Zeitschrift: Eclogae Geologicae Helvetiae
Herausgeber: Schweizerische Geologische Gesellschaft
Band: 96 (2003)
Heft: [1]: Lake systems from Ice Age to industrial time

Artikel: High-resolution seismic stratigraphy of an Holocene lacustrine delta in western Lake Geneva (Switzerland)

Autor: Baster, Ira / Girardclos, Stéphanie / Pugin, André

DOI: https://doi.org/10.5169/seals-169039

0012-9402/03/01S011-10
Birkhäuser Verlag, Basel, 2003

Eclogae geol. Helv. 96 (2003) Supplement 1, S11–S20

High-resolution seismic stratigraphy of an Holocene lacustrine delta in western Lake Geneva (Switzerland)

IRA BASTER[1,2], STÉPHANIE GIRARDCLOS[1,3], ANDRÉ PUGIN[1,4] & WALTER WILDI[1]

Key words: lacustrine delta, western Lake Geneva, Holocene, seismic stratigraphy, slope instability, gas blanking, 3-D model.
Mots-clés: delta lacustre, Lac Léman, Holocène, stratigraphie sismique, instabilité de pente, zone sourde, modèle 3-D.

ABSTRACT

A high-resolution seismic survey was conducted in western Lake Geneva on a small delta formed by the Promenthouse, the Asse and the Boiron rivers. This dataset provides information on changes in the geometry and sedimentation patterns of this delta from Late-glacial to Present. The geometry of the deposits of the lacustrine delta has been mapped using 300-m spaced grid lines acquired with a 12 kHz Echosounder subbottom profiler. A complete three dimensional image of the sediment architecture was reconstructed through seismic stratigraphic analysis. Six different delta lobes have been recognized in the prodelta area. Depositional centers and lateral extension of the delta have changed through time, indicating migration and fluctuation of river input as well as changes in lake currents and wind regime from the time of glacier retreat to the Present. The delta slope is characterized by a high instability causing slumps developing and by the accumulation of biogenic gas that prevents seismic penetration.

RESUME

Une campagne sismique haute résolution a été conduite sur le delta formé par les rivières de la Promenthouse, de l'Asse et du Boiron, dans la partie occidentale du Lac Léman (Suisse). Cette recherche a mis en évidence des changements importants quant à la géométrie et à la sédimentation du delta, du Tardiglaciaire à l'Actuel. La géométrie des dépôts deltaïques a été cartographiée à l'aide d'un échosondeur 12 kHz avec un espacement de 300 m entre chaque profil. L'analyse sismostratigraphique a permis de reconstruire la structure 3D des séquences glaciolacustres et deltaïques ainsi que l'histoire du remplissage sédimentaire. Six lobes deltaïques ont été reconnus dans le bassin. Les centres de dépôt et l'extension latérale du delta ont sensiblement changés au cours du temps, ce qui indique que d'importantes variations dans l'apport de sédiments ainsi que des changements dans le régime des courants et des vents ont eu lieu à partir du retrait glaciaire et jusqu'à nos jours. Le delta est caractérisé par une instabilité élevée, marquée par le développement de slumps, et par la présence de gaz biogénique qui réduit la pénétration sismique.

1.- Introduction

Lake deposits are sensitive archives of palaeoenvironmental conditions and climate change occurring in continental areas. Lacustrine deltas are of particular interest because their sedimentation is influenced not only by processes occurring in the catchment area but also by lacustrine processes (Smith 1991). Precipitation, erosion, changing soil occupation and other parameters determine the input of water and sediment to the lake. On the other hand, current regime and lake level fluctuations influence sedimentary history and delta morphology as well. Moreover, exceptional events such as floods and earthquakes can be recorded with a particular sedimentary signature.

High-resolution seismic investigations provide a powerful tool to determine the thickness, geometry and lateral extent of sedimentary sequences and to evaluate how rapid environmental changes in both the lake basin and catchment area influence sedimentation patterns. From the beginning of the

[1] Institut F.A. Forel, route de Suisse 10, CH-1290 Versoix (Switzerland)
[2] Present address: Departement of surface water - EAWAG, CH-8600 Dübendorf (Switzerland)
[3] Present address: Geologisches Institut – ETH Zentrum, CH-8092 Zürich (Switzerland)
[4] Illinois State Geological Survey, 615 E. Peabody dr., Champaign, IL 61820, (USA)
Corresponding author: ira.baster@eawag.ch

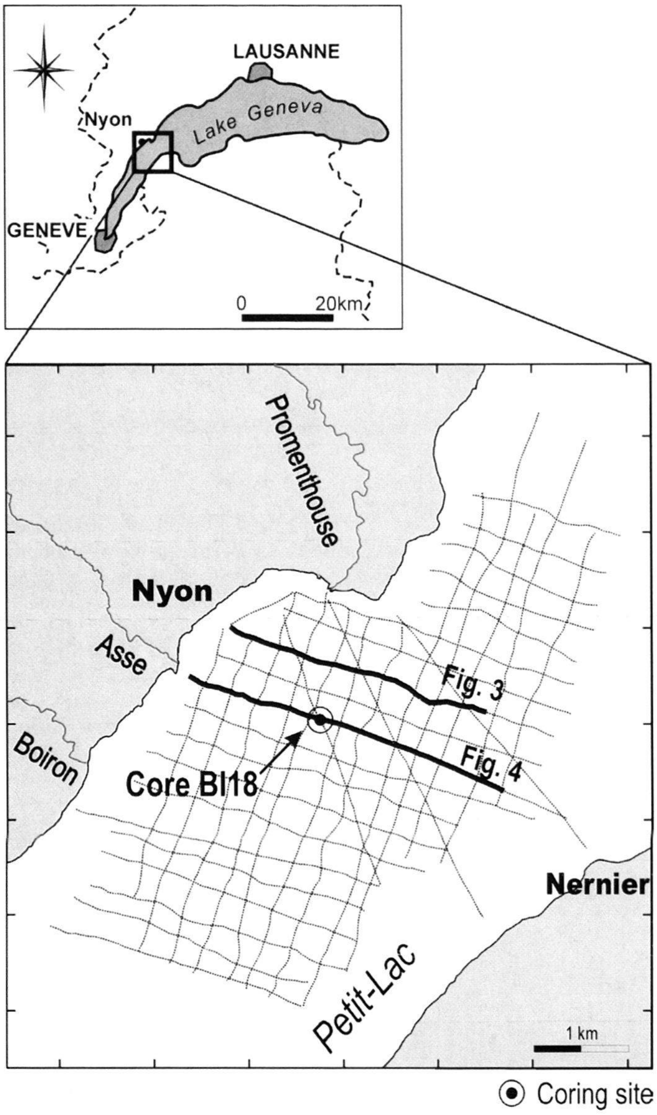

Fig. 1. Map of the study area with the location of Promenthouse, Asse and Boiron delta offshore of the town of Nyon, in western Lake Geneva: the enlarged section shows Echosounder survey lines and a coring site.

1970's, numerous perialpine lakes have been investigated with acoustic methods in order to study their basin and bedrock morphology and the sedimentary record of glacial and lacustrine processes. Based on seismic stratigraphy, Matter et al. (1971) and Finckh et al. (1984) postulated similar sedimentary histories for most perialpine lake basins.

In Lake Geneva, acoustic mapping was carried out on the Rhône delta by Houbolt & Jonker (1968) and Loizeau (1991); the basin infill has been investigated by Vernet & Horn (1971) and Vernet et al. (1974). A high resolution seismic survey in the Petit-Lac and Geneva Bay combined with geotechnical drilling, provided a detailed record of Pleistocene and Holocene sedimentary units (Moscariello 1996, Moscariello et al. 1998). These are, from base (top of the bedrock) to the top: (1) Glacio-lacustrine gravel, sand and mud; (2) glacial till; (3) esker deposits and proglacial deposits; (4) glacio-lacustrine fine sediments and (5) Holocene lacustrine deposits. For the first time stages of glacial retreat have been formally recognised in the City of Geneva, and in upstream locations near Coppet and Nyon (Moscariello et al. 1998). More recently, the Late-glacial and Holocene sedimentary sequences has been investigated in a part of the lake current-dominated Versoix transect by Girardclos (2001) and Girardclos et al. (2003).

The present research has been carried out on a small delta formed by the Promenthouse, Asse and Boiron rivers flowing into western Lake Geneva close to the town of Nyon (Fig. 1). Two different seismic methods, a 12 kHz echosounder subbottom profiler and a new source producing a frequency band of 2-3 kHz named "Impactor", have been applied in order to study the sedimentary features of the area from the time of glacier retreat and to investigate their possible link to recent climatic changes (Baster 2002). A closely spaced seismic survey was carried out to reconstruct the 3D geometry of sedimentary bodies and targeted sedimentary cores were used for calibration and dating of the main seismic reflectors.

This paper summarizes the seismic results in order to: (i) identify and describe seismic-facies within the slope and the central part of the lake basin; (ii) to determine the geometry and extension of individual seismo-stratigraphic units and (iii) to give a pseudo 3D architectural reconstruction of glaciolacustrine and deltaic units.

2.- Data acquisition and processing

The echosounder survey covers an area of 17.1 km^2 and is located in the eastern part of the Petit Lac, offshore the town of Nyon (Fig. 1). The survey was conducted aboard the Licorne, a 12 m long aluminium-hull research vessel. With a boat speed of up to 5 km/h, a total length of 110 km of seismic profiles was acquired with a Bathy-1000 echosounder (ODEC). The survey followed a regular grid with a spacing of 300 m (Fig. 1B). The acquisition parameters are summarized in Table 1.

Table 1. Acquisition parameters for echosounder survey.

Echosounder	Bathy-1000 ODEC
Source / receiver	Bathy-1000
Source to receiver length	0 m
Source / receiver depth	1.4 m
Echosounder source center frequency	12 kHz
Measured frequency range of the output data	350-8000 Hz
Transmission pulse rate	4Hz
Sampling interval	16.666 KHz
Recorder	Bathy-1000 ODEC

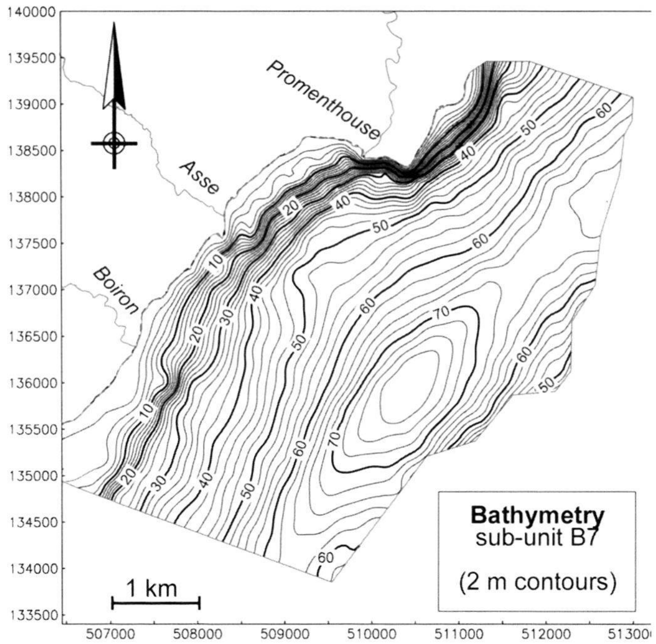

Fig. 2. Detailed bathymetric map of the study area with 2 m contour lines (Swiss coordinates).

The output signal of the receiver is processed and an average peak signal value is calculated using a sliding integration window with a length that is twice the transmitted pulse length (500 ms). The average peak value is then used to normalize the detected signal by applying an automatic gain control (AGC), which is proportional to the maximum signal level (AGC =max value/average peak value). Due to the dynamic normalization of each processed trace, primary amplitude information is lost.

From the amplitude spectra a dominant frequency of 1.5 kHz was calculated allowing a vertical resolution of 25 cm (Baster 2002, Fig. 3.7). Depth of acoustic penetration depends on gas content and grain size and generally varies between 2-6 m for the sandy coastal region and 30 m for the muddy lacustrine plain.

Navigation of the survey track-lines was achieved using 8-channel (Garmin 45) and 12-channel (Garmin 135) GPS systems. These positioning measurements were improved by integrating a real-time DGPS (Differential Global Positioning System) with accuracies of 5-10 m and 2-5 m, respectively.

Seismic data processing was basic and consisted in the positioning of traces stored in the data header using standard software. A conversion was made from the World Geodetic System (WGS 84) to the Swiss relative coordinates (CH1903). Since Bathy-1000 seismic traces are provided in the form of a wave envelope, only an automatic gain control over a 10 ms window and a coherency filter mixing 3 traces at 25%, 50%, 25% have been applied to the data. Several "in-house" data format conversion programs were necessary in order to achieve a final SEG-Y format so that they could be imported into the interpretation software (Seisvision Tm) for tracking horizons in three dimensions.

Each major reflection exported into an ASCII file was converted from time values into depths: water depth was calculated assuming a water column velocity of 1433 m/s as obtained for a temperature of 6.5 °C from the sound speed equation reported in Del Grosso and Mader (1972). According to MSCL measurements of P-Wave velocity on Kullenberg cores average velocities of 1455 m/s and 1550 m/s were used for time/depth conversion for Holocene and Late-glacial sequences, respectively. The seismic survey grid was dense enough to allow the construction of a detailed bathymetric map with a 2 m contours line, as well as contour maps of sequence A and B subunits.

The seismic results are combined and correlated with sediment core analyses in order to calibrate seismic sequences and to reconstruct the evolution of the investigated area from Late-glacial to Present. A well-dated core retrieved in the central part of the delta (Baster 2001; 2002) allowed age determination of reflections A5 to B6. All presented age data are uncalibrated radiocarbon ages.

Finally, a series of 3-D models were realized with Earthvision software (Mayoraz 1993a; 1993b). The seismo-stratigraphic analyses was used to create a 3-D volumetric structure representing the different layers overlapping, slumped areas and gas blanking.

3.- Seismic stratigraphy

Based on reflections characteristics and terminations (Baster 2002), the entire sedimentary infill is subdivided into 6 main depositional sequences. In this paper we focus on the uppermost 2 sequences (Late-glacial and Holocene), in which several sequences have been recognized in order to study the areal extent and evolution of the lake delta.

The underlying glacial units and the Molasse bedrock have been detected in a seismic line recorded by using the lower frequency source (Impactor) which allows a better penetration into the sedimentary subsurface. The lateral correlation of selected horizons throughout the seismic grid provides a three-dimensional framework of seismic units representing the depositional sequences, which are characterized by distinct geometries. Seismic reflection terminations and seismic facies are considered as result of stratal patterns and used for recognition and correlation of depositional sequences, interpretation of depositional environment, and estimation of lithofacies

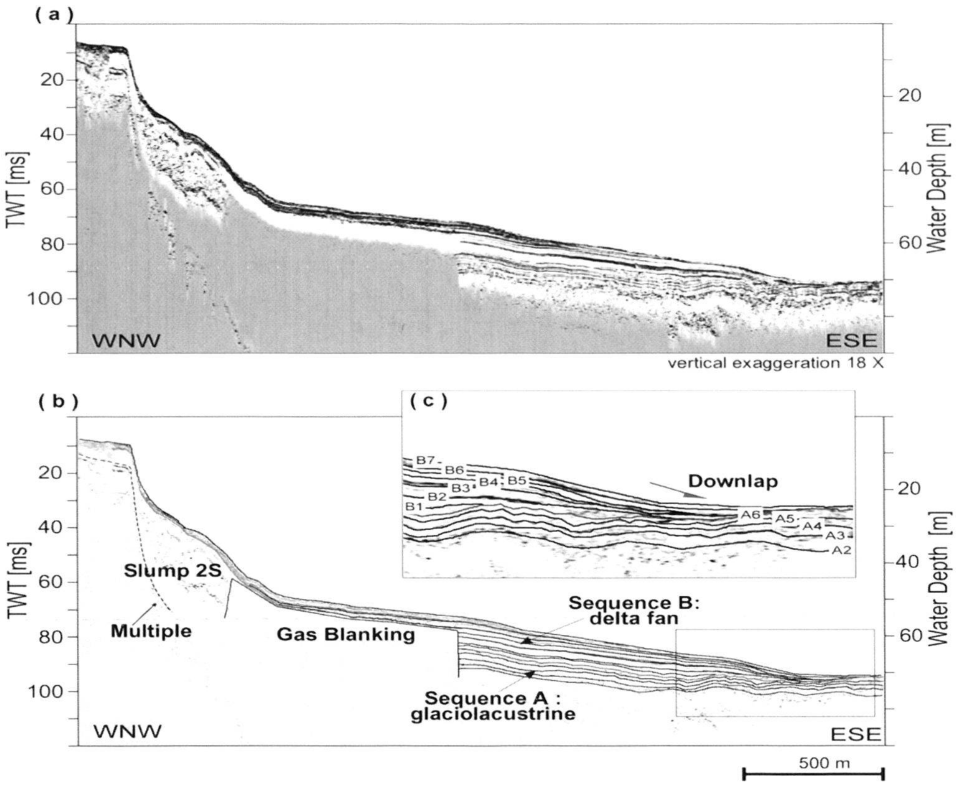

Fig. 3. (a) uninterpreted, (b) interpreted echosounder profile IB06. Enlarged window shows reflections downlapping on glaciolacustrine sequences (c). Refer to Fig. 1 for location.

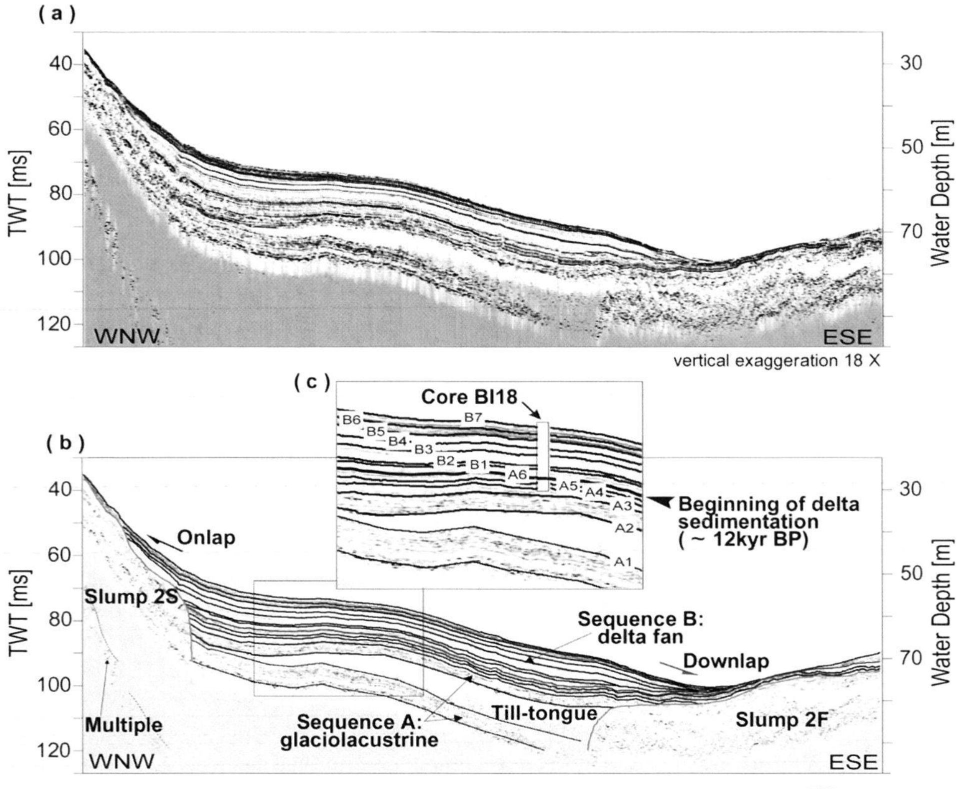

Fig. 4. (a) uninterpreted, (b) interpreted echosounder profile IB05 with enlarged window showing BI18 coring site (c). As indicated by downlap termination on glacio-lacustrine sequences, the delta sedimentation begun at around 12 kyr BP. Ages are obtained from the core BI18 (Fig. 5). Refer to Fig. 1 for location.

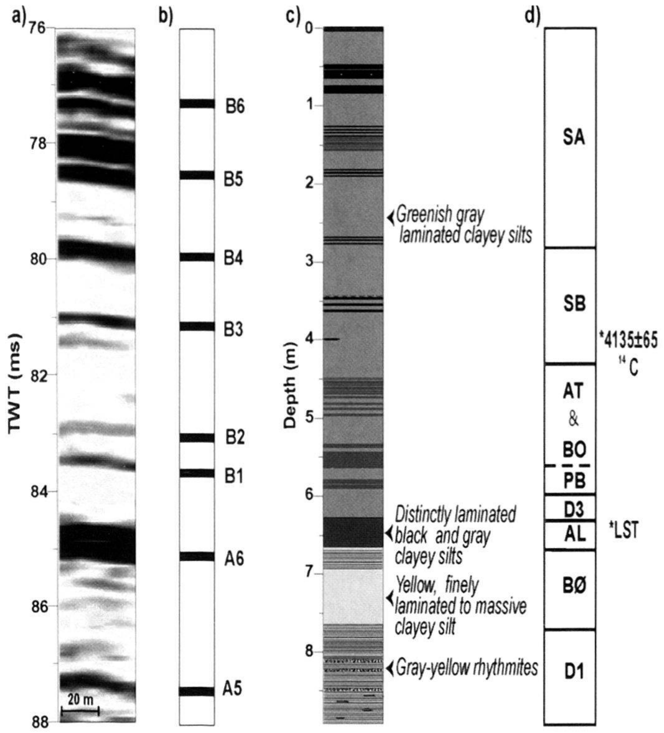

Fig. 5. Comparison of seismic-stratigraphy and lithological record: a) original echosounder record; b) interpretation of seismic sequence; c) lithological description of core BI18; d) sediment ages obtained by palynology, magnetic declination and inclination curves, radiocarbon dating and Laacher See tephra layer (Baster, 2001 and 2002). Acronyms explanation: D1 = Oldest Dryas; BØ = Bølling; AL = Allerød; D3 = Younger Dryas; PB = Preboreal; BO = Boreal; AT = Atlantic; SB = Suboreal and SA = Subatlantic, LST= Laacher see tephra (Baster, 2001 and 2002).

(Mitchum et al. 1977). Furthermore, using borehole data these units are interpreted within a chronostratigraphic framework using sediment core analysis.

Following the same acquisition methods and data processing, similar investigations were conducted by Girardclos (2001) in the Hauts Monts area. A long echosounder profile has been recorded between the two investigated areas along the central axis of the lake in order to compare seismic facies and sequence thickness so that a correlation is proposed for sequence A (Baster 2002, Tab. 3.7).

The bathymetric map in Fig. 2 shows a maximum depth of 77 m in the central part of the Petit Lac. An average inclination of 2.5°-3° characterizes the slope area, with a maximum value of 6° close to the shore line, gently decreasing towards the basin plain. Three small topographic lobes are observed near the mouth of Promenthouse, Asse and Boiron rivers.

Two seismic profiles (Figs. 3, 4) show the identified seismic-stratigraphic units in the central survey area close to Nyon. Fig. 3 shows a 2.36 km seismic profile (IB06) in a WNW-ESE direction at 700 m south of the mouth of the Promenthouse river. A vertical exaggeration of 18 x is applied in order to better identify all the seismic stratigraphic units. A maximum vertical penetration of 20 m was reached with the echosounder along this profile.

In the central area of the basin sequence A subunits are represented by semi-continuous parallel reflections becoming wavy-parallel at the eastern end of the profile. Reflection amplitude varies from medium to high whereas frequencies are moderate. Towards the west, these sequences are overlain by a series of sequences characterized by low-angle lakeward-dipping foresets that downlap on the top of sequence A (Fig. 3). This dipping units are characterized by variable seismic facies ranging from high reflective/continuous to low reflective/discontinuous. A zone with no seismic penetration occurs in the subsurface of lower slope; the upper boundary of this zone at approximately 5 ms subsurface depth is characterized by high reflective and coherent reflections. A succession of areas with chaotic facies is observed in the subsurface of the upper slope at the western end of the profile. Fig. 4 shows a seismic profile (IB05) located 300 m south of profile IB06 with its western end near the mouth of Asse river in front of the Nyon harbour. Maximum vertical penetration depth along this section is 25 m. This profile contains most of the features observed on the previously discussed section (Fig. 3). In addition, a reflection-free transparent unit interbedded within sequence A forms a wedge-shaped body thickening towards the east (Fig. 4).

4.- Discussion

Sequence A: glaciolacustrine

Glaciolacustrine sequences are characterized by a tabular, flat-lying geometry with maximum thicknesses of 15-20 m. Typically, the lower part of these sequences shows low reflectivity, discontinuous reflections that pass upwards into increasingly higher reflectivity and stratified facies. The gradual increase in stratification towards the top indicates a better sorting of sediment and an associated low-energy environment (Fig. 5). This part of the sequence corresponds to ice-distal glaciolacustrine sand and silt deposited by density currents from a glacial point source (Ashley 1975; Benn & Evans 1998).

In figure 4 a wedge-shaped body opening towards the centre of the lake is observed: this reflection-free transparent facies interbedded in glaciolacustrine sequences is interpreted as a glacier derived sediment feature, called "till tongue" (King et al. 1991; Josenhans 1997), due to the short glacial stop and advance at Nyon previously described by Moscariello et al. (1998). The deposition of upper glaciolacustrine sequence (e.g. A) is interpreted to be synchronous to the retreating of the glacier in the eastern part of Lake Geneva.

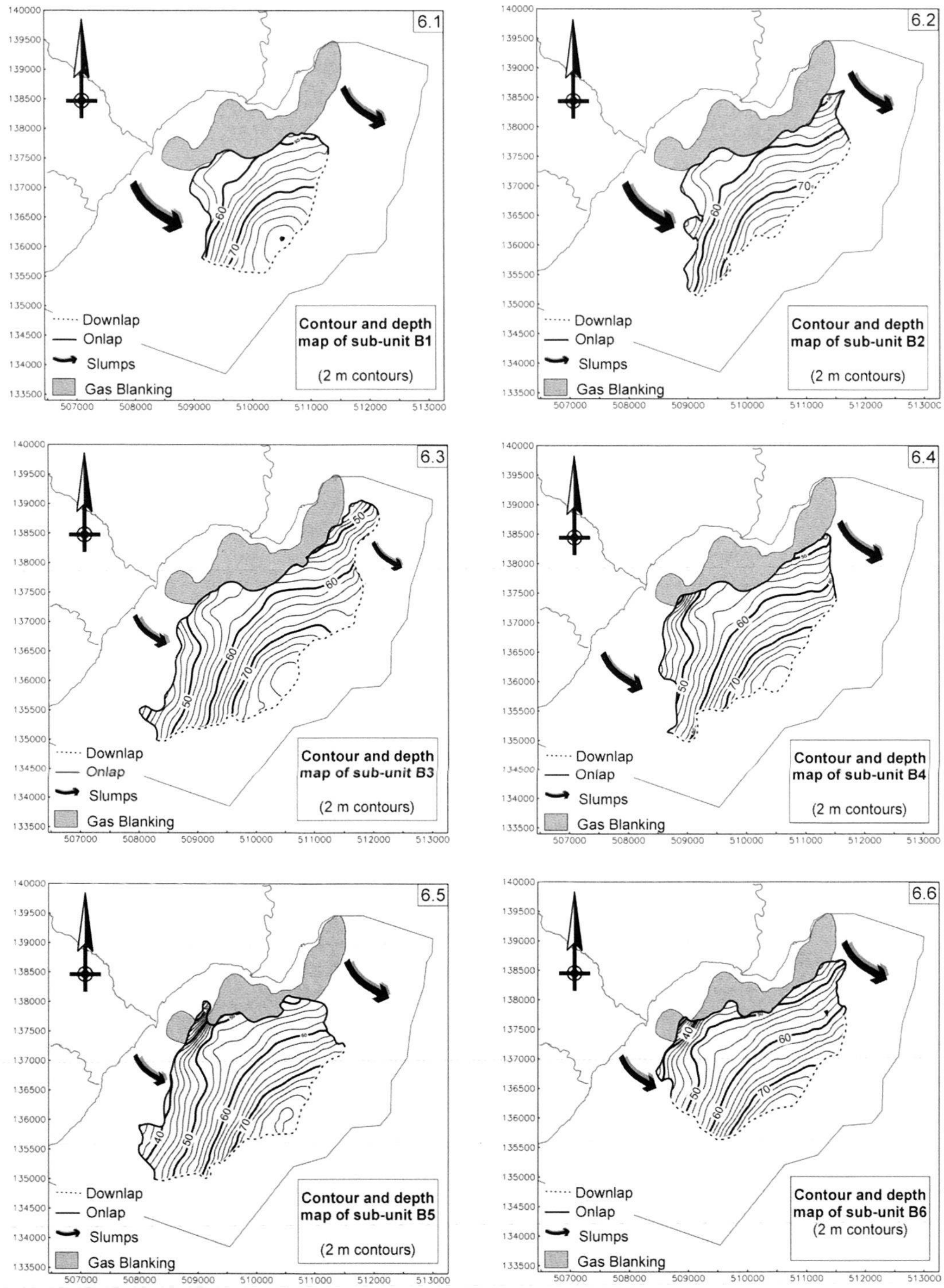

Fig. 6. Contour and depth maps of sequence B showing the paleobathymetry and distribution of six different delta lobes (sub-units B1 to B6). Slumps 1S (north) and 2S (south) are indicated by arrows. For seismic-units ages see Fig. 5 and 7.

Sequence B: delta fan

The uppermost sequence (e.g. B) corresponds to a delta depositional environment and is characterized by well defined low angle lakeward-dipping reflections originating from two depositional centers and downlapping in the central basin. This fan–shaped feature corresponds to the delta of the Promenthouse and Asse rivers. Maximum sediment thickness is 8-10 m in the prodelta area. A detailed seismo-stratigraphic interpretation led to a subdivision of this unit into seven sub-units, characterized by different geometries and lateral extent corresponding to individual delta lobes (Figs. 6 and 7). Deltaic units are limited in the western sector by slumps that originated from the northwestern slope of the lake basin and are masked by gas blanking towards the north, whereas they downlap to the southeast in the central basin.

Slumps

The slope sediments of both sequences (A, B) are characterized by medium to high-reflectivity chaotic reflections prograding below Holocene and Late-glacial sequences in the central basin. This seismic facies occurs in large channels with steep margins and is interpreted as slumped sediment mass originating from unstable sediment accumulations on the lake slopes. Four different slumps have been recognized in the Nyon region (Figs. 3, 4 and 7):

Slump 1S in the northern part of the investigated area originated from the northwestern slope, covering 2.9 km^2.
Slump 2S in the western part of the investigated area originated from the northwestern slope, covering 3.9 km^2.
Slump 1F in the eastern part originated from the southeastern slope, covering 1.9 km^2.

Slump 2F in the southern part of the investigated area originated from the southeastern slope, covering 0.2 km^2.
Gravity-flows and slumps have been documented in several locations and recognized as important processes of sediment transfer and deposition in many lacustrine and marine environments (e.g. Benn and Evans 1998). As for subaerial environments, sediment on subaqueous slopes can fail along internal shear planes and undergo downslope transport as slumps or slides. Submarine gravity gliding is a common process on delta slopes and can occur on extremely low angle slopes (<1°) (Mandl 1981; Prior and Coleman 1984). Slumping and creeping have been also observed on the upper slope of several deltas in Swiss lakes as recently reported in Adams et al. (2001) and Schnellman et al. (2001). Several concave-upward shear surfaces and shear planes were observed in the Asse prodelta area (slump 2S) using lower frequency sources (Baster 2002) whereas gas blanking prevented acoustic penetration at the high-frequency echosounder signal in the prodelta area of the Promenthouse. We can assume that slope instabilities has been developed from the time of ice-glacier retreat to present times. Sedimentary loading in the prodelta area, slope instability from the time of ice-glaciers retreat and low lake levels appear to be consistent with the features observed in the study area. However, the presence of earthquake-induced slumps cannot be excluded.

Gas

A reflection free, transparent area of 2.2 km^2 was identified at the front of the Promenthouse and Asse river mouths (Figs. 5, 6 and 7). This area is surrounded by a zone with normal penetration and resolution and is limited to the top by a high-intensity reflection. We interpreted this facies as being caused by the presence of gas originating from the degradation of river-derived organic material. This phenomenon, know as "gas blanking" (Fader 1997), is well known in lacustrine environments and has for instance also been described in Lake Annecy (Van Rensbergen et al. 1998) and in Lake du Bourget (Chapron 1999). In western Lake Geneva, other acoustic blanking areas have been recognized near Versoix (Girardclos 2001).

5.- 3-D model

Our seismic data allow us to reconstruct the 3-D geometry, thickness and architecture of glaciolacustrine and deltaic seismic sequences. The latter provides an effective method for reconstructing paleobathymetric surfaces and defining depositional morphologies of glacio-lacustrine and lacustrine sequences.

Core BI18 dated combining pollen stratigraphy, magnetic declination and inclination curves, ^{137}Cs and ^{210}Pb activity measurements, Laacher see tephra layer position and one AMS - ^{14}C (Baster 2002) was used to date seismic sequences A5 to B6 (Fig. 5). The top of Late-glacial facies consists of couplets of gray yellow silt-clay layers of aeolian origin. At the Late-glacial Holocene transition the source of sediment gradually changed from the Rhône glacier to local alluvial streams and the delta began to form in the lacustrine plain. Sedimentation in the prodelta area results mainly of deposition from suspension (Baster 1999).

From contour maps of the six identified deltaic lobes (Fig. 6), we observe that the delta is characterized by intervals of different activity most probably due to changes in climatic conditions and consequently changes in sediment input into the lake. The delta increased its influence area from 4.0 to 6.4 km^2 during the deposition of sub-units B1 to B3 (Figs. 6.1, 6.2 and 6.3). A subsequent opposite trend is shown in contour map of sub-unit B4 (Fig. 6.4) with a dramatic size decrease to 5.0 km^2 followed by a new expansion to 5.9 km^2 (sub-unit B5, Fig. 6.5). As observed in seismic profiles (Figs. 3 and 4), these sequences are limited in the western sector by slumps originating from the northeastern slope and are hidden toward the north by gas blanking, whereas they downlap in the central basin. The areal extension in a northeast direction can be explained by assuming that the mouth of the meandering Promenthouse river moved to the north during the deposition of sequences B2 to B3 and B6 (Figs. 6.2; 6.3 and 6.6).

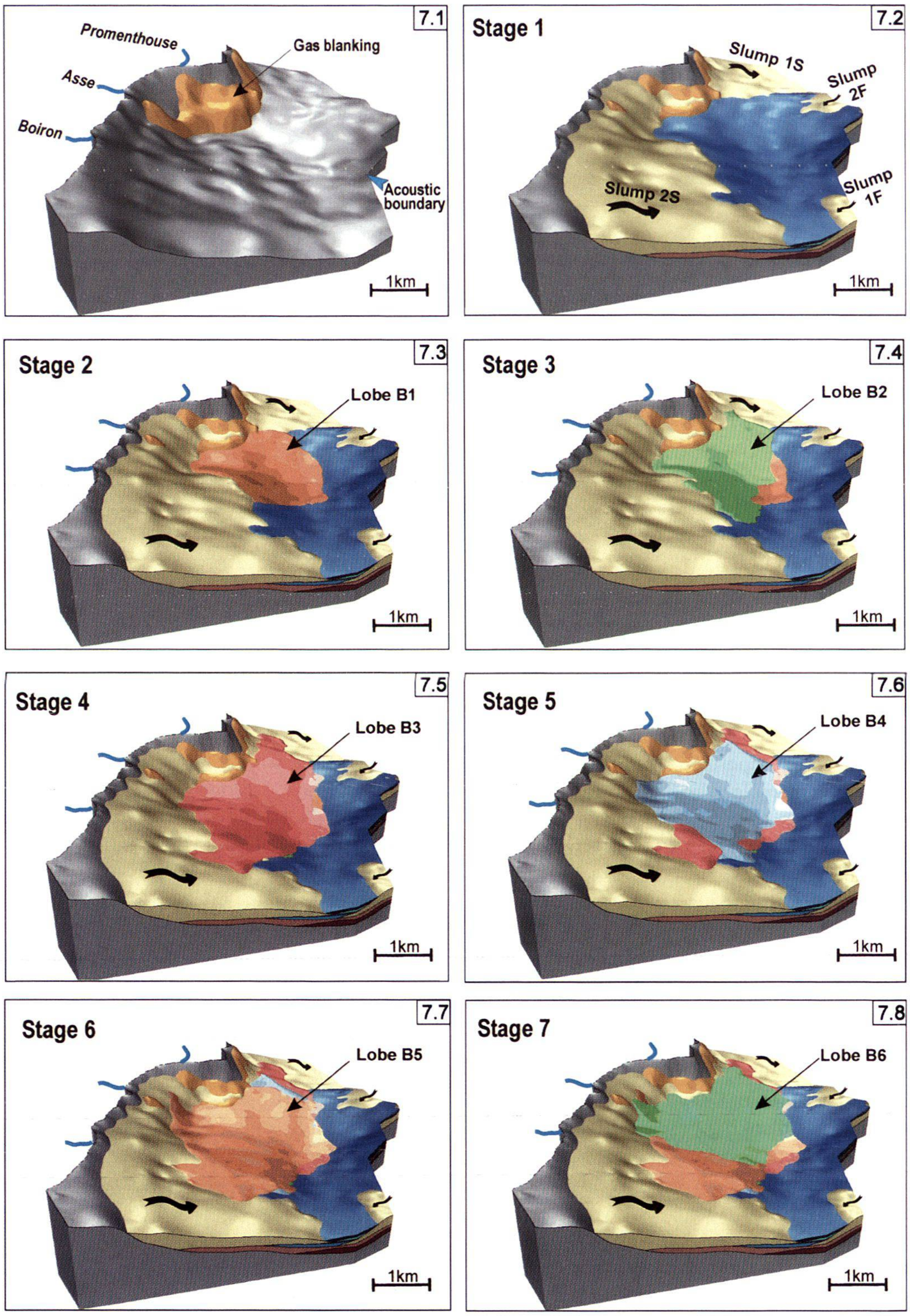

Fig. 7. 3-D views realized from seismo-stratigraphic units and representing the seven different steps of delta evolution from Bolling to Younger Subatlantic (12-1 kyr BP). The gas blanking area at the Promenthouse and Asse river mouths is represented in the first 3-D view. See text for detailed description of history.

In Fig. 7, the delta evolution is summarized in seven different stages with the help of a series of 3-D views (Earth vision software, Mayoraz 1993a; 1993b). The gas blanking zone is reported in gold yellow in the first 3D model whereas the gray surface corresponds to the penetration boundary of the echosounder data (Fig. 7.1):

Stage 1: Glaciolacustrine sequences are deposited in the basin plain until the end of the Bölling chronozone, while the glacier was retreating in the eastern part of Lake Geneva (Fig. 7.2).

Stage 2: The delta formation begins at the end of the Bölling (~12 kyr BP) and a first delta lobe of 3.5 km^2 appears at the beginning of the Boreal (~9.2 kyr BP) (Fig. 7.3).

Stage 3: Until the Boreal-Atlantic transition (~8 kyr BP) the delta increases its activity with an areal extension towards north and south (4 km^2). The erosion or non-deposition at the eastern limit of this second lobe documents the presence of bottom currents. Strong erosive bottom currents, probably due to a lowering of lake level, are documented during the same time interval at the base of the Hauts-Monts Promontory by Girardclos (2001) (Fig. 7.4).

Stage 4: During the Atlantic (~ 8 to 4.2 kyr BP) the river inputs increases and the delta extends its influence area to 6.4 km^2. A weakening of bottom current action is recorded in the deeper part of the basin. (Fig. 7.5)

Stage 5: An opposite trend to the previous stage is observed during the Sub-Boreal (~4.2 to 2.8 kyr BP) with a decrease of sediment surface to 5 km^2 and increased current activity.

Stage 6: During the Older Subatlantic (~2.6 to 1.7 kyr BP) the delta evolution consists in a new expansion of 5.9 km^2 towards the south (Fig. 7.6).

Stage 7: The delta deposition moves towards the northern part of the investigated area in the Younger Subatlantic (~1 kyr BP). This shift is synchronous with the shift of the Versoix delta towards the north (Girardclos 2001; Ulmann 2002) and most likely associated with a change in wind regimes (Fig. 7.7).

6.- Conclusion

The high-resolution seismic investigations carried out in western Lake Geneva offer the opportunity to determine the geometry and extent of the Promenthouse delta as well as to quantify the involved volume of sediments. For the first time, six different delta lobes downlapping on Late-glacial sediments were recognized in the lower slope and basin plain. Lobe progradation depends not only on river input but is also influenced by strong erosive bottom currents active in the deeper parts of the basin. The delta slope is highly unstable and characterized by the development of slumps and debris flows occurring during different intervals from the time of glacier retreat to the present. Moreover, an important gas blanking area, due to degradation of organic-rich sediment, was observed in front of the mouths of the Promenthouse and Asse rivers.

Combining seismic-stratigraphy with sediment core data it was possible to reconstruct palaeoclimatic conditions occurring during Late-glacial and Holocene periods. After glacier retreat the source of sediment gradually changed from the Rhône glacier to local alluvial streams and delta fan began to form in the lake. The delta formation started at the end of the Bölling chronozone (ca. 12 kyr BP). A first deltaic lobe appeared at the beginning of the Boreal and an enlargement of the delta is observed during the Boreal and the Atlantic. Conversely, an opposite trend is observed during the Sub-Boreal when the delta surface is reduced. A new enlargement towards the south followed by a shift towards the north is recorded during the Sub-Atlantic. Bottom currents activity increases during Boreal and Sub-Boreal chronozones.

The results of this study highlight the use of high resolution seismic profiles in combination with sediment cores to, 1) model delta development and, 2) quantify sediment deposition and erosion in lacustrine settings. Using the lobes shape, we have quantified a total volume of approximately $45 \cdot 10^6$ m^3 of sediment deposited by density currents to the delta. This volume is, however, underestimated because the presence of slumps and gas blanking on the delta slope prevents a more accurate estimation.

Acknowledgements

The authors wish to thanks E.W. Adams and F. Anselmetti for reviewing the first version of this manuscript, and D. Ariztegui for stimulating comments. We are grateful to A.M. Rachoud Schneider for pollen analyses, R. Mayoraz for the realization of the 3D model, and I. Hadjas for AMS-^{14}C dating. This study was supported by the Swiss National Foundation project n° 20-52432.97.

REFERENCES:

ADAMS, E.W., SCHLAGER, W. & ANSELMETTI, F.S. 2001: Morphology and curvature of delta slopes in Swiss lakes: lessons for the interpretation of clinoforms in seismic data. Sedimentology 48, 661-679.

ASHLEY, G.M., 1975: Rhythmic sedimentation in glacial Lake Hitchcock, Massachussetts-Connecticut. In: Glaciofluvial and glaciolacustrine sedimentation (Ed. by JOPLING, A.V.M. & MCDONALD B.C) Tulsa, Usa, Spec. Publ. Soc. Econ. Paleont. Mineral. 23, 304-320.

BASTER, I. & GIRARDCLOS, S. 1999: Dynamique lacustre et environnemts sédimentaire du Petit-Lac (Léman) depuis -15000 ans à aujourd'hui. In: Musée du Léman ed., Décourvrir le Léman 100 ans après François-Alphonse Forel (Ed. by SLATKINE) Genève, 451-456.

BASTER, I. 2001: Geomagnetic secular variation from Late Glacial and Holocene sediments of western Lake Geneva (Switzerland). In: IAS 2001: Davos (Switzerland), International Association of sedimentologists (Ed. by WORTMANN, U.G., & FUNK, H.), 151.

- 2002: Holocene lacustrine delta in western Lake Geneva (Switzerland) and its palaeoenvironmental implications: seismic and sedimentological approach. Terre & Environnement, 38, Institut F-A. Forel, Univ. de Genève, 159 pp.

BENN, D.I. & EVANS, D.J.A. 1998: Glaciers and glaciations. ARNOLD, 734 pp.

CHAPRON, E. 1999: Contrôles climatique et sismo-tectonique de la sédimentation lacustre dans l'avant-pays alpin (Lac du Bourget) durant le quaternaire récent. Phd thesis, Univ. Joseph Fourier, Grenoble, 261 pp.

DEL GROSSO, V.A. & MADER, C.W. 1972: Speed of sound in pure water: J. of Acoustical Soc. America 52, 1442-1446.

FADER, G.B.J. 1997: The effects of shallow gas on seismic reflection profiles: In Glacial continental margins: an atlas of acoustic images (Ed. by DAVIES, T.W., BELL, T., COOPER, A.K., JOSENHANS, H., POLYAK, L., SOLHEIN, A., STOCKER, M.S., & STRAVERS, J.A.) Chapman and Hall, 29-30.

FINCK, P., KELTS, K. & LAMBERT, A. 1984: Seismic stratigraphy and bedrock forms in perialpine lakes. Geol. Soc. America Bull. 95, 1118-1128.

GIRARDCLOS, S. 2001: Sismostratigraphie et structure sédimentaire en 3D d'un bassin lacustre du retrait glaciaire à nos jours (Lac Léman, Suisse), Terre & Environnement, 33, Institut F-A: Forel, Univ. de Genève, 182 pp.

GIRARDCLOS, S., BASTER, I., WILDI, W., PUGIN, A. & RACHOUD-SCHNEIDER, A.M. 2003: Bottom currents and wind-pattern changes as indicated by Late-glacial and Holocene sediments from western Lake Geneva (Switzerland). Eclog. geol. Helv., this volume.

HOUBOLT, J.J.H.C. & JONKER, J.B.M., 1968: Recent sediments in the eastern part of the lake of Geneva (Lac Léman): Geol. en Mijnb. 47, 131-148.

JOSENHANS, H. 1997: Water-Glacially overdeepened troughs and ice retreat "till tongue" deposits in queen charlotte sound, British Columbia, Canada. In: Glacial continental margins: an atlas of acoustic images (Ed. by DAVIES, T.W., BELL, T., COOPER, A.K., JOSENHANS, H., POLYAK, L., SOLHEIN, A., STOCKER, M.S., and STRAVERS, J.A.) Chapman and Hall, 40-41.

KING, L.H., ROKOENGEN, K., FADER, G.B.J. & GUNLEIKSRUD, T. 1991: Till-tongue stratigraphy: Geol. Soc. America Bull. 103, 637-659.

LOIZEAU, J.-L. 1991: La sédimentation récente dans le delta du Rhône, Léman: processus et évolution. PhD thesis, Univ. Genève, 209 pp.

MAYORAZ, R. 1993a: Modélisation et visualisation infographiques tridimensionelles de structures et propriétés géologiques. PhD thesis, Ecole Polytecnique Fédérale de Lausanne, Lausanne (Switzerland), 215 pp.

- 1993b: Three-dimensional modelling of complex geological structures: Geoscientist 3, 24.

MANDL, G.,1981: Gravitational gliding in deltas, In: Thrust and Nappe tectonics; International conference (Ed. by MCCLAY-K-R & PRICE, N-J:) Geol. Soc. of London Spec. Pub. 9, 41-51.

MATTER, A., SÜSSTRUNK, A.E., HINZ, K. & STURM, M. 1971: Ergebnisse reflexiosseismischer Untersuchungen im Thunersee. Eclogae geol. Helv. 64, 505-520.

MITCHUM, R.M., VAIL, P.R. & THOMPSON, S. 1977: Seismic stratigraphy and global changes of sea level, Part 2: the depositional sequence as a basic unit for stratigraphic analysis: AAPG Mem. 26, 53-62.

MOSCARIELLO, A. 1996: Quaternary geology of the Geneva Bay (Lake Geneva, Switzerland): Sedimentary record, Paleoenvironmental and Paleoclimatic Reconstruction since the last Glacial Cycle, Terre & Environnement, 4, Univ. de Genève, 230 pp.

MOSCARIELLO, A., PUGIN, A., WILDI, W., BECK, C., CHAPRON, E., DE BATIST, M., GIRARDCLOS, S., OCHS, S.I., RACHOUD-SCHNEIDER, A., SIGNER, C. & VAN CLAUWENBERGHE, T.V. 1998: Déglaciation würmienne dans des conditions lacustres à la terminaison occidentale du bassin lémanique (Suisse occidentale et France): Eclogae geol. Helv. 91, 185-201.

PRIOR, D.B.& COLEMAN, J.M. 1984: Submarine slope instability, In Slope instability (Ed. by BRUNSEN D. & PRIOR, D.B.), John Wiley & Sons, 419-455.

SCHNELLMANN, M., MONECKE, K., ANSELMETTI, F.S., AND MCKENZIE, J.A. 2001: Sedimentary architecture and distribution of lacustrine slump-deposits in Lake Lucerne: A paleoseismological tool: IAS Meeting, Abstracts, Davos.

SMITH, D.G. 1991: Lacustrine deltas: The Canadian Geographer 35, 311-316.

ULMANN, M., WILDI, W. & LEMMIN, U. 2003: Sediment distribution on a current dominated lake delta (Versoix – Delta, Lake Geneva, Switzerland), Eclogae geol. Helv. this volume

VAN RENSBERGEN, P., DE BATIST, M., BECK, C. & MANALT, F. 1998: High-resolution seismic stratigraphy of late Quaternary fill of Lake Annecy (Northwestern Alps): evolution from glacial to interglacial sedimentary processes. Sediment. Geol. 117, 71-96.

VERNET, J.-P. & HORN, R. 1971: Etude sédimentologique et structurale de la partie occidentale du Lac Léman par la méthode sismique à réflexion continue: Eclogae geol. Helv. 64, 291-317.

VERNET, J.-P., HORN, R., BADOUX, H. & SCOLARI, G. 1974, Etude structurale du Léman par sismique réflexion continue: Eclogae geol. Helv. 67, 515-529.

Communication submitted October 17 - 18, 2001
Manuscript accepted November 25, 2002