER and LIKHOSHWAY 1993, RYVES et al. 2001), is based on the ratio of (partially) dissolved to pristine valves, where F_i = F index of sample i, n = pristine valves of species j in sample i, N = sum of pristine + dissolved valves (girdle views are excluded):

$$F_i = \frac{\sum_{j}^{m} n_{ij}}{\sum_{j}^{m} N_{ij}} \qquad (1)$$

Values range from 0 (all valves visibly dissolved under LM) to 1 (no valves show signs of dissolution).

The other index is the Diatom Dissolution Index (DDI; RYVES et al. 2006) which compares diatoms in an assemblage across all dissolution states (categorised into 2 to 4 dissolution »stages«, depending on species, and denoted S). Dissolution patterns (stages) are illustrated for a number of major diatom morphologies in RYVES et al. (2009). For an assemblage i, n_s = sum of valves of all taxa in each stage S, N = total number of valves classified

(again, girdle views are excluded), and S_{max} is the theoretical end point for dissolution in the assemblage (i.e. largest value of S recognised for any significant component of the assemblage; generally $S_{max} = 3$ or 4):

$$DDI = \frac{\sum_{s=1}^{s=4} n_s \bullet (S-1)}{N \bullet (S_{max} - 1)} \tag{2}$$

DDI indices range from 0 to 1, but here with 0 indicating excellent preservation (all valves in stage 1, the undissolved or »pristine« state), to 1 (very poor preservation, with valves in the most dissolved state recognised). Both indices (F and DDI) can be applied to individual taxa or whole assemblages, and enable quite diverse and different assemblages to be compared.

Diatom preservation in sediments of two saline lakes

Diatom distributions and preservation states were explored in sediment core material from two lakes that have experienced fluctuating salinity across the freshwater/saline threshold. The first is Spiritwood Lake in North Dakota, USA, (area 1.67 km^2) where salinity has varied between around 1 and 4 g L^{-1} in the past 100 years (RYVES et al. 2009). The second is from a much more complex lake, Lake Qarun, located in the Faiyum Depression of Middle Egypt at the edge of the Western Desert. This fairly large lake (around 40 x 10 km) is fed via a regulated branch of the River Nile and its salinity has varied considerably, by between around 7 and 30 g L^{-1}, during the past nearly 100 years (see FLOWER et al. 2006).

Spiritwood Lake is a relatively deep ($z_m = 16$ m), dimictic meso/eutrophic lake developed in a glacial meltwater channel, largely filled with glaciofluvial sediments. Diatom analysis was performed on core SW1 (82 cm long), collected close to the lake centre in August 1991 from c. 14 m depth, and dated using ^{210}Pb (APPLEBY 2001). Full details of the diatom stratigraphy and dating methods are given in RYVES et al. (2009).

Lake Qarun is now a shrunken remnant of a much larger lake (see HASSAN 1986) and currently has a maximum depth of around 9 m (FLOWER et al. 2006). Following initial coring in 1997 (FLOWER et al. 2006), an 8.3 m core (QARU2) was collected from near the centre of this lake in 2004 where water depth was 8.4 m. The core spans approximately the last 2000 years (see FOSTER et al. 2008) and the availability of only one date (from near the core base) prevented calculation of sediment accumulation rate variations.

Methods

Methods for preparing sediment samples from both lake cores were similar and involved treatment with hot, 30% hydrogen peroxide and concentrated hydrochloric acid (after BATTARBEE et al. 2001) before washing and mounting on cover slips in Naphrax diatom mountant. Diatom valve concentrations in the Lake Qarun sediment core samples were estimated by adding microspheres (BATTARBEE and KNEEN 1982). Diatom inferred salinities or conductivities were calculated using separate diatom-salinity models developed from regional training sets: for Spiritwood Lake, the original North American Great Plains

(NGP) model of FRITZ (1990), initially unadjusted for diatom dissolution (see RYVES et al. 2009) and for Lake Qarun, the North African training set of the European Diatom Database Initiative (http://craticula.ncl.ac.uk/Eddi/jsp/).

Results

Spiritwood Lake: Diatom analysis of the short core from this plankton-dominated lake showed major changes both in the proportions of dissolved values of two *Stephanodiscus* species (*S. niagarae* and *S. minutulus*-complex) and *Cyclotella meneghiniana* (Fig. 1) and in the proportions of the species themselves (RYVES et al. 2009). Diatom preservation of assemblages (as F index) is weakly inversely correlated with dissolution-unadjusted inferred salinity (Fig. 2A, $r^2 = 0.18$, $p = 0.05$) and more strongly, positively with sediment accumulation rate in cm yr^{-1} (Fig. 2B, $r^2 = 0.51$, $p < 0.001$), with weak correlation with sediment flux rate (as g^{-1} dry wt cm^{-2}; $r^2 = 0.24$, $p = 0.03$, not shown). Pair-wise comparisons of the three main species using DDI (Fig. 3) show markedly different patterns of dissolution behaviour, with *S. niagarae* and *C. meneghiniana* following the same pattern (Fig. 3A), but the dissolution behaviour of *S. minutulus* is only weakly correlated to that of *S. niagarae*
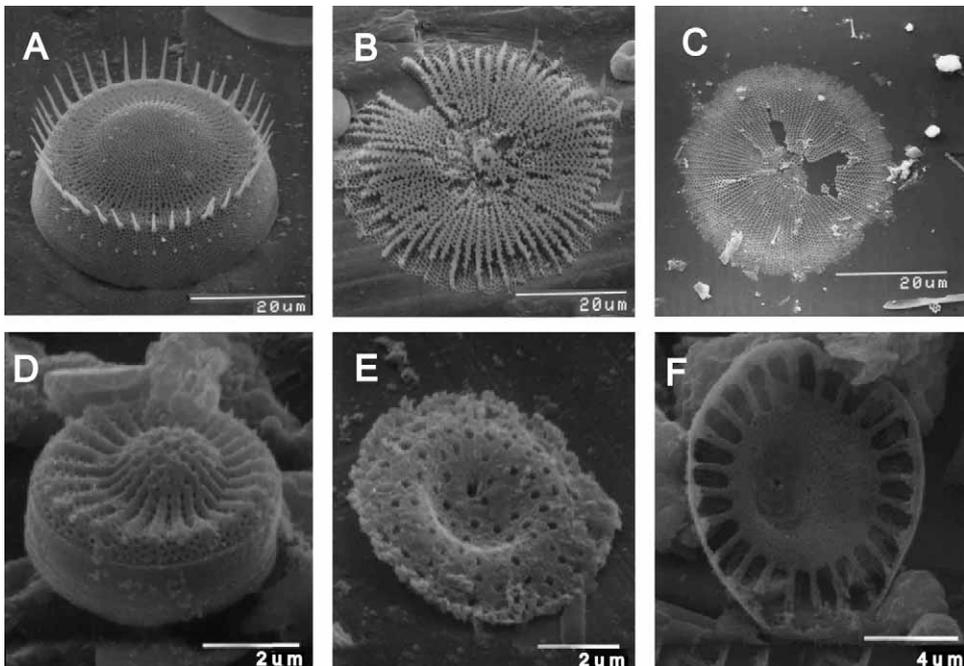

Fig. 1.   SEM micrographs of diatoms common in the Spiritwood Lake short core, across a range of preservation states (»dissolution stages«). (A)–(C): *Stephanodiscus niagarae* (A: pristine = stage 1, B: dissolved valve, stage 2, C: dissolved valve, stage 3). (D)–(E): *Stephanodiscus minutulus* (D: pristine, E: dissolved valve, stage 3). (F): *Cyclotella meneghiniana*, dissolved valve: stage 2. Adapted from Supplementary Material in RYVES et al. (2009).
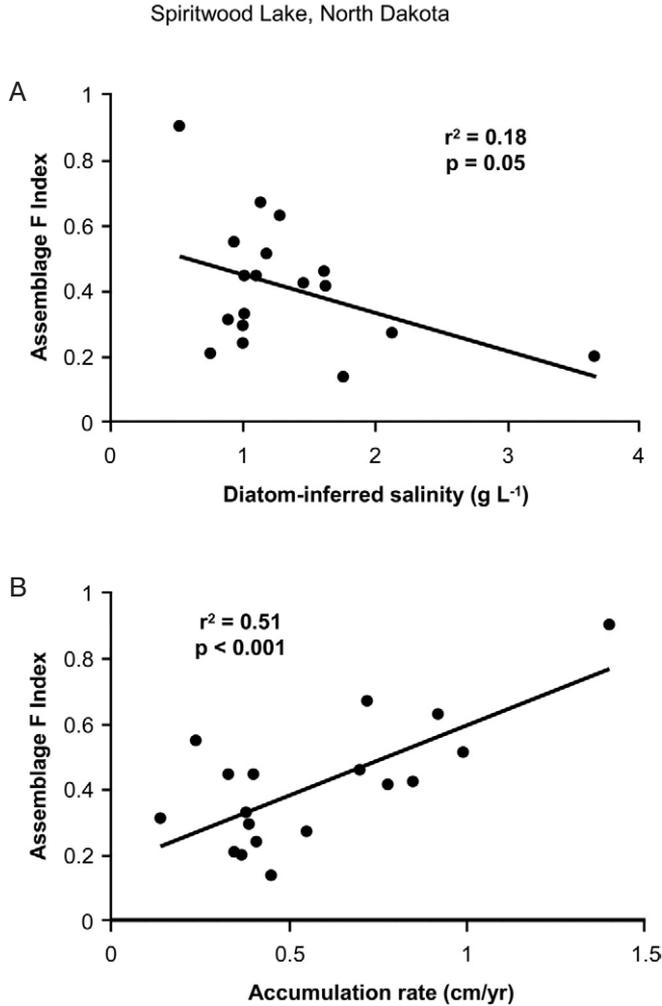
Spiritwood Lake, North Dakota

Fig. 2. Spiritwood Lake short core SW1. Scatter plots of (A) assemblage F index and diatom-inferred salinity (using the original NGP model of FRITZ, 1990, FRITZ et al., 1993, not adjusted for dissolution data) and (B) assemblage F index and accumulation rate (cm yr^{-1}).

(Fig. 3B), with the smaller, less robust valves of *S. minutulus* being better preserved on average than the larger, silica-rich *S. niagarae*, contrary to expectation from gross valve morphology and dissolution experiments (BARKER et al. 1994, RYVES et al. 2001).

Lake Qarun*:* In the lake sediment core QARU2, diatoms were present throughout but showed major changes in concentration, with the section between 6 and 7.5 m containing much higher diatom concentrations than above or below. Diatom assemblages were dominated by *Aulacoseira granulata* but *Cyclostephanos dubius* and *Cyclotella meneghiniana* were also common. *Thalassiosira faurii* was also abundant but only within the depth interval 6–7.5 m. Differential diatom preservation in the core is demonstrated in figure 4 with *Campylodiscus* (Fig. 4C) and particularly *Cyclostephanos* (at 150 cm depth) showing sig-
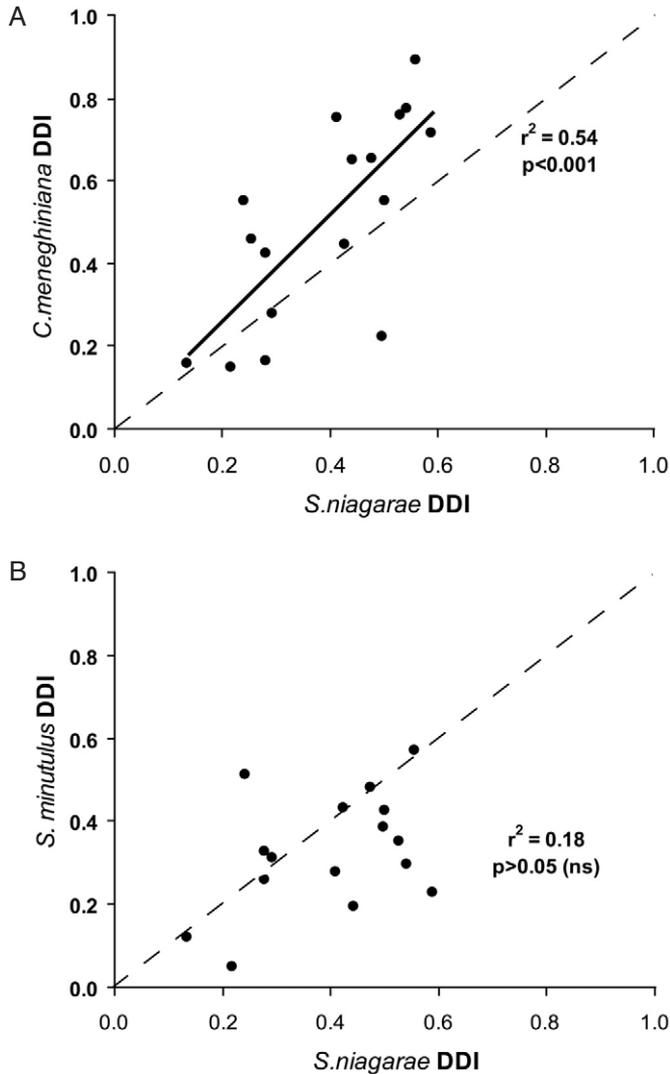
Fig. 3. Correlations between DDI (diatom dissolution index) scores for the 3 dominant taxa from Spiritwood Lake short core SW1. Increasing values indicate poorer preservation for DDI (in contrast to the F index). The dotted line shows the 1:1 line of equal preservation. (A) *Stephanodiscus niagarae* against *Cyclotella meneghiniana*; (B) *Stephanodiscus niagarae* against *Stephanodiscus minutulus* complex.

nificant valve damage (Fig. 4B) but with *Thalassiosira faurii* (at 700 cm depth) showing pristine valve condition (Fig. 4A). The distribution and extent of diatom dissolution was assessed by applying the F index, both to the whole assemblage (for those taxa present at frequencies > 5%) and to individual taxa.

According to the F index evaluated for the whole assemblages (Fig. 5A), good preservation was principally confined to between 6 and 7.5 m depth in the core. In this zone the F
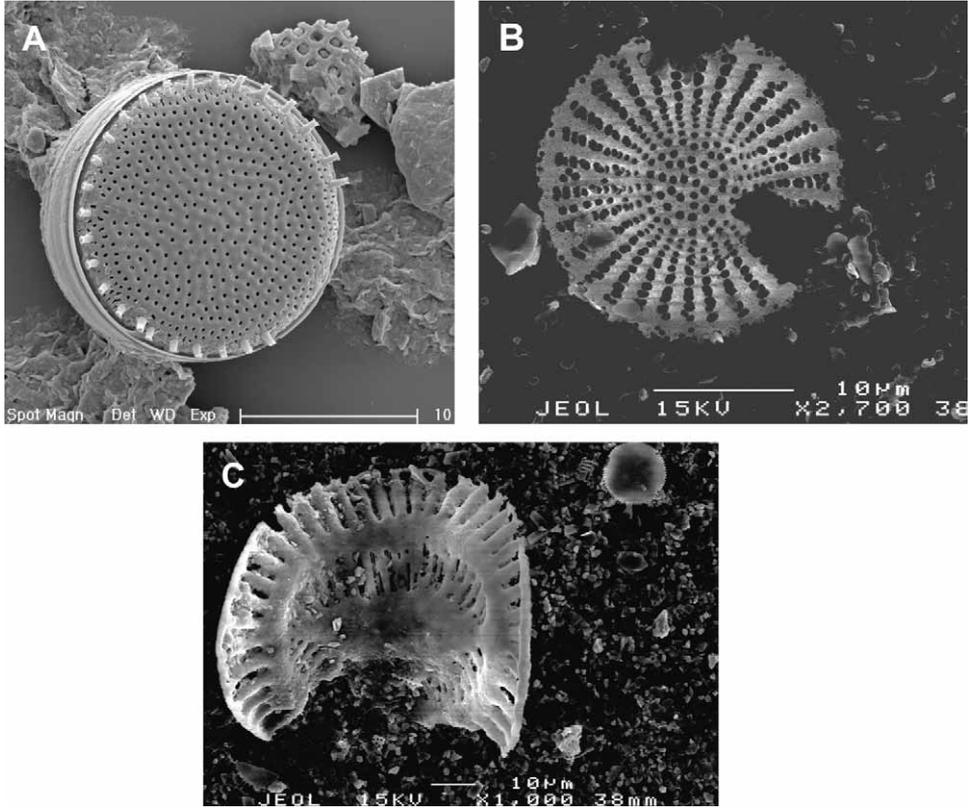
Fig. 4. SEM micrographs of diatoms extracted from a sediment core from Lake Qarun (QARU2, see text). (A): a near pristine valve of *Thalassiosira faurii* sampled from around 670 cm depth in the core; (B): a valve of *Cyclostephanos dubius* (though identification is hampered by dissolution) from around 420 cm in the core with extensive dissolution features; (C): a *Campylodiscus* valve from around 420 cm depth in the core showing marginal dissolution features (note, the *Cyclotella meneghiniana* valve central area in the top right of this image; dissolution stage 4).

index was generally between 0.3–0.65. Above 6 m depth, preservation was generally very poor with most F index values being between 0.1 and 0.2 and only exceeding 0.3 at around 375, 220, 160 and 150 cm point depths. Below 750 cm depth, the assemblages were again very poorly preserved with index values of 0.2 or less. Indices for the whole assemblage were generally lower than those for the most common diatom, *Aulacoseira granulata* (Fig. 5C). The other two common planktonic diatoms, *C. meneghiniana* and *T. faurii* (Fig. 5B and D), were less uniformly distributed within the core. *C. meneghiniana* was present from above 800 cm depth and occurred sporadically. *T. faurii* was restricted to between 775 and 597 cm depth in the core. Preservation of both taxa exceeded around 0.3 only in the lower core section but several levels displayed exceptional preservation for *T. faurii* with F index ≈ 1 (almost all valves were pristine). Preservation of *C. meneghiniana* never exceeded an F index value of 0.63.
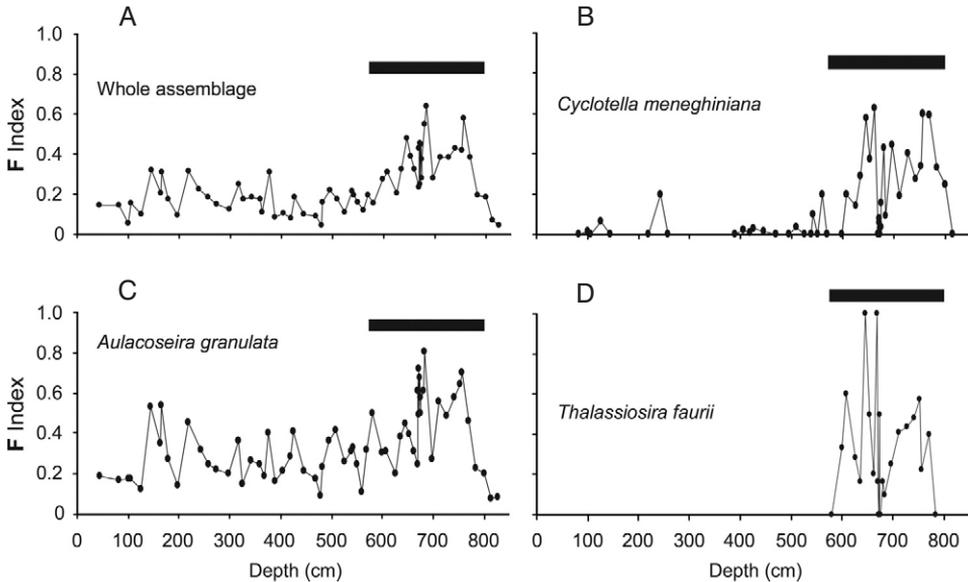
Fig. 5. Graphs A–D show the down-core (QARU2) variations in F index values for the (A) total diatom assemblage, (B) *Cyclotella meneghiniana*, (C) *Aulacoseira granulata,* and (D) for *Thalassiosira faurii*, respectively (see text). Solid bars indicate core sections with good valve preservation.

The relative preservation of individual taxa can be demonstrated more clearly by plotting the index scores against one another (Fig. 6). Three patterns emerge and there is a fairly good correlation ($r^2 = 0.79$; $p = < 0.0001$, cf. Fig. 5A and B) between the F index values of *A. granulata* and of the whole assemblage (as expected as this is the dominant diatom in the core). However, the whole assemblages are relatively less well preserved than are the *Aulacoseira* assemblages. When *C. meneghiniana* and *A. granulata* are compared (Fig. 6A) there is a positive correlation between F index values of the two taxa ($r^2 = 0.18$, p < 0.001). However, the relationship shows a strong and consistent skew in favour of relatively better preserved *A. granulata*. When *T. faurii* and *A. granulata* are compared (Fig. 6B) there is no significant relationship between the valve preservation states of these two taxa ($r^2 = 0.11$, p > 0.1). Although some of the sample points indicate better preservation of *A. granulata*, several samples of *T. faurii* were much better preserved than those of *A. granulata* and in two core samples (Fig. 5D) the valves of *T. faurii* were in near pristine condition (as verified by SEM, Fig. 4A).

Comparing total valve concentration with whole assemblage F index values indicated no trends (Fig. 7A) other than that the diatoms in most samples with low diatom concentrations tended to be poorly preserved. However, the data suggested a causal positive link between the F index and diatom concentrations from around 1 to 20 x 10^6 valves g^{-1} dry sediment ($r^2 = 0.51$, p < 0.005, Fig. 7A). Considering the diatom-inferred palaeosalinity values for the core assemblages, no correspondence was identified between these and whole assemblage preservation F index values except that the highest diatom concentrations occurred when inferred salinities were < 2500 µS cm^{-1} (Fig. 7B). Similarly, no clear relation-
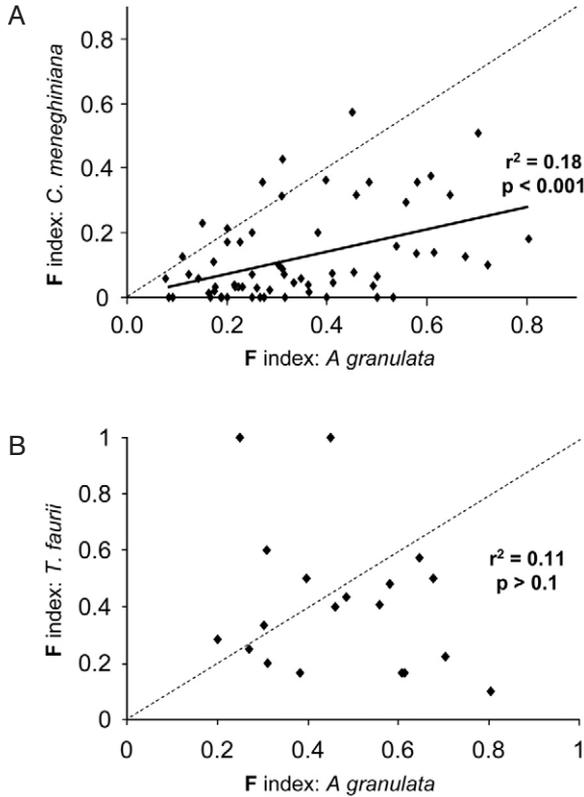
Fig. 6. Correlations between the F index scores for dominant taxa from the Lake Qarun core QARU2. Decreasing values indicate poorer preservation for the F index (in contrast to DDI). The dotted line shows the 1:1 line of equal preservation. (A) *Aulacoseira granulata* against *Cyclotella meneghiniana*; (B) *Aulacoseira granulata* against *Thalassiosira faurii.* The significant correlation between F index scores in (A) and the trend (solid) line is indicated.

ship between inferred salinity and diatom concentration was observed, although no samples with an inferred salinity value > 1000 μS cm^{-1} exceeded 25 x 10^6 valves g^{-1} dry sediment.

Discussion

Diatom preservation is a major issue in saline lake palaeolimnology, yet by recognising that dissolution is dependant on a variety of processes and conditions and by applying an objective assessment methods, interpretation of damaged valves can be improved. Dissolution of diatoms is a progressive process that seems to differ according to whether the valves are exposed to sub aerial, aquatic or sub-aquatic sedimentary conditions. Dissolution sequences are relatively well known for a range of diatoms in aquatic or sub-aquatic sedimentary environments (BARKER 1992, FLOWER et al. 2006, WARNOCK et al. 2007, RYVES et al. 2009) but much less is known around the combinations of environmental factors that promote dissolution in a particular lake.
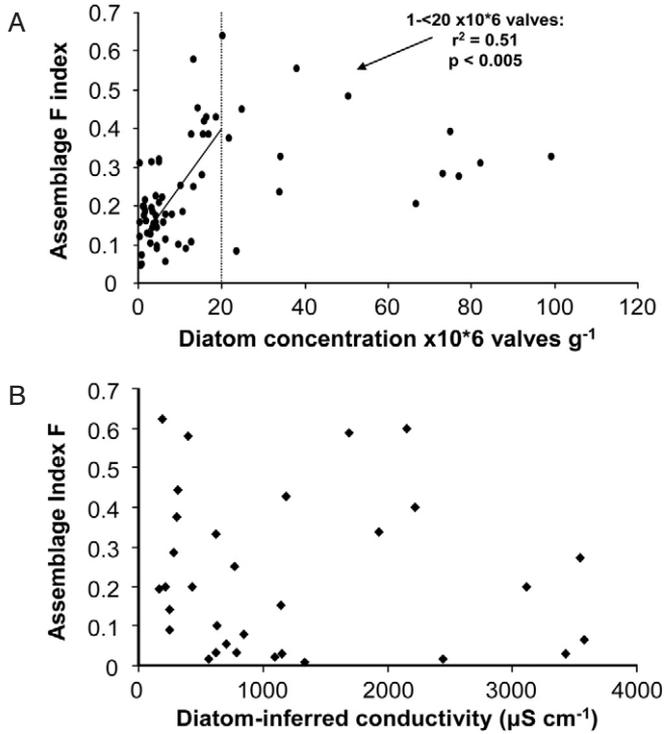
Fig. 7. (A) The relationship between sedimentary diatom concentrations against depth in core QARU2 over the entire range of diatom concentrations, $1 – 20 \times 10^6$ valves g^{-1} dry sediment. Preservation and diatom concentration appear to be correlated at lower values (between 1 and $< 20 \times 10^6$ valves g^{-1} dry sediment and the regression is plotted over this range). (B) The relationship between assemblage F index scores and diatom-inferred conductivity values for QARU2.
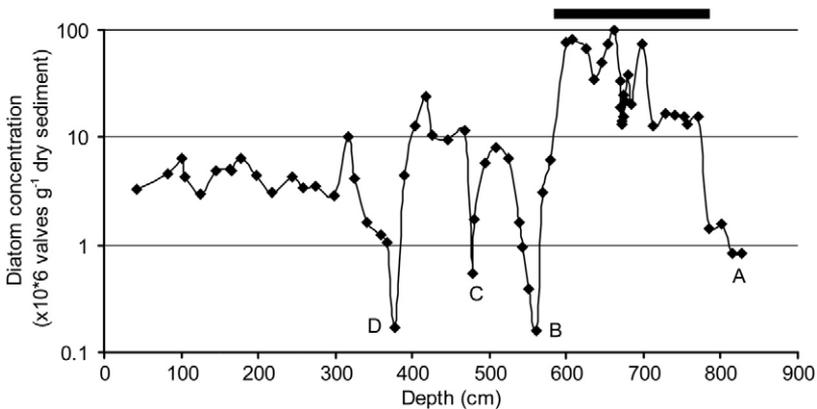

Fig. 8. Diatom concentrations in QARU2 plotted on a log scale to show four (A–D) very low diatom abundance zones (Tab. 2) which fall below the range where valve concentration and poor preservation are related (see Fig. 7). The solid bar indicates the core section with good valve preservation.

Tab. 2. Lake Qarun sediments. Four levels (around 377, 478, 560 and 820 cm depths) with very low diatom abundances (A–D) in sediment core QARU2 are selected to indicate diatom assemblage F index values, diatom valve concentrations (DC, in million valves g^{-1} dry sediment weight), sediment characteristics (CO_3 = carbonate, OM = organic matter and BMS = bulk magnetic susceptibility), the common diatom taxa and the presence of ostracod remains. Some taphonomic and environmental aspects are indicated on the right of the table.

Concentration depth minimum	F index	DC (x10*6)	Sediment characteristics	Microfossil assemblage	Taphonomy and environment
A (c. 820 cm)	0.06	0.8	higher BMS higher CO_3 high % dry wt.	*A. granulata* *C. dubius* (few ostracods)	Near desiccated lake, sediment reworking
B (560 cm)	0.11	0.2	higher OM higher CO_3	*A. granulata* *C. meneghiniana* (many ostracods)	Rapid sediment redeposition and focusing
C (478 cm)	0.05	0.5	higher OM higher CO_3	*A. granulata* *C. meneghiniana* (few ostracods)	Rapid desiccation and sediment reworking
D (377 cm)	0.31	0.2	higher BMS higher CO_3	*Surirella* cf. *smithii* (few ostracods)	Low lake level

Sedimentary diatom dissolution: The sedimentary diatom records for Spiritwood Lake (SW1) and Lake Qarun (QARU2) reflect different time scales with the former extending a little over 150 years and the latter around 2000 years. The lakes also differ in size, present--day salinity, stratification pattern, morphology, climatic setting (and sensitivity) and have different human impacts. For example, Spiritwood Lake is ice-covered for several months of the year, and is dimictic, while the water temperature of Lake Qarun rarely falls below 16 ºC and is monomictic. These differences will particularly affect kinetic rates of dissolution and biologically-mediated taphonomic processes, which makes direct comparisons between the two sites inappropriate. They are markedly different aquatic ecosystems characterized by different diatom species. In recent Spiritwood Lake sediments, *Stephanodiscus* is the most common genus while in Lake Qarun sediment *Aulacoseira granulata* has been generally most abundant. Nevertheless, taphonomic processes strongly influence the integrity of the sedimentary diatom record in both lakes. Further, it is likely that in both lakes the preservation states of diatom valves result mainly from water column and surface sediment conditions at the time of diatom deposition (cf. RYVES et al. 2003, FLOWER et al. 2006). Using diatom dissolution indices (e.g. F index and DDI), however, the quality and taphonomy of these sediment records as diatom archives can be directly and fruitfully, compared.

Preservation status of diatoms in the Spiritwood Lake core (SW1)

In this core, sediment accumulation, as both flux (g dry sediment cm^{-2} y^{-1}) and as rate (cm y^{-1}) increase towards the core top. While F index values also increase towards the top of SW1, as preservation improved, there was a weak, yet significant, correlation between F index values and reconstructed salinity. A stronger agreement between both the sediment accumulation rates and F index was seen, possibly indicating that sedimentary diatom ac-

cumulation and diatom abundance promotes preservation in this core. The possible diatom accumulation and preservation relationship is yet only one factor (see below) and the dissolution indices of individual taxa showed that while preservation states between some species showed good correspondence (i.e. *S. niagarae* and *C. meneghiniana*), those between *S. niagarae* and *S. minutulus* do not. This may reflect differences in the pathways by which valves of particular diatom species are incorporated into the sediment record (cf. RYVES et al. 2009). In the Northern Great Plains, *S. minutulus* is a summer blooming species, reaching peak abundance at a time when the lake is strongly stratified and the hypolimnion is anoxic. In contrast, *S. niagarae* (and *C. meneghiniana*) tend to be autumn blooming species (e.g. HOLLAND 1969, BAKER and BAKER 1981), forming seston which sinks through a less strongly stratified water column. Anoxia has been linked with enhanced preservation, as bioturbation is reduced, and organic coatings are less likely to be mineralized (RYVES et al. 2006).

Preservation status of diatoms in the Lake Qarun core (QARU2)

Only one date is available for QARU2 and so calculating diatom accumulation rates is inappropriate. Nevertheless, the concentration of sedimentary diatoms shows strong down--core variations with high values (> 20 x 10^6 valves g^{-1}) only in the deeper part of the core (around 600–760 cm depth). While diatom concentration shows no overall relationship with the total diatom assemblages dissolution states, a positive link between valve preservation and concentration (over the range 1 to 20 x 10^6 valves g^{-1}) does hint at a diatom concentration-mediated preservation effect, although other factors clearly influence diatom abundance within and beyond this range (Tab. 1). Concerning individual taxa, the preservation state of *A. granulata,* overall the most common sedimentary diatom, unsurprisingly corresponds most closely with the total assemblage preservation. However, other taxa do not show this relationship and *Cyclotella meneghiniana* is relatively and consistently more poorly preserved compared to *A. granulata*, an observation which confirms the relative susceptibility of the former to dissolution from experiment and observation (FLOWER et al. 2006). Due to its robust central area, *C. meneghiniana* can remain identifiable despite considerable dissolution (cf. BARKER 1992) and it has a long »dissolution half-life« (see terminology of RYVES et al. 2001), in common with other species of this genus (RYVES et al. 2009). *Thalassiosira faurii* preservation, on the other hand, is unrelated to the preservation state of *A. granulata* (Fig. 6B) and this indicates that the former has undergone a different sediment entrainment pathway. The almost perfect preservation of many valves of this species at several levels in the core indicates either a more rapid mode of valve incorporation into the sediment, mass abundances of growing source populations, or sedimentation at a time of year when limnological conditions were extremely favourable to good preservation (e.g. during summer anoxia of deeper waters and lack of bioturbation). This unusually good preservation of *T. faurii*, as for *S. minutulus* (above), is contrary to expectations based on gross valve morphology (SA:V ratio; see BARKER et al. 1994).

Interpreting diatom dissolution

For Lake Qarun, diatom-inferred (DI) salinity shows no relationship with valve concentration or with the F index but sedimentary diatom concentration in QARU2 was always

relatively low when DI salinity exceeded c.1000 µS cm^{-1}. This seems to indicate that, although high salinity is inimical to diatom valve preservation (cf. RYVES et al. 2006), other processes also control sedimentary diatom concentrations. Placing diatom abundances in QARU2 on a log scale clearly picks out four abundance minima (Fig. 8, A–D) and for at least three of which poor preservation is implicated. These minima seem to have different causes which can be at least partly identified by taking a multi-proxy approach and using information provided by other sediment characteristics such as carbonate content, magnetic minerals, organic matter and ostracod remains (from FOSTER et al. 2008, K. KEATINGS, pers. comm.). Additional stratigraphic information is added for each of the four levels with low diatom concentrations (Tab. 2). Each level is associated with elevated sedimentary carbonates, and minimum D seems to be associated with a low lake level stage (benthic *Surirella* spp. exceed 20% abundance at this depth). Assemblage preservation in this level is highest of the 4 minima (F = 0.31), suggesting that low diatom abundance is (partly) reflecting low productivity. Minima A and C probably indicate periods of falling lake level since the F index values are low but not as low as in levels B and D. Lake desiccation is inferred for minimum A (and possibly C) since ostracods are very few (and broken) and sediment density is high. For minimum B, many ostracods and higher organic matter could indicate sediment reworking as well as shallower water. There is no direct, simple correspondence between the diatom concentration minima and DI-salinity. Diatom productivity and ecology, low lake level, sediment in-wash and sediment reworking all must influence Lake Qarun's sedimentary diatom record, both quantitatively and qualitatively. Identifying the combined causes of diatom concentration minima is made particularly difficult because variations in sediment accumulation rate remain unknown. Clearly however there are different factors operating during the accumulation of QARU2 but, despite the lack of sediment flux data, considerable information around particular events can be gleaned by taking a multi-proxy approach. Interrogating the detail of the stratigraphic record at points of change by using preservation states as well as multi-proxy evidence offers a promising way of extracting more palaeolimnological information.

Contrary to its importance in surface sediments across the NGP lakes (RYVES et al. 2006) and over the last around 120 years for Devils Lake (RYVES et al. 2009), salinity only appears to have a muted role in diatom preservation in Spiritwood Lake. In part, this may reflect the lower salinities this lake has experienced over the last around 150 years, during which it has generally remained subsaline (0.5–3 g L^{-1} TDS), although dissolution is known to be driven by salinity even across short gradients (e.g. in West Greenland lakes below 3 g L^{-1}, RYVES et al. 2006). Additionally, it may also reflect inaccuracies within the original NGP diatom model itself (FRITZ 1990, FRITZ et al. 1993), where dissolution within the training set and fossil data may alter model performance and inferred values (RYVES et al. 2009). Applying two dissolution-adjusted models to the Spiritwood Lake data (one where dissolution stages are considered as »dissolution taxa« in their own right, and another where percentages are re-calculated according to individual species' F values; see RYVES et al. 2009) did improve salinity-F index correlations here (r^2 = 0.25 and 0.35 respectively; p < 0.02; not shown). Even given some slight potential effect for involving dissolution data in the process of generating salinity inferences as well as fossil F index scores, this does appear to strengthen the argument that salinity has some role on preservation at Spiritwood Lake.

The role of salinity is however often subsidiary to that of physical processes, and the F index remains more strongly correlated with sediment accumulation rate (cm yr^{-1}, Fig. 2B). This suggests that diatom preservation is controlled more by the rate of volumetric accumulation of fine material that buries diatom valves within a matrix. This further suggests that the rapid build up of saturation silica levels in pore water may be important, preventing recently sedimented diatom valves from dissolving further and reducing diffusion of silica to undersaturated upper sediments and overlying water (perhaps especially important when the lake bed is rarely oxic with infrequent bioturbation and reduced mineralization of organic valve coatings). There is clearly an interplay between accumulation rate and initial sedimentary diatom concentration, by which pore waters become saturated with dissolved silica. The strong relationship between diatom concentration and preservation observed at low diatom abundances in Qarun sediments (Fig. 7A) may be, in part, the taphonomic (post-dissolution) imprint of such an interaction. Sedimentation rate may thus be an important factor affecting diatom preservation across a range of freshwater and subsaline lakes where high salinity, or extreme lake level fluctuations and even periodic desiccation, are not the primarily drivers of diatom taphonomy.

Implications of diatom dissolution assessments

Undertaking an objective assessment of the preservation states of sedimentary diatoms in these two markedly different lakes provides taphonomic insights into the preservation of diatom species and of diatom assemblages within sediment cores and between samples. Using an index to measure dissolution allows quantification of valve damage but making generalizations will always present problems because: (1) dissolution pathways can vary between species and between sites; (2) down-core changes in diatom dissolution and diatom abundance result from a variety of interacting contemporary processes; (3) exceptional but different events such as high salinity episodes, sediment in-wash and sediment redeposition conspire to obfuscate simple interpretation of stratigraphic signals; and (4) the nature of individual diatom species, their seasonal productivity and sedimentation characteristics all influence the sedimentary diatom record. Multi-proxy sedimentary data are often required to help explain diatom dissolution and abundance relationships in sediment cores. Diatom dissolution information can aid qualitative and quantitative palaeo-environmental inferences, however. For example, in surface sediment diatom inferred salinity models, the addition of dissolution data alone can reduce both apparent and prediction error by 10–15% (RYVES et al.2009).

Conclusions

Exploring diatom preservation in sedimentary sequences from two saline lakes, Spiritwood Lake and Lake Qarun, indicates that poor preservation is often associated with low sedimentary diatom concentrations (as cause and effect) and/or higher (DI) salinity, even when salinity changes are small. In the Qarun core, however, neither diatom concentrations nor preservation indices were high when DI-lake salinity was high. Although 3 of the 4 down-core diatom concentration minima in core QARU2 are linked with very poor diatom preservation, there are clearly different contributory factors that reflect a variety of pro-

cesses that differ according to environmental conditions operating at particular points in time. The higher resolution study permitted at Spiritwood Lake highlights the role that seasonal diatom succession and stratification pattern has on the taphonomic pathway of different species. The Lake Qarun record, on the other hand, reveals broader taphonomic processes from larger-scale climatic and lake level changes (though salinity changes appear significant for preservation at both lakes). Spiritwood Lake further provides evidence that bulk sedimentation rate is an important control on diatom preservation over shorter time scales, though further examples from a range of different lake types and time periods are needed to assess this critically.

Assessing dissolution can improve diatom based inferences about past environments, both qualitatively (by inferring planktonic diatom seasonality and sinking characteristics, for example) and quantitatively (by improving diatom inferred models and calibrating sedimentary diatom frequencies and accumulation rates; e.g. MACKAY et al. 2005, BATTARBEE et al. 2005, FLOWER et al. 2006, RYVES et al. 2006, 2009). The mechanisms, conditions and interactions that influence diatom dissolution states in saline lakes (especially those in which lake level and salinity fluctuate markedly) require further study especially since predicted climate change (influencing for example salt balances, lake levels and stratification intensity) will likely affect diatom dissolution patterns and pathways and therefore, potentially, inferences based on existing training sets.

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