Petit-Lac (western Lake Geneva) environment and climate history from deglaciation to the present: a synthesis

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During the past decade, the presentation of seismic and sedimentological data has allowed reconstruction of the environment and climate history of the Petit-Lac (western Lake Geneva). Methods such as high-resolution seismics, sediment core analysis (macroscopic description, grain-size analysis, mineralogy) and palynology have been used to infer the changes in the lake's environment from deglaciation to the present. However, no final synthesis has been attempted to link this information in the development of a comprehensive evolution model of the Petit-Lac and its surrounding region. The Petit-Lac deglaciation occurred in three phases during the Rhône glacier retreat: the Geneva stage and the Coppet and Nyon re-advances. In the Versoix area, rivers developed just after the retreat of the Rhône glacier from the Nyon stage. The Nyon fan delta started at the end of the Bølling, and its lobe fluctuated in size and orientation in six phases from the Lateglacial to the present. The action of bottom currents (i.e. erosion, non-deposition surfaces) arising at the beginning of the Holocene indicates that the frequency and direction of strong wind regimes varied greatly. Lacustrine mass failures occurred at different time intervals: two between deglaciation and the end of the Oldest Dryas, two between the Bølling and the Younger Dryas, and four during the Holocene. From the Oldest Dryas to the Contemporary Epoch, the vegetation changed from a steppe to a climate-influenced forest, and finally to a mostly human-controlled forest.

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Lakes and glaciers, like other natural archives (trees, speleothems, etc.), follow shifts in environmental conditions (temperature, precipitation, seasonality, etc.) and are therefore good tracers of climate change (Ariztegui & Wildi 2003). Depending on the size of the catchment area, the lacustrine and glacial sediments reflect past environment and climate changes on local, regional or global scales. Small basins tend to record local conditions (Lotter & Birks 2003) and are usually highly sensitive to environmental and climatic change (Gilli *et al*. 2001; Hu *et al*. 1999), whereas large lakes are likely to react to long-term and large-scale events (Ariztegui *et al*. 1997; Thevenon *et al*. 2002; Ellis *et al*. 2004; Xiao *et al*. 2004). These natural archives are influenced by both external (i.e. environmental) and internal (currents, mass movements, etc.) processes. Many lacustrine records are continuous and express an almost uninterrupted sedimentological history. Lake sediment records can therefore provide the data for calibrating and improving climate models on scales of 10^{-1} to 10^{6} years (von Grafenstein *et al*. 1999; Heiri *et al*. 2004; Magny 2004), and consequently add to our understanding of the evolution of climate.

Beginning in the mid-1980s, the interest in lacustrine sediment records in the Swiss alpine region grew along with a general concern about understanding global and regional climate change. Lacustrine lithostratigraphies and their stable isotope curves, inferred from large Swiss Plateau lakes, revealed the general coeval evolution of those basins with the global climate (e.g. cooling trend of Younger Dryas) and their particular regional signature from limnologic, geologic or anthropogenic events (Lake Geneva: Filippi *et al*. 1997; Lake Neuchâtel: Filippi *et al*. 1999; Lake Zürich: Lister 1989; Lake Lugano: Niessen & Kelts 1989). In Lake Constance, Holocene interflow horizons indicate flood events of the Alpine Rhine and are related to documented glacial advances in the Alps (Wessels 1998). In the Swiss Alps, Holocene vegetation, timberline and air temperatures have been reconstructed from the sediment record of various small lakes and ponds (e.g. Hinterburgsee: Heiri *et al*. 2004; Gouillé Rion: Tinner *et al*. 1996). Other multi-proxy high-resolution data in small Swiss alpine lakes have revealed the interaction between human impact and climate change (Seebergsee: Hausmann *et al*. 2002) and the evolution of the trophic state of the lake

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(Lake St. Moritz: Ariztegui & Dobson 1996). The correlation between recent lacustrine varves and the instrumental climatic record has been demonstrated in both peri-alpine and alpine areas (Baldeggersee: Lotter *et al.* 1997; Lake Silvaplana: Ohlendorf *et al.* 1997). A synthesis of lake-level fluctuations in the Jura Mountains, the French Pre-Alps and the Swiss Plateau region has indicated phases of synchronous change that suggest a climatically driven lake-level variability (Magny 2004).

The environment and climate history of the Petit-Lac (western Lake Geneva) from deglaciation to the present has been investigated using a multitude of methods and approaches during the past decade. As part of the large Rhône glacier system during deglaciation, and with its present catchment area at the foot of the Alps, the Petit-Lac provides a long and significant record of the environment and climate in the Alpine region.

Study area

Lake Geneva is the largest freshwater basin in western Europe (surface area 580.1 km^2, volume 89 km^3, outflow 250 m^3/s) and is thus of major significance in our understanding of the continental climate and environmental history. It lies in the Alpine foreland between Switzerland and France (Fig. 1A), which is mostly formed by the Tertiary Molasse basin (Gorin *et al.* 1993). In the Geneva region, the Molasse basin extends from Mount Salève in the southeast to the internal Jura Mountains in the northwest. These mountains comprise Jurassic and Cretaceous strata underlying the Molasse series of Oligocene and Miocene age, which are composed mainly of marl and sandstone (Charollais & Amberger 1984; Blondel 1990; Deville 1990).

Lake Geneva is subdivided into two contrasting sub-basins: the Grand-Lac (eastern part) and the Petit-Lac (western part; Fig. 1A). The Petit-Lac is a medium-sized basin 23.3 km long and 4.7 km wide (Table 1), representing only 4% of the total volume of Lake Geneva (3 km^3, Table 1); its catchment area covers 325 km^2 between the foot of the Jura mountain range and the Prealps.

In the Petit-Lac area, the Quaternary glacial cycles have left narrow gorges in the bedrock filled with sediments (Amberger 1978; Pugin 1988; Wegmüller *et al.* 1995) that can be traced on seismic profiles (Wildi & Pugin 1998). However, most of the older sediments were eroded during the Würm glaciation. During the last Ice Age, the Rhône glacier extended into the Rhône valley near Lyon and was in contact with the local ice cap of the Jura mountain range (Florineth & Schlüchter 1998; Buoncristiani & Campy 2004). The glacial maximum of the Rhône glacier occurred between 25 000 (Arn 1984) and 18 940 ^{14}C yr BP (Moscariello *et al.* 1998), and around 21 000 ^{14}C yr BP in the eastern Alps (van Husen 1997). In the Geneva region, a large part of the deglaciation occurred under lacustrine conditions, with a lake-level decreasing through time. Four glacier stages linked to the known lacustrine terraces (Burri 1981) are located 55, 30, 10 and 3 m above the present lake level (Moscariello *et al.* 1998). The Laconnex stage corresponds to a 470 m a.s.l. lake with an outlet near Fort de l'Ecluse. A 430 m a.s.l. lake is associated with the '55 m terrace'. The Geneva stage coincides with a lake level at 405 m a.s.l. and probably with the '30 m terrace' described by Gabus *et al.* (1987). Till-tongues inferred from high-resolution seismic profiles express the Coppet and Nyon stages in western Lake Geneva (Moscariello *et al.* 1998). Chapron (1999) describes another glacial stage upstream in the central part of Lake Geneva, near the town of Thonon. The Chessel-Noville Hills (Fig. 1A), situated 3 km SE of the Rhône River mouth in the Grand-Lac, are interpreted by many authors as a side or frontal moraine of the Rhône glacier, but Beres *et al.* (2000) have demonstrated that this morphology has a mud-diapir rather than glacial origin. By approximately 11 000–10 500 yr BP the Rhône glacier had retreated into the Swiss Rhône Valley up to east of Sierre (Badoux 1995).

At present, the Petit-Lac is a monomictic and mesotrophic lacustrine basin with water depths of 50–76 m. Near Versoix (Fig. 1B), a tongue-shaped underwater shelf (9–14 m below the present lake level), defined as a Molasse bedrock high that resisted glacial erosion, restricts a section of the lake basin (Institut F.-A. Forel & SITG Etat de Genève 2000). The Petit-Lac is well oxygenated and the water surface temperatures range yearly between 5 and 20°C. The allochthonous sediments are brought by five main rivers: the Versoix, the Boiron, the Asse and the Promenthouse on the western bank, and the Hermance on the eastern bank (Fig. 1B). The lake's coastal areas are the main source for autochthonous sediment production. In the Versoix area, as a consequence of the basin narrowing, a regime of strong lake currents contributes to the dispersion of allochthonous and autochthonous sediments (Girardclos *et al.* 2003; Ulmann *et al.* 2003). Waves during strong wind storms (10–15 m/s) are capable of reworking bottom sediments to water depths of 7–15 m (Bruschin & Schneiter 1978).

Methods

High-resolution seismic stratigraphy

Seismic stratigraphy, originally used in the oceanic realm, is now widely used with high resolution in lacustrine basins. Seismic sequence analysis provides information on sequence geometry and thickness,

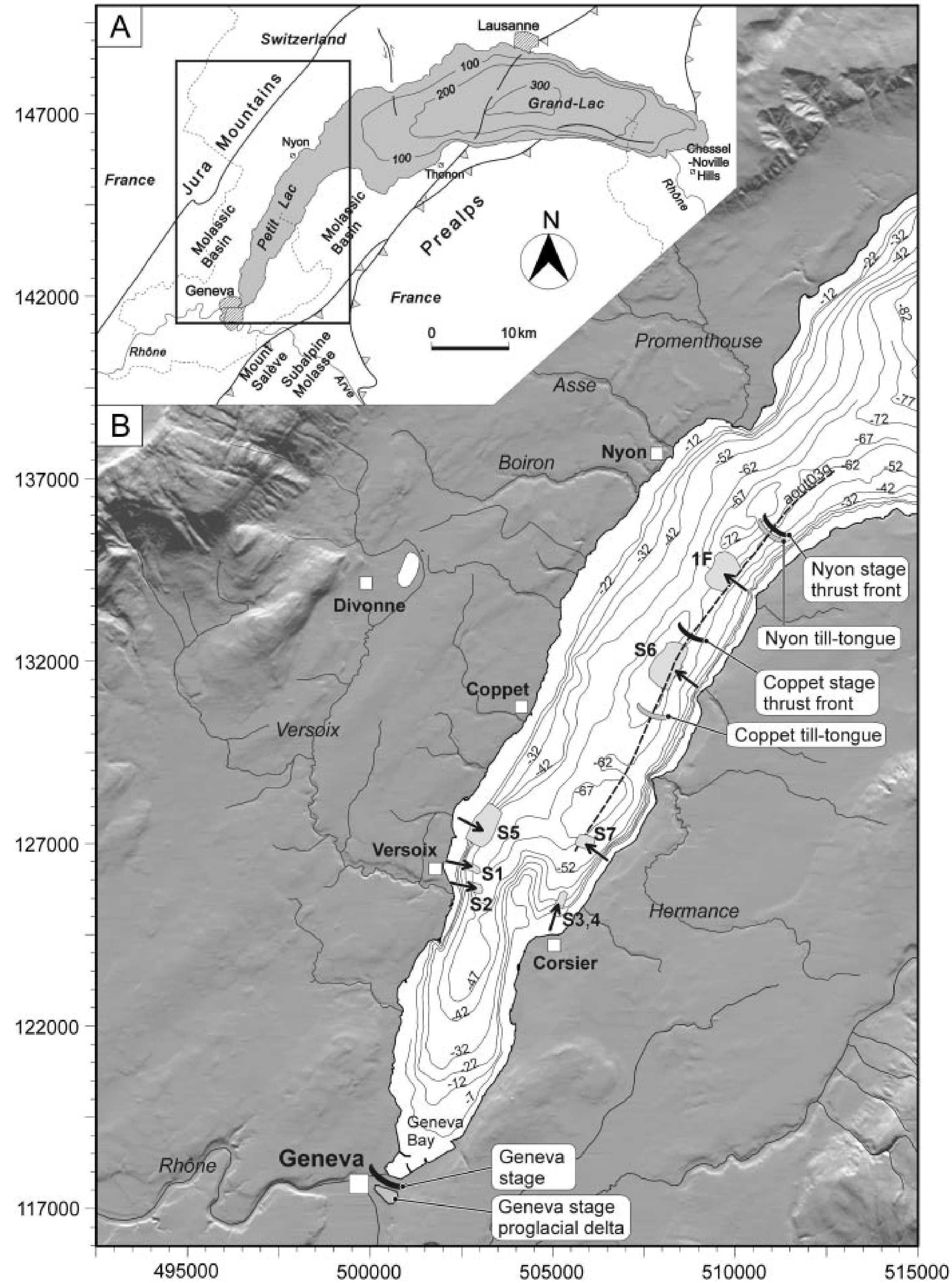

Fig. 1. A. Location map of western Lake Geneva (Petit-Lac) with rectangle representing the study area. B. Enlargement of the lake basin with position of the 'aout03g' seismic longitudinal profile (dotted line). The Rhône glacier during the Geneva stage and its proglacial delta and the Coppet and Nyon re-advances with their till-tongues are indicated. Location of known mass failure deposits (grey shade) and their directions (arrows) are shown on the present lake bathymetry (in metres). The shaded background topography is extracted from Digital Terrain Model DTM25 (Swiss Federal Office of Topography 2000) and the axes show Swiss grid coordinates (in metres).

Table 1. Morphometric characteristics of Lake Geneva sub-basins (Petit-Lac and Grand-Lac) (CIPEL 2003).

Lake basin	Surface (km^2/%)	Volume (km^3/%)	Maximum depth (m)	Length (km)	Maximum width (km)	Catchment area (km^2/%)
Petit-Lac	81.2/14	3/4	76	23.3	4.7	325/4.4
Grand-Lac	498.9/86	86/96	310	49	13.8	7070/95.6
Lake Geneva (total)	580.1/100	89/100	310	72.3	13.8	7395/100

and on acoustic facies. Data interpretation allows reconstruction of the basin history; for example, lake-level variations and changes in the sedimentary system or facies (Scholz & Rosendahl 1988; Mullins *et al.* 1996; Valero Garcés *et al.* 1997; Van Rensbergen *et al.* 1998; Van Rensbergen *et al.* 1999; Abbott *et al.* 2000; Ariztegui *et al.* 2001; Beck *et al.* 2001).

Seismic data were produced between 1998 and 2003 with diverse sources: a Bathy-1000 ODEC echo-sounder, an impact source (carpenter's hammer) and a 1 inch^3 airgun (Girardclos 2001; Baster *et al.* 2003). Rayleigh's equation (1885) for these data gives a theoretical vertical resolution between 0.25 m (echo-sounder, impactor) and ~2 m (airgun) for a seismic velocity of 1500 m/s. The depth of acoustic penetration in the sediment varies from 2 to 10 m for coastal or deltaic proximal areas, and ~70 m for the deep lacustrine basin. The recording system was connected to a Differential Global Positioning System (DGPS) with ±2–10 m positioning accuracy.

Sediment analysis

Most sediment samples were collected from short Benthos cores (1–2 m) and a modified Kullenberg coring system (5–10 m; Girardclos 2001; Baster 2002). In Geneva Bay, sediments were drilled with a dry rotary corer from an anchored platform (20–90 m; Moscariello 1996). Macroscopic sedimentological descriptions were performed directly after core opening and colours were determined with Munsell® Soil Color Charts. Particle-size analysis of bulk sediments was measured with a Coulter LS-100 laser diffraction instrument (Loizeau *et al.* 1994). Mineralogical analyses of Geneva Bay sediments were based on smear slides and X-ray diffraction on bulk samples using a Scintag XRD 2000 diffractometer (Moscariello 1996).

Dating, palynology and vegetation history

In the well-oxygenated basin of Petit-Lac, sediment material suited for ^{14}C radiocarbon dating is sparse, with age models relying mostly on palynology and palaeomagnetism.

Pollen counting was carried out in Geneva Bay and in the Versoix and Nyon areas (Moscariello 1996; Girardclos 2001; Baster 2002). The subdivision of pollen diagrams into biozones (LPAZ = local pollen assemblages zones) and the chronology were established by comparing with regional pollen zones (Ammann & Lotter 1989; Ammann *et al.* 1996; van der Knaap & Ammann 1997; Lotter 1999b; Rachoud-Schneider 1999; van der Knaap *et al.* 2000). The estimated biozone ages (Girardclos 2001) were converted into calibrated years BP (Stuiver *et al.* 1998) and are indicated at the bottom of chronological figures (Figs 3–6). A few ^{14}C AMS dates confirm the chronology inferred from palynology (Moscariello 1996; Girardclos 2001; Baster 2002). In addition, a high-resolution magnetostratigraphic investigation was carried out on two sediment cores retrieved from the central part of the Nyon delta. The palaeosecular variation curve, extending back to 16 cal. kyr BP, shows good correlation with pollen stratigraphy (Baster 2002).

Reconstruction of past currents and wind regimes

The present Petit-Lac limnology serves as a model for reconstructing past lake bottom currents and dominant strong wind directions. During the present Versoix flooding events, net sediment transport is oriented opposite to the dominant wind direction, explained by the strong deep counter-currents measured in this area (Ulmann *et al.* 2003). Presently, heavy rain and resulting river floods are generally linked to barometric depressions and winds blowing from the SW, whereas strong NE winds are associated with maximum fetch and sediment reworking on the lacustrine shelf. For interpreting sediment distributions inferred from high-resolution data, it has therefore been postulated that the recent sedimentation SW and N–NE of the Versoix River mouth is linked to SW and NE winds, respectively (Girardclos *et al.* 2003).

Because the lake basin narrows in Versoix, strong bottom currents disturb the normal hemi-pelagic sedimentation at −60 m water depth (Girardclos *et al.* 2003; Ulmann *et al.* 2003). The varying size of a non-deposition area at the bottom of the Hauts-Monts underwater promontory and the presence/absence of truncations shown in the high-resolution seismic record allow semi-quantitative estimation of bottom-current strength (i.e. more erosion and/or larger non-deposition area means stronger currents) and its relation to the frequency of strong winds (Girardclos *et al.* 2003).

In this study, the 'Petit-Lac environment and climate history' is presented chronologically, and is structured in subsections around key elements such as 'atmospheric input', 'limnology', etc. These subsections also refer to the rows of Figs 3–6. Time windows in which elements occur (i.e. mass failures, delta lobes, ooids formation, etc.) are indicated with dotted lines (Figs 3–6). The vegetation history reconstructed from the Petit-Lac pollen sequences is represented in block diagrams showing the proportional evolution of main detected vegetation taxa (Figs 4–6). For purposes of clarity, significant but not dominant taxa may appear in the text but not on the vegetation blocks. For original pollen diagrams, see Baster (2002), Girardclos (2001), Moscariello (1996) and Rachoud-Schneider (1999), and for biozone definition, see Ammann *et al.* (1996). The legend of the vegetation blocks is shown in Fig. 4B.

Seismic longitudinal section of the Petit-Lac (western Lake Geneva)

The 'aout03g' seismic line (Fig. 2), shot with a 1 inch^3 airgun, is approximately 13 km long and located along the SE shore of the Petit-Lac (Fig. 1B). It shows a succession of two types of seismic facies: continuous, subhorizontal, high-amplitude facies, interpreted as glaciolacustrine and lacustrine sediments, and chaotic facies bodies, interpreted as glacial deposits (mainly diamicts) (Girardclos 2001). The interpreted profile is considered representative of the sediment record of glacial retreat along the lake basin axis. Lacustrine sequences are interpreted to be from the Lateglacial to Holocene (Girardclos 2001; Girardclos *et al.* 2003).

The geometry and facies of the chaotic sequences indicate two glacial re-advances: Coppet and Nyon (Fig. 2B). 'C' and 'N' indicate seismic reflections corresponding to the end of the Coppet and Nyon stages, respectively. Each re-advance led to the burying and deformation of the underlying proglacial lacustrine sediments, which transformed them into glaciotectonites (Banham 1977). Owing to their erosive power, these re-advances may also have erased remnants of smaller and older re-advances. During the Coppet re-advance, the glacier deposited an extensive 2-km-long wedge-shaped, acoustically subtransparent body at the glacier front (Fig. 2B). This 'till-tongue' structure (King *et al.* 1991; Van Rensbergen *et al.* 1999) was deposited from the pushed and extruded sediments as glacigenic debris flows ('GDF') (Boulton *et al.* 1996; Stravers & Powell 1997). The later Nyon re-advance formed a smaller 'till-tongue', *c.* 300 m long.

The lacustrine seismic facies between reflection N and the lake bottom is disturbed at three locations and different sequence levels: two large mass failure deposits, originating from the SE lake shore, occur above the Coppet push-moraine (1F) and above the Coppet 'till-tongue' (S6). Mass failure S6 did not entirely cross the lake basin (Girardclos 2001). A small mass failure occurs at the southern end of the line (S7). The extent of these mass failures is mapped on Fig. 1B. The large mass failure deposit 1F was also recognized and mapped from echosounder data (Baster 2002).

Petit-Lac environment and climate history

Deglaciation stages and chronology

Deglaciation of the Rhône glacier system in the Geneva area is represented by four deglaciation stages: Laconnex, Geneva, Coppet and Nyon, the latter three in the lacustrine infill of the Petit-Lac (Fig. 3):

- Geneva stage (Fig. 1B), which is reported from outcrops, seismic lines and sediment cores in Geneva Bay, is the oldest Würmian Rhône glacier stage recorded in the present lake extent. Unit C sediments of Geneva Bay indicate deposition in a proglacial lake close to the position of the melting Rhône glacier, and the 18 940 ^{14}C yr (~22 500 cal. yr BP) date at their base gives a minimum age for the retreating glacier (Moscariello 1996; Moscariello *et al.* 1998). The present Geneva Old Town hill contains a 400-m-long and 20-m-thick body of gravel and sand of variable foreset slopes, which is interpreted as a lacustrine delta formed at the front, or laterally in the frontal part, of the Rhône glacier (Moscariello *et al.* 1998). Based on this delta structure, a contemporary lake level at ~405 m a.s.l. (i.e. ~30 m above today's lake level) can be reconstructed. Following Arn (1984) and Gabus *et al.* (1987), this 405-m lake level probably lasted until the Oldest Dryas.
- Sediment sequences of the Coppet and Nyon stages representing re-advances in a proglacial lake with frontal glacier debris flow deposits ('till-tongues').

In the Versoix and Nyon areas, between the Nyon and Coppet glacial re-advances, seismic sequences of varying amplitude and low to medium continuity are interpreted as debris flow and underflow sediments deposited in the proglacial lake from the base of the active glacier front (Girardclos 2001; Baster 2002). Mixing of these proglacial and lacustrine processes generates 'stratified tills' (Evenson *et al.* 1977). The increasing continuity of the seismic facies toward the top of the deglaciation sequence represents the increasing influence of lake processes over glacial activity. This evolution in glacial lakes has been described by Van Rensbergen *et al.* (1998, 1999).

The fluctuation of the Rhône glacier ice front is represented by a chart showing the Laconnex

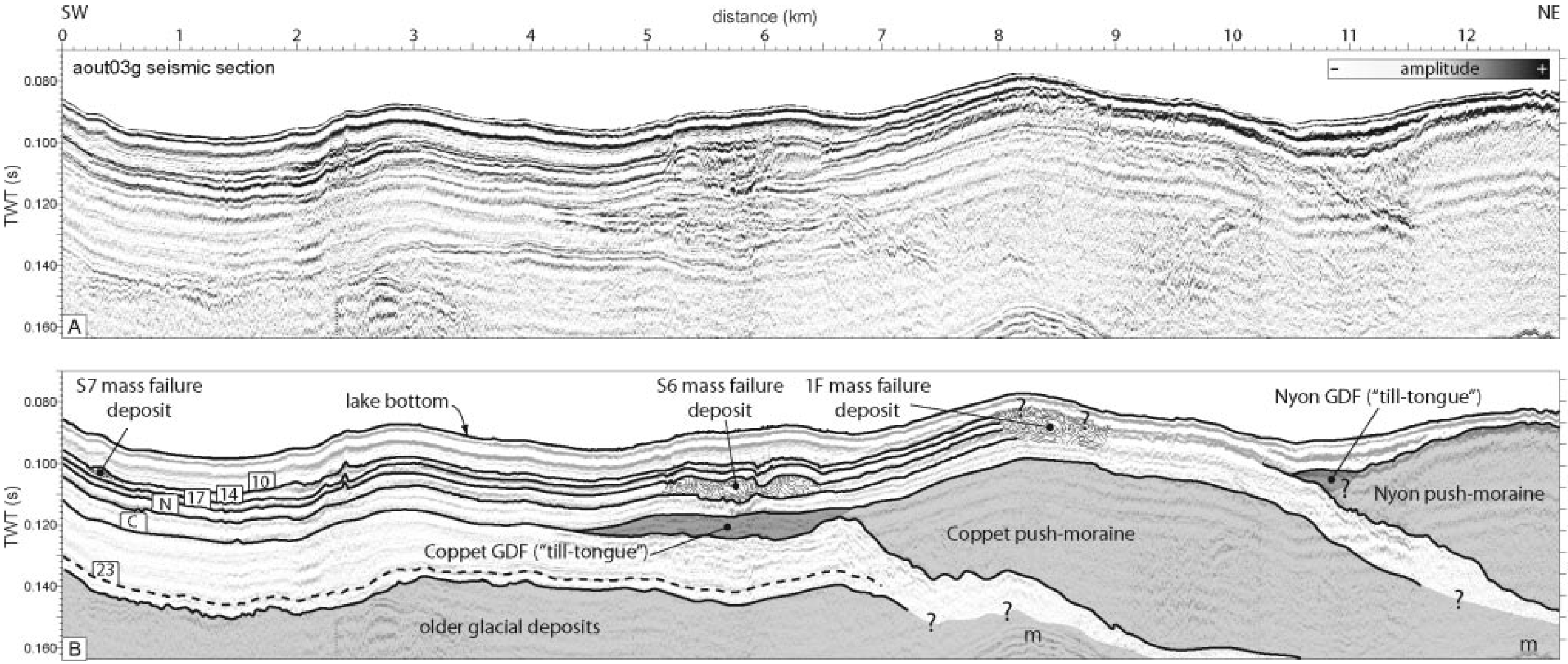

Fig. 2. A. Processed longitudinal seismic profile from the Petit-Lac (western Lake Geneva). The relative amplitude scale and depth below lake level are indicated on the right. B. Interpreted seismic section illustrating two Rhône glacier re-advances: Coppet and Nyon push moraines and their 'till-tongues' underlain by older till and/or glaciolacustrine sediments. 'C' and 'N' indicate seismic reflections corresponding to the end of Coppet and Nyon stages, respectively. Overlying top units represent Lateglacial and Holocene lacustrine sediments. Reflections 10, 14, 17 and 23 refer to Versoix seismostratigraphy (Girardclos 2001; Girardclos *et al*. 2003). Three mass failures, crossed perpendicularly by the profile, are labelled 'S7', 'S6' and '1F'. These mass movements originate from the nearby lake shore and have different ages. The lake bottom multiple is labelled 'm'. Vertical exaggeration is about 35 times. For location, refer to Fig. 1.

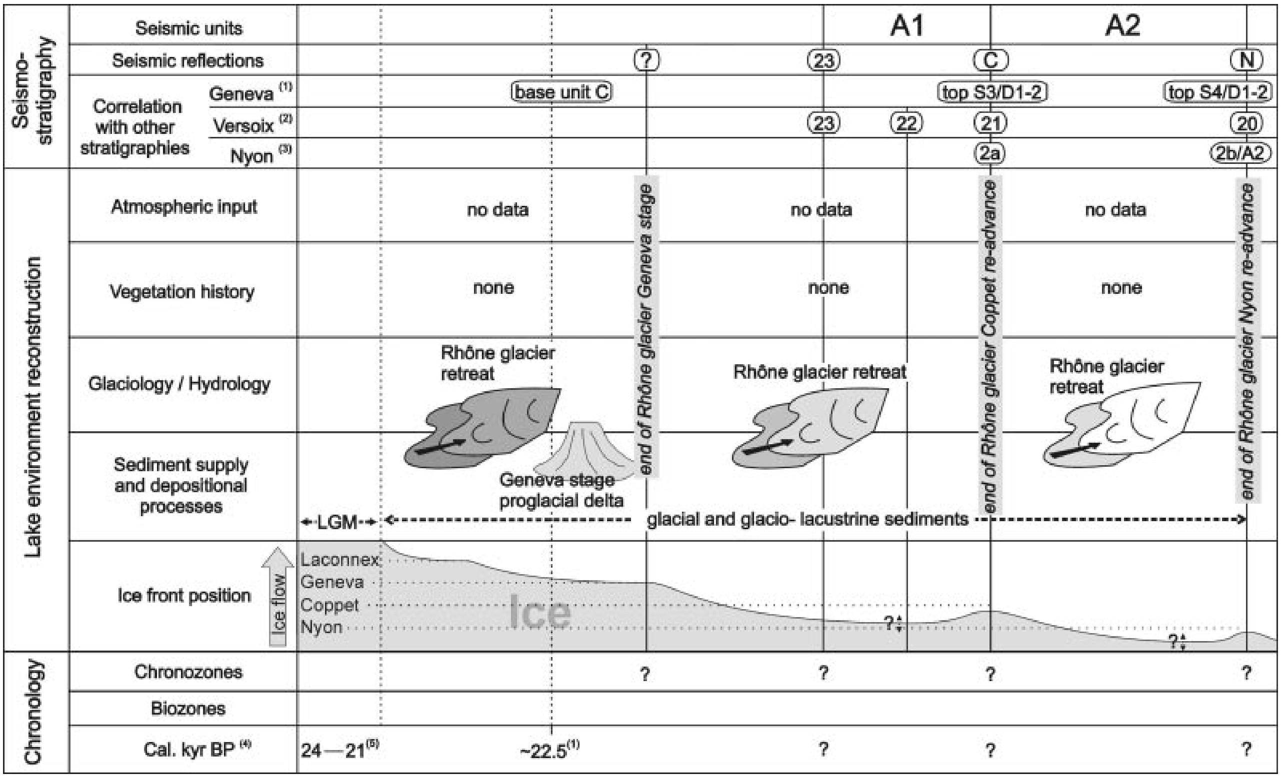

Fig. 3. Deglaciation history of the Petit-Lac. After the Laconnex stage, the Rhône glacier retreats in at least three phases: Geneva stage, Coppet and Nyon re-advances. During the Geneva stage, a lacustrine proglacial delta forms at the front or the side of the Rhône glacier. Coppet and Nyon re-advances produce frontal glacigenic debris flow deposits 'GDF' ('till-tongues'). For chronology, refer to the text. References: (1)(Moscariello *et al*. 1998), (2)(Girardclos 2001; Girardclos *et al*. 2003), (3)(Baster 2002; Baster *et al*. 2003), (4)(Stuiver *et al*. 1998), (5)(Preusser 2004; van Husen 1997).

(Moscariello *et al*. 1998) and Geneva stages, and the Coppet and Nyon re-advances (Fig. 3). The latter two were initially named by Moscariello *et al*. (1998) after the geographic position of their till tongue, and not after the inferred glacier position. Therefore, the ice front did not actually reach these two localities during the glacial re-advances. Furthermore, the re-advancing glacier may have overridden and eroded sediments of smaller ice-front fluctuations.

Chronological representation of the Petit-Lac deglaciation history (Fig. 3) shows the correlation between local seismostratigraphies established at Geneva, Versoix and Nyon, and the three Rhône glacier stages of the Petit-Lac. The lack of deep coring and consistent dating for western Lake Geneva deglaciation means that the chronology of this period is uncertain. Van Husen (1997) proposes a LGM (Last Glacial Maximum) in the eastern Alps of between 24 and 21 ka BP, a date supported by Preusser (2004). In western Switzerland, the time markers for the retreating Rhône glacier have a minimum age of 18 940 ± 210 ^{14}C yr (~22 500 cal. yr BP) in Geneva Bay (Moscariello 1996; Moscariello *et al*. 1998) and indicate the Rhône glacier breakdown occurring between 21.1 and 19.1 kyr in the Wangen an der Aare region (Ivy-Ochs *et al*. 2004). With respect to these data, Lake Geneva stages are important lithostratigraphic reference levels for establishing a relative chronology.

Lateglacial

The Lateglacial sediment record shows the onset of a purely lacustrine environment in western Lake Geneva, and develops soon after the Rhône Glacier Nyon re-advance (reflection N) (Figs 2B, 4A). The exact duration of unit B1 is not documented, but its top is attributed to the Oldest Dryas. Unit B2 lasts until the beginning of the Bølling and unit B3 is included in this same biozone. Unit C1 starts at the end of the Bølling and ends at the Younger Dryas/Preboreal transition.

Atmospheric input. – The Oldest Dryas sediments from Geneva Bay (sediment unit D3; Moscariello 1996) and the Nyon area (Baster 2002) show yellow sediment layers of silty-sandy non-graded facies. These deposits, commonly found in other Swiss and European lakes (Niessen *et al*. 1992), are interpreted as aeolian dust (loess) deposited under the influence of very strong winds. Niessen *et al*. (1992) date the

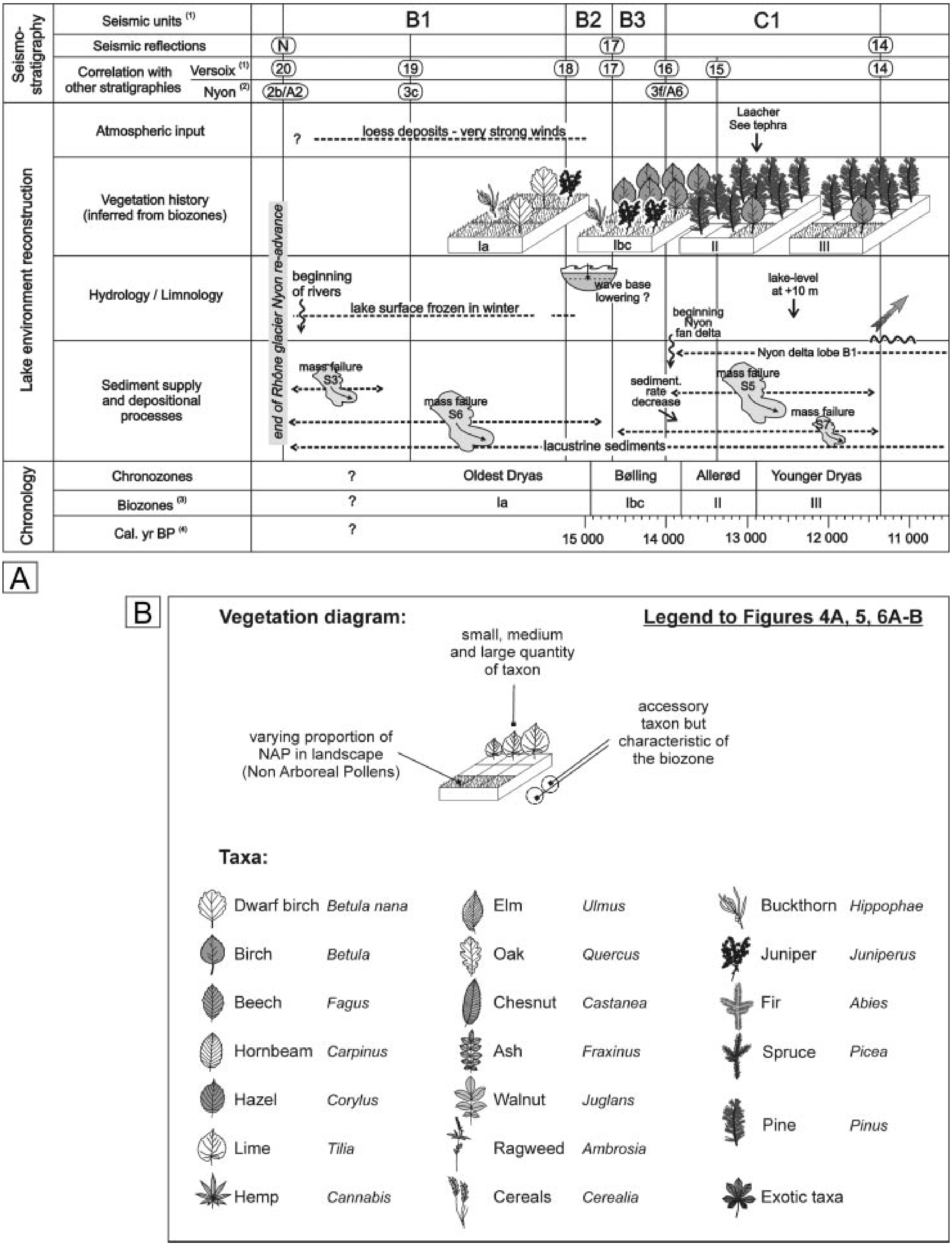

Fig. 4. A. Lateglacial environment and climate history of the Petit-Lac. During unit B1, rivers develop, the lake surface is mostly frozen in winter and very strong winds deliver loess. Four small to large mass failures are triggered during the Lateglacial. The vegetation expands from Oldest Dryas, and the Nyon fan delta forms at the end of the Bølling. References: (1)(Girardclos 2001; Girardclos *et al*. 2003), (2)(Baster 2002; Baster *et al*. 2003), (3)(Ammann *et al*. 1996), (4)(Stuiver *et al*. 1998). For vegetation legend, refer to Fig. 4B. B. Legend for 3D vegetation blocks with taxa symbols.

termination of intense aeolian dust sedimentation in central Europe to 14 000 yr ^{14}C (~16 800 ± 500 cal. yr BP), but in the Nyon area the loess deposits are still present at the Oldest Dryas/Bølling transition (~15 cal. kyr BP; Baster 2002). Since the geomagnetic correlation between Lake Constance, Lake Zurich, Lake Lugano and Lake Geneva is consistent (Baster 2002), this time lag is most likely due to inaccuracies in the Lake Constance chronology.

The Laacher See tephra, dated 12 900 ± 560 yr BP (van den Bogaard 1995) and 12 880 varve yr BP (Litt *et al.* 2001), is present in the Petit-Lac sediments at the Allerød/Younger Dryas transition (Moscariello *et al.* 1998; Baster 2002) and was identified by Moscariello (1996) as the Upper Laacher See Tephra (ULST); this concurs with van den Bogaard & Schmincke (1985) and van den Bogaard (1995).

Vegetation history. – Oldest Dryas or biozone Ia (prior 12.6 ^{14}C kyr BP): During the Oldest Dryas biozone, local vegetation was scarce and consisted of a Lateglacial steppe rich in heliophilous plants with shrubs such as dwarf birch, juniper and buckthorn, i.e. a treeless vegetation that is present in Geneva Bay and the Versoix and Nyon areas. The Oldest Dryas palynological signature does not imply that these deposits date exactly from the same period, but rather that they were deposited shortly after local deglaciation.

Bølling or biozone Ib/c (12.6 to 12 ^{14}C kyr BP): the Bølling interval corresponds to the landscape reforestation, which begins with a first scrub phase rich in juniper, buckthorn and the first birch trees; this time period is followed by widespread open birch woodland.

Allerød or biozone II (12 to 10.8 ^{14}C kyr BP): pine immigrates and then expands into the birch woodland: dense pine and birch forests dominate the landscape, and NAP (non-arboreal pollen) reaches minimum Lateglacial values.

Younger Dryas or biozone III (10.8 to *c.* 10 ^{14}C kyr BP, in a radiocarbon plateau): pine forests with birch are still widespread, and the advance of NAP is interpreted as a slight increase in open-ground vegetation. This zone corresponds to the last major cooling of the Lateglacial period.

Hydrology and limnology. – Seismic data in the Versoix area show that soon after the Nyon re-advance of the Rhône glacier the sediment input direction reverses, indicating the beginning of major river input to the lacustrine environment (Girardclos 2001). Sediment cores from the Oldest Dryas in Geneva Bay (sediment unit D3; Moscariello 1996) and in the Nyon area (Baster 2002) show couplets of grey and yellow silt-clay layers with laminae of variable thickness. These sediments, similar to those observed in Lake Constance and Lake Zurich (Giovanoli 1979; Niessen *et al.* 1992), are interpreted as annual layers due to alternation of the winter ice cover of the lake and the spring melting. In the Versoix area, the disappearance of these yellow/grey rythmites into mixed yellow/grey layers (Girardclos 2001) indicates that the systematic winter freezing of the lake ended not later than the beginning of unit B3 (reflection 17). According to the minimum age of loess deposits (cf. ‘atmospheric input’), lake-surface freezing probably ends even earlier, at the end of the Oldest Dryas (Fig. 4A).

As indicated by sediment thickness distribution in the Versoix area, small coeval slope deposits triggered during unit B2 (end of the Oldest Dryas/beginning of Bølling) (Girardclos 2001) are possibly due to an earthquake or to a wave base lowering (increase in the intensity and/or frequency of wind-induced waves and/or a lowering of the lake level). In Dorigny (SW of Lausanne) a peat deposit dated to 10 520 ± 140 yr ^{14}C (~12 430 ± 480 cal. yr BP) suggests that during the Younger Dryas the lake level was about 10 m above the present lake level (Gabus *et al.* 1987).

Sediment supply and depositional processes. – In the Nyon region, seismic and sediment core data indicate that the postglacial fan delta developed at the end of the Bølling (Fig. 4A), representing a shift of the main sediment source from the Rhône glacier catchment to local alluvial streams (Baster *et al.* 2003). The first Nyon delta lobe (B1) grows until the beginning of the Boreal (Baster 2002; Baster *et al.* 2003). In the Versoix area, the decrease in sedimentation rate from unit B3 (>1.71 mm/yr, Bølling; Girardclos 2001) to unit C1 (0.47 mm/yr, end of Bølling to Younger Dryas; Girardclos 2001) is explained by a reduction of allochthonous sediment input linked to the expansion of foresets during the Allerød (Moscariello *et al.* 1998) and/or to decreasing precipitation and aeolian input.

The laminated black pigmented and grey clayey silts from the Allerød period change to homogeneous grey clayey silts during Younger Dryas (Baster 2002). In Geneva Bay, the mineralogy also indicates sedimentological changes in calcite and detrital content during the Younger Dryas (Moscariello 1996), but these variations are not prominent and thus make their interpretation less straightforward.

Four individual mass failures are triggered during the Lateglacial at different locations. The medium-sized mass failure S3 (Figs 1B, 4A) starts at the beginning of unit B1 and may be related to possible high runoff following the lake watershed thaw (Girardclos 2001). The large mass failure S6 (Figs 1B, 2B, 4A) is possibly triggered during unit B1 or B2, but its cause is undefined. Another large mass failure is S5 (Figs 1B, 4A), which starts during the second half of the Lateglacial (Girardclos 2001) and is probably simultaneous with the Lake Lucerne and Lake Annecy slumps (Beck *et al.* 2001; Brauer & Casanova 2001; Schnellmann *et al.* 2002).

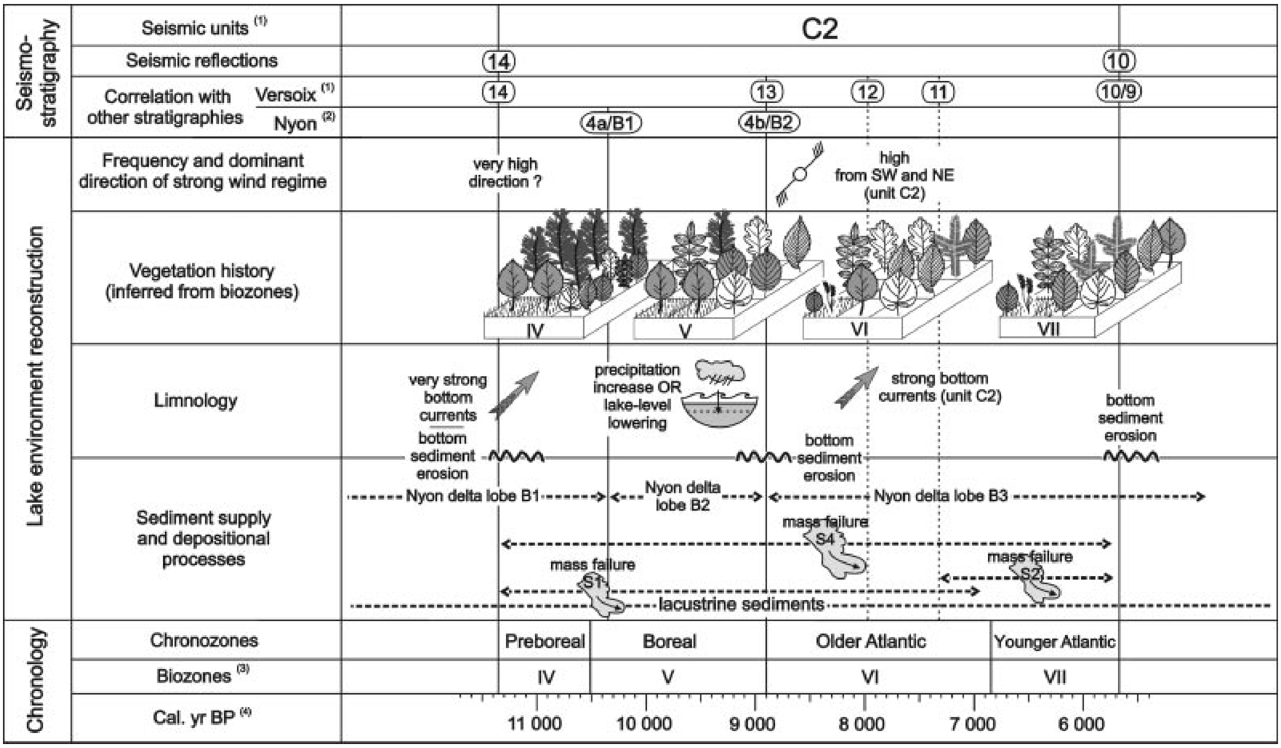

Fig. 5. Preboreal to Younger Atlantic environment and climate history of the Petit-Lac. During unit C2, the frequency of strong winds ranges from very high (at the beginning of the Preboreal) to high, and the dominant regime is from both SW and NE. Mesothermophilous trees (hazel, oak, elm, lime) immigrate to the dense pine and birch forests and then expand. Very strong bottom currents start at the beginning of the Preboreal, and the Nyon delta fan continues to develop. Three small to medium mass failures are triggered during this period. References: (1)(Girardclos 2001; Girardclos *et al*. 2003), (2)(Baster 2002; Baster *et al*. 2003), (3)(Ammann *et al*. 1996), (4)(Stuiver *et al*. 1998). For vegetation legend, refer to Fig. 4B.

Holocene I (Preboreal to Atlantic)

Seismic unit C2 represents the first part of the Petit-Lac Holocene sedimentological and climatic history (Holocene I). It starts at the Younger Dryas/Preboreal transition and lasts about 5700 cal. yr until the Younger Atlantic/Subboreal limit (Fig. 5).

Frequency and direction of dominant strong wind regimes. – Seismic data from the Versoix area indicate very strong bottom-current action at the beginning of the Preboreal (beginning of unit C2), which is interpreted as a record of very high-frequency strong wind regimes (Girardclos *et al*. 2003). In the Versoix area, sediment distribution and a slight decrease of the non-deposition surface from the Preboreal to the end of the Younger Atlantic (unit C2) shows a high frequency of strong wind regimes equally from the NE and the SW (Girardclos *et al*. 2003).

Vegetation history. – Preboreal or biozone IV (*c*. 10 to *c*. 9.5–9 ^{14}C kyr BP): the Preboreal biozone represents a climate warming trend in central-west Europe (Davis *et al*. 2003). Mesothermophilous trees such as hazel, oak, elm and lime immigrate to the dense pine and birch forests. The birch population increases distinctly at the beginning of this biozone. The decline of the NAP shows a decrease of open-ground vegetation.

Boreal or biozone V (*c*. 9.5–9 to *c*. 9–8 ^{14}C kyr BP): the rapid expansion of hazel woods and dense broad-leaved forests (oak, elm and lime) is characteristic of the Boreal biozone. Ash and ivy immigrate, and the regression of pine and birch forests is definitive.

Older Atlantic or biozone VI (*c*. 9–8 to *c*. 6 ^{14}C kyr BP): dense mixed oak forests mainly with elm, lime, oak and ash are widespread. Ivy and mistletoe are abundant. Fir and then beech immigrate. The first cereal phases related to Early Neolithic agriculture are recorded on the Swiss Plateau (Haas 1996).

Younger Atlantic or biozone VII (*c*. 6 to *c*. 5–4.8 ^{14}C kyr BP): the spreading of fir and especially beech are major events of the forest history. These seem closely correlated to the regression of dense mixed-oak forests, which is mainly due to the decline of elm and lime. Ivy and mistletoe decrease, indicating a temperature increase. Spruce immigrates and yew expands. Middle Neolithic human impact on the vegetation is indicated by cereal phases synchronous with surges of apophyte taxa (*Plantago lanceolata* and *Rumex*, among others) and phases of distinctive forest clearance.

Limnology. – In the Versoix area, a widely eroded sediment surface points to very strong bottom currents at the beginning of the Preboreal (Fig. 5). A continuous but smaller non-deposition surface during the Preboreal to the end of the Younger Atlantic (unit C2) is interpreted as the persistent action of strong bottom currents (Girardclos *et al*. 2003).

Sediment cores of Boreal age in Corsier Bay (Girardclos 2001) and Geneva Bay (Moscariello 1996) show a brownish colour and thin darker brown layers indicating terrestrial input mixed with lacustrine sediments. This increase in terrestrial input is interpreted as a lowering of the lake level and/or increased runoff.

The erosion and non-deposition at the eastern limit of the Nyon delta lobe B2 documents the presence of strong erosive bottom currents at the Boreal/Older Atlantic transition (Baster *et al*. 2003). During this time (reflection 13), the same erosive events are reported in the Versoix sector (Girardclos 2001), indicating a probable large-scale event in the hydrodynamics of the Petit-Lac. In the Nyon region, a weakening of bottom-current activity is reported during the Atlantic (biozones VI and VII) in deeper parts of the basin (Baster *et al*. 2003), but this phenomenon is not apparent in other areas. At the Younger Atlantic/Subboreal transition, the truncation of seismic unit C2 in Versoix indicates another erosive event due to strong bottom currents (Girardclos 2001).

Sediment supply and depositional processes. – As already mentioned, bottom sediments are heavily eroded in the Versoix and Nyon areas at the beginning of the Preboreal (Versoix reflection 14), at the Boreal/Older Atlantic transition (Versoix reflection 13 and Nyon delta lobe B2) and at the Younger Atlantic/Subboreal transition (Versoix reflection 10/9) (Baster *et al*. 2003; Girardclos *et al*. 2003).

In the Nyon region, the first delta lobe (B1), which starts at the end of the Bølling (reflections 3f/A6), grows until the beginning of the Boreal (reflection 4a/B1) (Baster 2002; Baster *et al*. 2003). During the Preboreal, this delta shows a higher sedimentation rate (0.53 mm/yr) than during the beginning of its formation at the end of the Lateglacial (0.22 mm/yr; Baster 2002). This probably represents the effects of Preboreal climate warming. During the Boreal, the Nyon delta lobe B2 grows toward the north and the south, demonstrating an increase in the river input of sediments. During the Atlantic and the first part of the Subboreal, the Nyon delta lobe B3 further extends its influence area (Baster *et al*. 2003). In the Versoix area, unit C2 (Preboreal to beginning of Younger Atlantic) has a low mean sedimentation rate (0.32 mm/yr; Girardclos 2001), certainly due to the reported persistent action of bottom currents (Girardclos *et al*. 2003).

During the Holocene, the distal Nyon delta and hemi-pelagic Versoix sediments show deep-water sediment facies: greenish-grey clayey silts with dark grey and brownish layers (Girardclos 2001; Baster 2002). At the end of the Preboreal, sediment mineralogy of the Geneva Bay shows a calcite content increase from 40% to 70% and a decrease of terrigenous sediments from 70% to 20% (Moscariello 1996). These values, which remain fairly stable until the end of the Holocene, indicate the definitive establishment of endogenic calcite precipitation, reflecting the important climate and lake productivity change at the beginning of the Holocene.

Three mass failures were triggered during the Preboreal to Younger Atlantic period (unit C2). Mass failures S1 and S2 are of relatively small volume and lie close to the Versoix River mouth (Figs 1B, 5) (Girardclos 2001). Their size and location within the Versoix delta extent point to a local triggering effect (floods?). Mass failure S4 near Corsier (Figs 1B, 5) is of medium size and may be related to the disturbed seismic unit of Lake Le Bourget, triggered at the Lateglacial/Holocene transition (Chapron *et al*. 1996). Alternatively, it could be contemporaneous with Lake Lucerne's slump at 9770 cal. yr BP (i.e. Boreal; Schnellmann *et al*. 2002). In either case, an earthquake could have triggered mass failure S4.

Holocene II (Subboreal to Subatlantic)

The second part of the Petit-Lac Holocene environment and climate history (Fig. 6A, B) is reconstructed from seismic units C3 to D3 (reflection 10 to lake bottom). Unit C3 starts at the Younger Atlantic/Subboreal transition and lasts until ~AD 1000 (beginning of Younger Subatlantic). Unit D is subdivided into three subunits corresponding to high resolution vegetation and sedimentological changes (Girardclos 2001; Girardclos *et al*. 2003): Late Middle Ages (11th–15th century, unit D1), Modern Times (16th–18th century, unit D2) and the Contemporary Epoch (19th–20th century, unit D3).

Frequency and direction of dominant strong wind regimes. – Seismic records in the Versoix area show evident changes in bottom-current activity from unit C3 to D3; these are interpreted as changes in the frequency and direction of the dominant strong wind regime (Girardclos *et al*. 2003). During Subboreal and Older Subatlantic (unit C3), the strong-wind frequency is medium and the dominant direction is mainly from the SW (Fig. 6A). The frequency of strong winds decreases to low during Late Middle Ages (11th–15th century, unit D1) and becomes very low during Modern Times (16th–18th century, unit D2). During this time, the dominant strong wind direction shifts to the NE (unit D1 and D2). Unit D3 demonstrates important changes during the Contemporary Epoch (19th–20th century): the frequency of strong winds is very high and the dominant regime moves back to the SW (Fig. 6B; Girardclos *et al*. 2003).

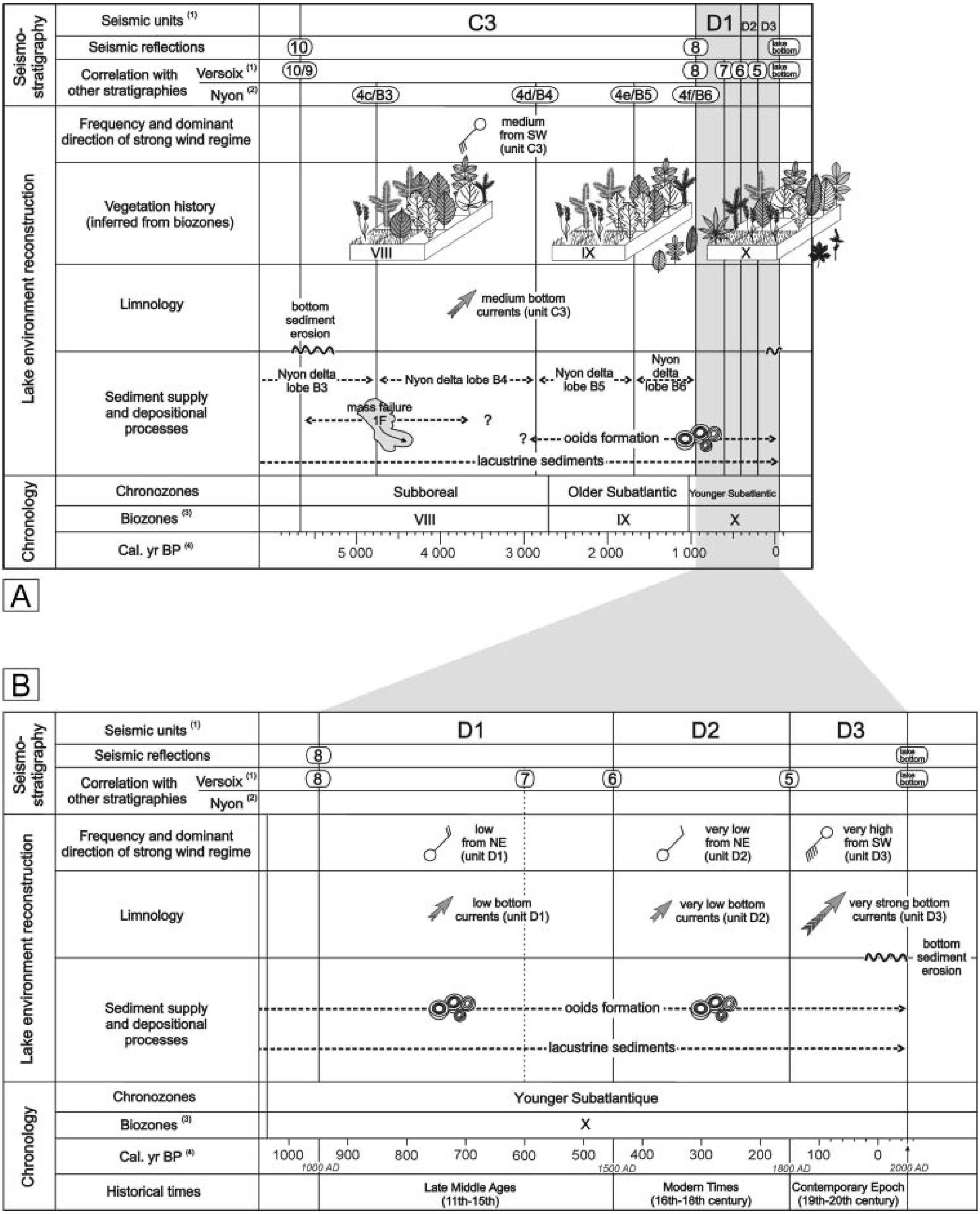

Fig. 6. A. Subboreal to Younger Subatlantic environment and climate history of the Petit-Lac. Two important erosion events mark the beginning and end of this period. The Nyon fan delta shows a varying morphology from Subboreal to the beginning of Subatlantic (cf. text). The earliest possible triggering time for large mass failure 1F is the beginning of the Subboreal. The human impact on vegetation, such as deforestation, cultivation of cereals and hemp, and introduction of exotic taxa, increases with time. B. Detailed Petit-Lac environment and climate history during the Younger Subatlantic. Bottom currents, and inferred strong-wind frequency and direction vary greatly from the Late Middle Ages to the Contemporary Epoch. References: (1)(Girardclos 2001; Girardclos *et al*. 2003), (2)(Baster 2002; Baster *et al*. 2003), (3)(Ammann *et al*. 1996), (4)(Stuiver *et al*. 1998). For vegetation legend, refer to Fig. 4B.

Vegetation history. – Subboreal or biozone VIII (5–4.8 to 2.7–2.5 ^{14}C kyr BP): the establishment of beech, fir and spruce and the decrease of existing mixed oak forests are characteristic features of the Subboreal biozone on the Swiss Plateau. In the Geneva basin, neither beech nor fir is capable of replacing oak, which still plays a major role in the landscape. Elm-, lime- and ash-declines are definitive. Late Neolithic and Bronze Age human impact on the vegetation cover is clearly reflected by the advance of cereals and apophyte taxa and by deforestation phases.

Older Subatlantic or biozone IX (2.7–2.5 to 1.3–1 ^{14}C kyr BP): there is no major change in the evolution of the landscape during the Older Subatlantic biozone. Exploited oak-hornbeam woods expand and fir and beech forests are still widespread. Hornbeam appears during the Iron Age, walnut and chestnut during the Roman Period. The landscape becomes more and more open, especially during Early Middle Ages. Rye and hemp are now cultivated.

Younger Subatlantic or biozone X (1.3–1 ^{14}C kyr BP to the present): at the onset of the Younger Subatlantic biozone, the rise in NAP, both as percentages and as number of taxa, is sharp and can be interpreted as a generalized opening of the landscape due to intensive human activity since the Middle Ages. Cultivated fields (cereals, rye and hemp), intensive grazing, wood pastures and exploited forests expand. Beech and fir forests decrease. The plantations of walnut and chestnut followed by spruce and pine grow. Oak forests are still favoured by man. The appearance and development of exotic taxa such as cedar, horse chestnut trees and the rise of ragweed (around AD 1945) are typical features of Modern Times (16th–18th century) and the Contemporary Epoch (19th–20th century).

Limnology. – In the Versoix area, seismic data reveal changing non-deposition/erosion patterns and sediment distribution, which are interpreted as the result of varying bottom currents (Fig. 6A, B). The truncation of unit C2 (cf. 'Holocene I') at 65-m depth occurs at the Younger Atlantic/Subboreal transition and indicates an erosive event due to strong bottom currents (Girardclos 2001). During the Subboreal and Older Subatlantic period (unit C3), thickness distribution marks an overall medium bottom-current activity. In the Nyon sector, Subboreal delta lobe B4 points to an increase in bottom-current activity in comparison to the preceding lobe B3 period (Baster *et al.* 2003). This trend does not seem consistent with the Versoix data, which show an overall current activity decrease from unit C2 to unit C3 (Girardclos *et al.* 2003), but may be due to different time-scale resolutions.

The action of bottom currents decreases to low and very low during Late Middle Ages (11th–15th century, unit D1) and Modern Times (16th–18th century, unit D2), respectively. During the Contemporary Epoch (19th–20th century, unit D3), bottom current action increases to very strong in the Versoix region and heavily erodes sediments at 35–55 m depth along the slope of Corsier bay (Girardclos *et al.* 2003). Recent *in situ* measurements in the Versoix area confirm present deep-current activity (Ulmann *et al.* 2003).

Sediment supply and depositional processes. – As already mentioned, bottom sediments are heavily eroded in the Versoix area at the Younger Atlantic/Subboreal transition and at the end of unit D3.

The Nyon delta lobe B4 forms during Subboreal (reflection 4c/B3 to 4d/B4) with a decrease in surface area compared to the previous lobe (Fig. 6A). During the beginning of the Older Subatlantic, the next delta sequence (lobe B5) expands in size toward the south (Baster *et al.* 2003). Finally, the Nyon delta lobe B6 moves northward during late Older Subatlantic and the very beginning of the Younger Subatlantic. This Nyon delta shift to the NE seems anterior to the same shift of the Versoix delta (starting with unit D1; Girardclos *et al.* 2003) and can be explained by a northward displacement of the Promenthouse River mouth, reflecting a change in the local catchment area rather than in the lake internal processes (Baster *et al.* 2003).

In Versoix, the constant low sedimentation rate (0.31 mm/yr) of unit C3 (Subboreal to beginning of Subatlantic) contrasts with the significant sedimentation rate increases during Subboreal and Older Subatlantic times in Lake Zurich and Lake Lugano (Lister 1988; Niessen & Kelts 1989). This low value is certainly linked to the transport and erosive action of bottom currents on the hemi-pelagic sedimentation of the Versoix area. Contrary to unit C3, units D1–3 (Younger Subatlantic) reveal a sharp rise in sedimentation rate (3.46–4.53 mm/yr; Girardclos 2001), which is interpreted as the combined effect of local and regional processes: the local sediment budget increases with the northward shift in current direction and with the decrease of erosion (unit D1–2), and the regional runoff increases due to the impact of human deforestation (Girardclos *et al.* 2003).

In the coastal realm of the Versoix area, Subboreal and Older Subatlantic sediment layers indicate a depositional environment quieter than today (lower part of core sg10; Girardclos 2001), which may represent the +3-m-high lake level reported by archaeological data from Late Bronze to Roman age (Gallay & Kaenel 1981).

The large mass failure 1F (Figs 2B, 6A) was triggered after reflection 10, i.e. at the beginning of the Subboreal (unit C3), but the lack of relevant seismic lines in the proximal sector and the limited seismic resolution mean the possibility of a later triggering.

Coring and diving observations reveal an irregularly shaped well-sorted ooidal sand body at 1.5–6 m depth in Geneva Bay (Fig. 6A, B). The age of 2805 ± 60 ^{14}C yr (~2925 ± 150 cal. yr BP), determined on ooid cortices, indicates that their formation started not later than the end of the Subboreal (Davaud & Girardclos 2001; Moscariello 1997). Recent work in Geneva Bay, showing that bacteria rapidly colonize organism-free surfaces and trigger carbonate precipitation, indicates that ooids still form today (Plée *et al*. 2004).

Discussion

This synthesis of the climate and environmental history of the Petit-Lac (western Lake Geneva) presents the first general scenario from deglaciation to the present for a central European lake of medium size. External sediment input and internal lake processes of this lake basin and its watershed produce a sediment record that differs from the records of small lakes of the Swiss Plateau (van der Knaap & Ammann 1997; Magny & Richoz 1998, 2000; Lotter 1999a, 2001; van der Knaap *et al*. 2000). In small lake basins, the physical, chemical and biological balances react rapidly to small environmental changes (Hu *et al*. 1999; Gilli *et al*. 2001; Heiri *et al*. 2004). Runoff, winds, currents and human impact are likely to have a local rather than a regional influence (Lotter & Birks 2003). In contrast, currents and inferred wind data in the Petit-Lac, like the Ammersee isotopic record (von Grafenstein *et al*. 1999), are of regional to continental significance, as only large-scale and long-term changes can imprint the overall sedimentological record of those medium-sized lake basins.

The potential correlation between the Petit-Lac data with records of timberline fluctuations and glacier extent in the Alps was tested (Tinner *et al*. 1996; Haas *et al*. 1998; Hormes *et al*. 2001) but no coherent parallelism was found. This suggests that during the Holocene the Petit-Lac integrated the climatic signal in a different manner or with a lower sensitivity than did the alpine ecosystems. However, the CE2 'Central European cold humid phase' during the Boreal (Haas *et al*. 1998) supports the record of a possible precipitation increase in the lake (cf. Fig. 5).

A correlation exists between the trend of the Petit-Lac wind record and the subtraction of winter (MTCO) temperature with reconstructed summer (MTWA) anomalies (Davis *et al*. 2003). The subtraction of winter with summer area-averaged temperature anomalies in central-west Europe continuously decreases from 12 000 cal. yr BP to 6000 cal. yr BP, when it reaches a 'temperature anomaly difference' plateau around zero (Davis *et al*. 2003). The period of highly different summer and winter temperature anomalies corresponds to high-frequency strong winds in western Lake Geneva, while the medium-to-low frequency strong winds occur when the anomaly difference is close to zero. This suggests a link between the Petit-Lac wind record and the global atmospheric circulation changes during the Holocene. However, the temperature anomaly curves do not explain the apparent increase of strong wind frequency during the Contemporary Epoch (Fig. 6B).

Conclusion

The synthesis of the Petit-Lac (western Lake Geneva) environment and climate changes shows a continuous record from deglaciation to the present.

The Rhône glacier retreat occurs in at least three stages (Geneva, Coppet and Nyon stages). The Coppet and Nyon stages represent re-advances in a proglacial lake with frontal glacier debris flow deposits ('till-tongues'). Loess deposits, brought by very strong winds, are present until the Oldest Dryas/Bølling transition (~15 cal. kyr BP), indicating a young age for the termination of aeolian dust in central Europe. Winter lake-freezing ends between the end of the Oldest Dryas and Bølling. Deposition of the Nyon fan delta starts at the end of the Bølling, indicating a shift of the main sediment source from the Rhône catchment to local alluvial streams. At the beginning of the Preboreal, very strong bottom currents are interpreted as a result of the very high frequency of strong winds. The Holocene variations of the current activity point to changes in frequency and direction of the dominant strong wind regime. During the Boreal, the increase in terrestrial input implies a lowering of the lake level and/or an increase in runoff due to increased precipitation. At the Boreal/Older Atlantic transition, the widespread erosion indicates a large-scale hydrodynamic event in Lake Geneva. In Versoix, the sharp rise in sedimentation rate during the Younger Subatlantic is interpreted as the combined effect of local (bottom currents) and regional (human impact) processes. Two mass failures are triggered between deglaciation and the end of the Oldest Dryas, two between the Bølling and the Younger Dryas, and four during the Holocene.

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