Palaeolimnological records of regime shifts from marine-to-lacustrine system in a coastal Antarctic lake in response to post-glacial isostatic uplift

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Low altitude coastal lakes along the Antarctic margin often contain both marine and lacustrine sediments as a result of relative sea level changes due to deglaciation. The sediments also record changes in regional climate. A sediment core from a coastal lake in Larsemann Hills, East Antarctica, viz. Stepped Lake (Heart Lake), records distinct changes in C, N, C/N$_{atomic\ ratio}$, $\delta^{13}C_{OM}$, $\delta^{15}N_{OM}$ and diatom abundance during the mid-Holocene (8.3 to 4.6 kyr BP). Lower values (C_{org} ~1%; C/N 8, $^{13}C_{OM}$ ~ –18‰) during the early Holocene (8.3–4 kyr BP) are consistent with marine conditions, while higher values [C_{org} 6%; C/N 12; $^{13}C_{OM}$ ~ –12‰) suggest a shift to lacustrine conditions (5.5–4.6 kyr BP). The diatom community shows similar shift with the major part of Holocene (8.3–5.5 kyr BP) dominated by sea-ice and open-ocean diatoms while the core-top sections (5.5–4.6 kyr BP) transitions to lacustrine diatoms (*Stauroforma inermis*). These observations confirm that the basin was marine, and later became isolated as a result of post-glacial isostatic uplift after 4.7 kyr BP.

Keywords: Diatoms, Holocene climate, Larsemann Hills, stable isotopes, sedimentary organic matter.

FRESHWATER lakes in ice-free oases of Antarctica respond instantly to climate-driven seasonal environmental changes and this is well reflected in algal communities (diatoms and cyanobacteria). Lakes, during austral winter (summer) are ice-covered (ice-free) which prevents (enhances) wind-induced mixing and creates a stable (well mixed) water column leading to stratification (well mixed) condition[1] leading to decreased (increased) productivity as a result of reduced (increased) light penetration and also lowered (higher) sediment deposition in the lake. Under ice cover conditions, the benthic communities thrive as compared to the planktic[1].

Palaeolimnological records from coastal Antarctica have shown interesting results pertaining to post-glacial isostatic changes[2,3]. The use of diatoms[3] and sedimentary organic proxies[4] in past-climate reconstruction is well documented. Here, we present time-series of elemental and isotopic composition of sedimentary organic matter (OM) along with diatom abundance from Stepped Lake (SL) to understand changes in lake dynamics.

The Larsemann Hills (LH), an isolated landmass of 200 sq. km, is located at 69°24′S and 76°20′E on the Ingrid Christensen Coast of Princess Elizabeth Land, East Antarctica. It is marked with ~150 pristine lakes varying from small ephemeral ponds to large lakes[5]. The SL is an open-lake located in Broknes Peninsula of LH (Figure 1). The lake has a sill height of ~5 m amsl with a maximum water depth of 5 m located about 200 m from the coast and 2.6 km from the continental ice-sheet[4]. The austral summer (December–January) temperature is positive (>0°C) with day air temperature frequently exceeding 4°C resulting in abundant melt-water[5].

A 135 cm long sediment core was retrieved using a UWITEC piston coring device from SL (SL-3) (Figure 1) during the 33rd Indian scientific expedition to Antarctica in January 2014. The core-liner was removed from the core barrel, frozen at –20°C and transferred to the land-base laboratory at National Centre for Antarctic and Ocean Research (NCAOR). The core was then litho-logged (Figure 2), sub-sectioned into 0.6 cm slices and freeze-dried for further analysis.

Chronology of the core was derived from four AMS radiocarbon dates calibrated using CLAM 2.2 software[6] (Table 1). Reservoir corrections were not applied because surface sediment dates indicate that ^{14}C in freshwater lakes of LH is in near-equilibrium with modern atmospheric CO_2.

Sample preparations for elemental and isotopic measurements are described elsewhere[4]. The external precisions on $\delta^{13}C$ and $\delta^{15}N$, C% and N% measurement are ±0.02‰, ±0.09‰, ±0.2 and ±0.3 respectively (1σ

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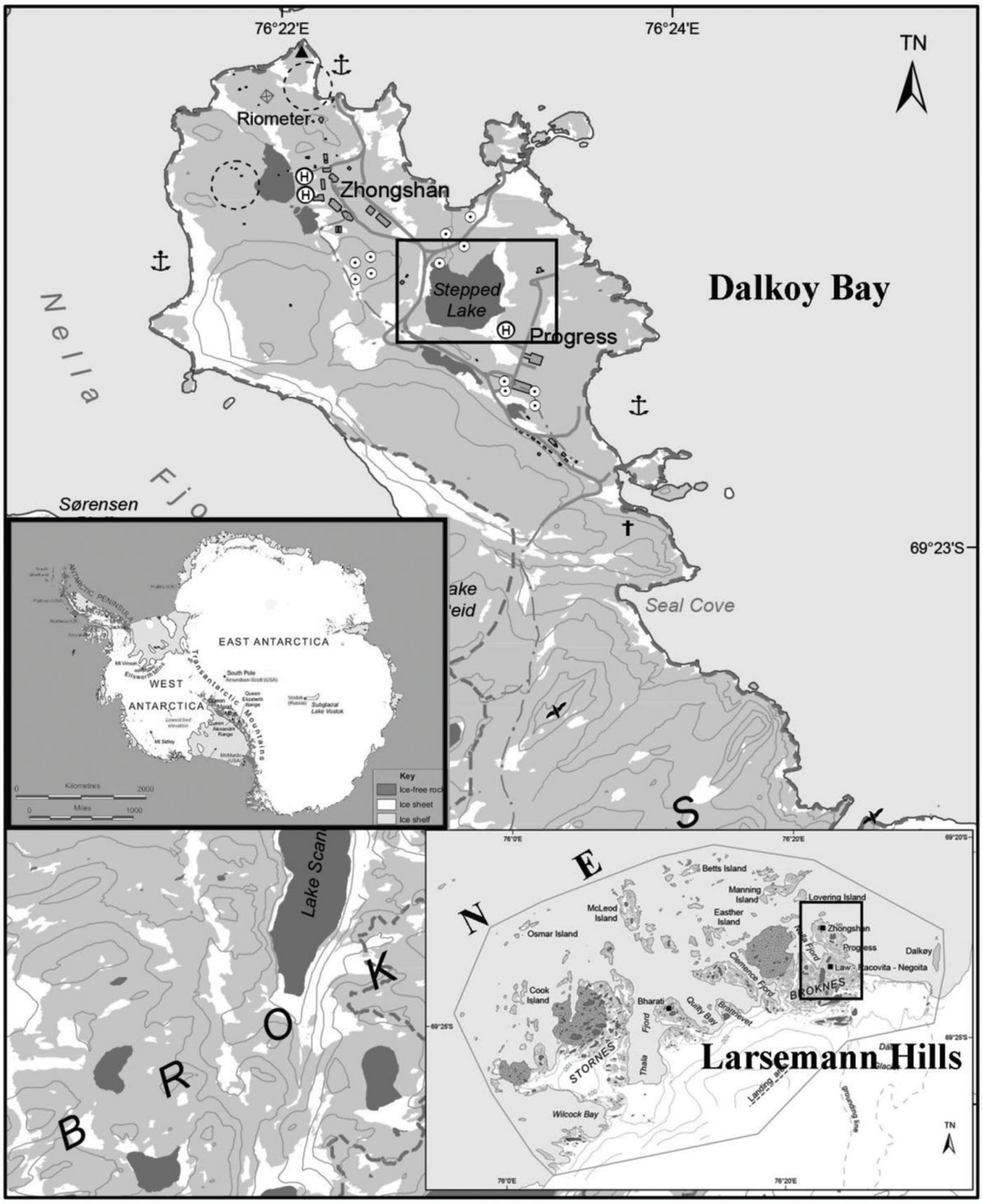

Figure 1. Location of stepped lake.

Table 1. Details of AMS ^{14}C dates

Lab id	Sample id	Depth (cm)	Lab code	AMS ^{14}C year BP	$\delta^{14}C$ age	$\delta^{13}C$ (‰)	2-sigma range	Mid-calibrated age (kyr BP)	Calibrated age – 95% confidence intervals
X28189	SL-3 (A)	0.6	AA105020	4137	32	–15	3629–5657	4643	94.6
X28190	SL-3 (B)	32.0	AA105021	5775	37	–18.3	5821–7342	6605	93.5
X28255	SL-3 (D)	99.8	AA105023	6957	33	–18.4	7086–8241	7664	93.2
X28256	SL-3 (E)	135.8	AA105024	7078	39	–19.5	7532–8892	8310	94.8

standard deviation). Sediment processing, slide preparations, diatom abundance, identification and taxonomy of diatoms[7] were carried out for the top 30 cm to assess for any changes in regime shifts.

The lithology is dominated by fine sand and OM (23–38 cm and 93–134 cm) interspersed with layers of algal matter and fine–medium–coarse sand layers marked with rock pieces (38–48, 54–58 and 78–92 cm) between 6.8

and 7.4 kyr BP. The presence of rock pieces indicates retreating ice-sheet through which they were deposited as drop-stones coinciding with the completion of East Antarctic ice-sheet retreat at 7 kyr BP (ref. 8). A major shift in sediment texture, i.e. from low-to-high OM content is observed from 20 cm to the core-top. The sedimentation rate varies between 12 and 62 cm/kyr (Figure 3). The radiocarbon dated sediment core covers the mid-Holocene period (4.6–8.3 kyr) indicating loss of late-Holocene sediments during coring operation.

The SL-3 core is divided into two zones wherein the first zone (6.5–5 kyr BP) is dominated by sea-ice and marine diatoms whereas the second zone (5–4.6 kyr BP) is dominated by freshwater diatom (*Stauroforma inermis*) (Figure 4). The time-series also recorded the presence of brackish water tolerant taxa such as *Amphora veneta*, *Luticolamuticopsis*, *Pinnularia microstauron* and *Navicula shackletoni* (Figure 4). The higher abundance of marine and sea-ice diatom taxa between 6.5 and 5 kyr BP reflects coastal marine conditions, thereby indicating higher RSL in LH during Holocene as a result of eustatic and isostatic sea-level changes[2,3]. During Holocene, relative sea level (RSL) rise observed in LH (8.9–8.5 kyr BP, 3 m rise at 9.4 mm/year) is considered to be mainly driven by eustatic sea-level rise[2]. This is followed by a decreasing trend in the sea-ice and marine diatom abundance (6.5–5 kyr BP) reflecting the gradual RSL fall (between 7 and 2.7 kyr BP)[2].

Our diatom data records the shift of marine to freshwater lake system (dominance of *S. inermis*) from *ca*. 5 kyr BP onwards which is little inconsistent[3] wherein the transition of sea-ice to lacustrine diatom was observed at ~2.7 kyr BP (Figure 5)[3]. Hence, the present diatom records suggest that the acceleration of sea level fall, which was originally considered at 2.7 kyr BP (refs 2 and 3) might have started from *ca*. 5 kyr BP onwards at SL. The wet-warm lacustrine conditions and cool-dry oceanographic conditions can be identified from variation in relative abundance of marine and freshwater diatoms (Figure 4). Such differences in the timings of shift from sea-ice to lacustrine fresh water diatoms within the same lake need further study.

The time-series for the elemental and isotopic composition measured for SL-3 core shows significant variation within the mid-Holocene. The C_{org}% (1$\%_{avg}$) and N% (0.1%) show marginal variation for the entire mid-Holocene period and show a dramatic increase for the last 0.2 kyr. Such high values are due to high productivity due to presence of benthic algal mats which are well recorded in LH lakes[3]. The presence of benthic algal mats indicates a shift in the lake sedimentary OM, i.e. from marine to freshwater system. The N% also shows similar variation to that of the C_{org} content. Higher N% (0–4 cm; 0.6%) from 4.7 kyr BP is most likely due to the presence of cyanobacterial benthic mats capable of fixing nitrogen directly from the atmosphere.

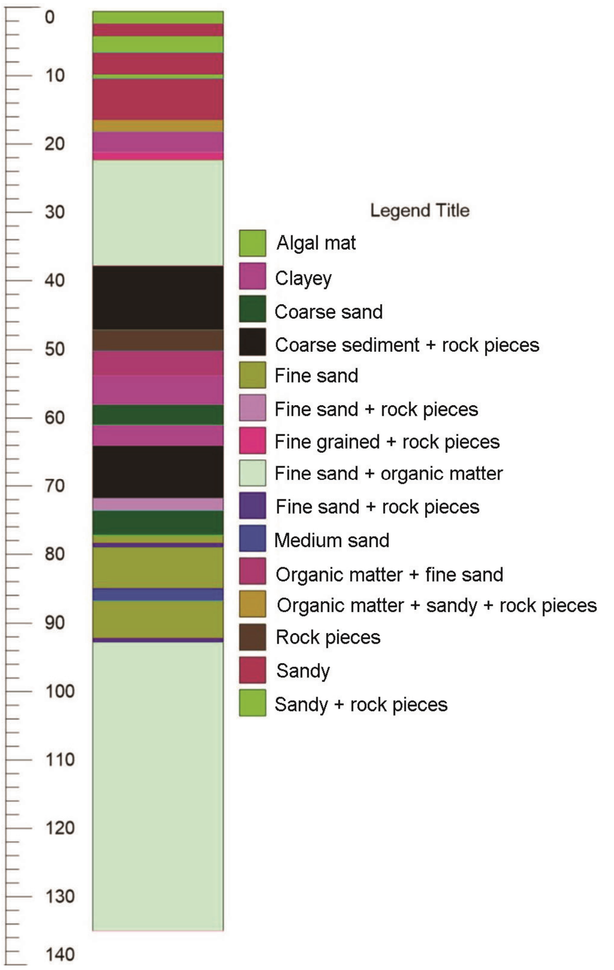

Figure 2. Lithology for SL sediment core.

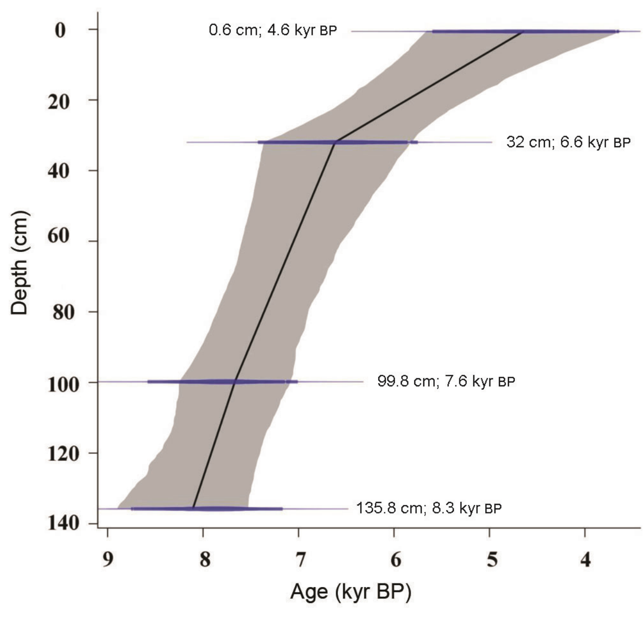

Figure 3. Age-depth model for SL-3 sediment core.

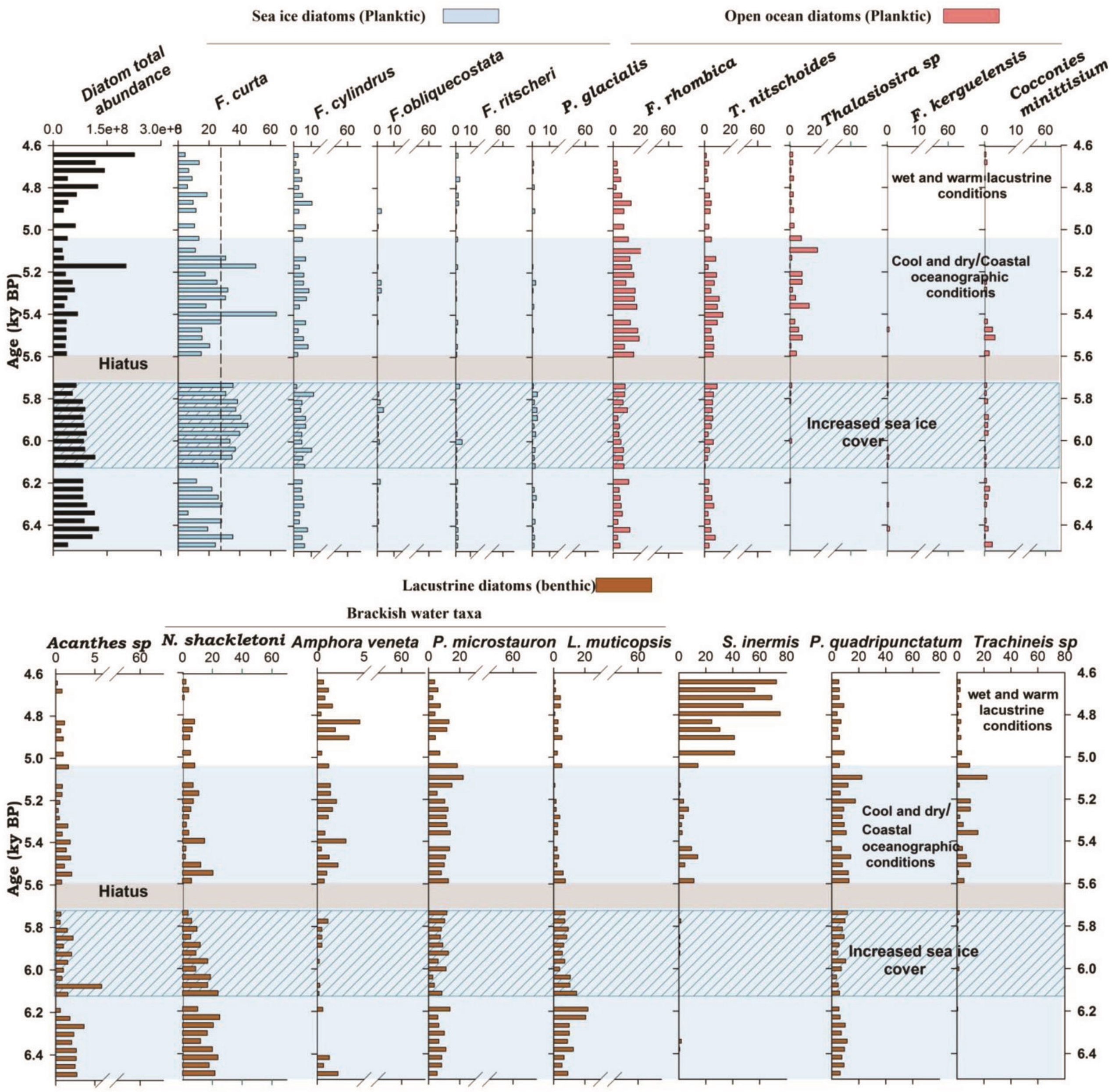

Figure 4. Time-series of relative diatom abundance in SL-3. Zone 1: wet-warm lacustrine condition; zone 2: cold-dry coastal oceanographic settings.

The C/N ratios for SL-3 time-series are predominantly below 10 throughout the mid-Holocene indicating *in situ* productivity[9] and exceed values of 10 only after 4.6 kyr BP (Figure 5) indicating input from terrestrial OM. Interestingly, the presence of terrestrial OM is in consistent with higher C% and N% from 4.7 kyr BP suggesting retreat of ice-sheet exposing the lake catchment area and hence facilitating the growth of terrestrial OM such as lichens and mosses.

The δ^{13}C range from –21‰ to –12‰ with the lowest values (–20‰) recorded at 5.5 kyr BP (Figure 5). For the major part of mid-Holocene, δ^{13}C varies between –15‰ and –18‰ whereas the enrichment in δ^{13}C begins at ~5 kyr BP attaining higher value (–12‰) for the core-top sections. The mid-Holocene values are in consistent with non-marine aquatic plants and algae[10], whereas the core-top section values are similar to aquatic plants[11] representing two end-members. The δ^{15}N for the down-core variation range from 3‰ (0–4 cm; 4.7 kyr BP – coastal marine plankton[12]) to 8‰ (5.8 to 8.3 ky BP – aquatic end member[13]). The enrichment in δ^{15}N values from 4.7 kyr BP is due to the addition of terrestrial OM whose values are

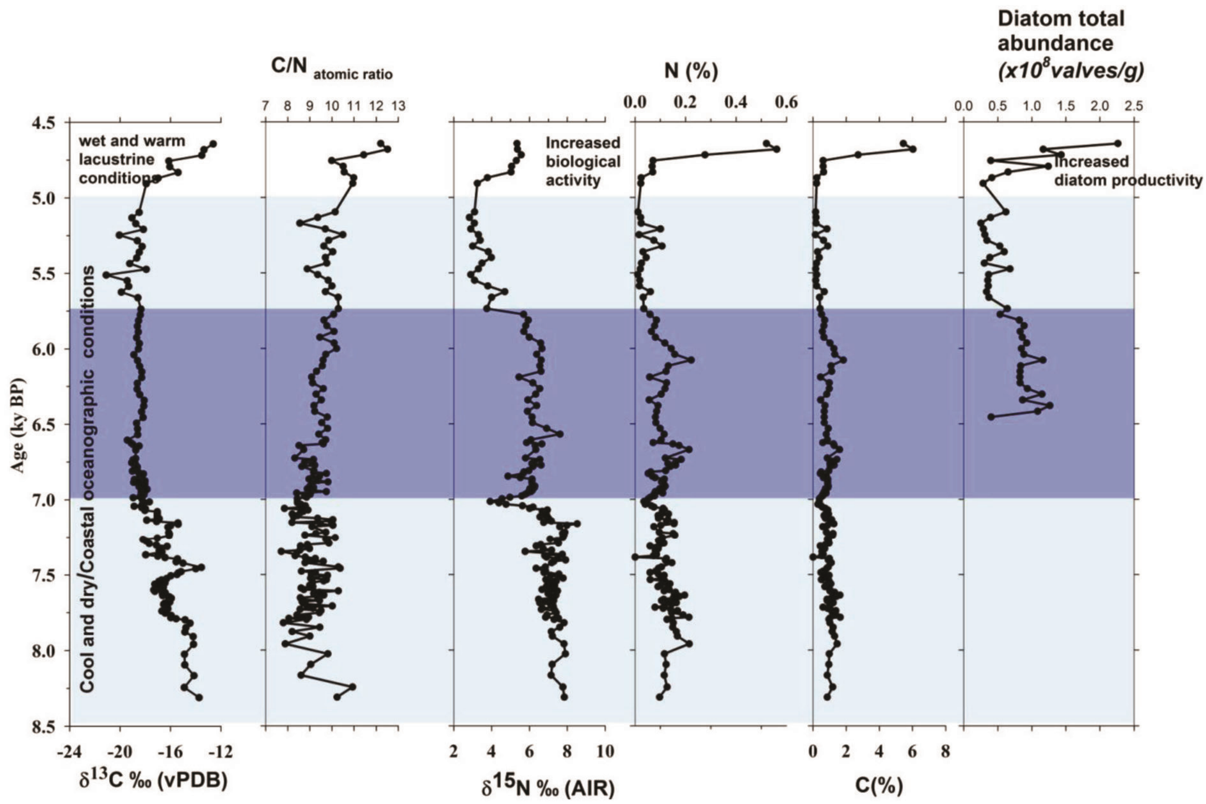

Figure 5. Down-core variations of elemental (C_{org} and N%), C/N ratios, isotopic ($\delta^{13}C_{OM}$ and $\delta^{15}N_{OM}$) and diatom abundance for mid-Holocene. Zone 1: wet-warm lacustrine conditions; zone 2: cool-dry coastal oceanographic conditions. The increased influence of sea-ice cover is marked in darker band.

around 3‰ (ref. 13). The increase in values of all parameters from a marine signature to lacustrine signals indicates a shift from cool-dry oceanographic conditions to warm-wet lacustrine conditions (Figure 5).

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