*Journal of Paleolimnology* **25:** 149–161, 2001.

# The Late Quaternary sedimentary infill of Lake Annecy (northwestern Alps): an overview from two seismic-reflection surveys*

Christian Beck[1], Pieter Van Rensbergen[2]**, Marc De Batist[2], Fernand Berthier[3], Serge Lallier[3] & Frédéric Manalt[1]
[1]*Laboratoire de Géodynamique des Chaînes Alpines, U.M.R. C.N.R.S. 5025, Université de Savoie, 73 376 Le Bourget-du-Lac Cedex, France (E-mail: beck@univ-savoie.fr)*
[2]*Renard Centre of Marine Geology, University of Ghent, Krijgslaan 281 S8, B-9000 Gent, Belgium*
***Present address: Department of Petroleum Geosciences, Universiti Brunei Darussalam, Bandar Seri Begawan 2028, Darussalam, Brunei*
[3]*B.R.G.M., 3, rue Dupanloup, 74 000 Annecy, France*
[4]*B.R.G.M., S.G. N., B.P. 6009, 45 018 Orléans Cedex, France*

Received 21 June 1999; accepted 31 June 2000

*Key words*: deglaciation, Holocene, Alps, lacustrine sedimentation, seismic stratigraphy, slumping

## Abstract

The sedimentary fill of Lake Annecy (northwestern Alps) – related to the last glacial/post-glacial episode – was investigated through high resolution (sparker) and very high resolution (2.5 kHz) seismic-reflection surveys. A seismostratigraphic approach led to subdivision of a 150 m-thick pile (maximum thickness in axial part) into five units. Basal units (1 and 2) represent an imbrication of subglacial and glacio-lacustrine deposits, close to the grounding line of the glaciers' fronts (respectively at the northern and southern terminations of the lake). The first acoustically well-stratified unit (3) developed during a fast retreat of the glaciers fronts far from the lake basin, and a progradational alluvial regime, with abundant underflows, in a lake larger than the present one. Unit 4 represents the progressive decrease of this clastic input mixed with the progressive development of *in situ* bio-induced production. As in many other alpine lakes, a topmost unit (5), relatively thin (about 8–10 m) and with a conspicuous drape configuration, is the signature of the Holocene interglacial climatic conditions with a sedimentation rate of about 1 mm/yr. On the lacustrine basin slopes, slumps and debris flow occurred mainly within Unit 3; they may be due to, either climate-induced high rate terrigenous sedimentation, or/and to a period of increased seismo-tectonic activity.

## Introduction

Among the different imprints of the last glaciation/deglaciation cycles, large lakes characterize the northwestern side of the Alps (Switzerland, Austria, eastern France) as well as the southeastern edge (northern Italy, southern Switzerland). Although they developed during the last (post-Würm) deglaciation, most of them filled depressions previously occupied by Riss glaciers and Riss-Würm interglacial palaeolakes. Consideration of the still *in situ* sedimentary infills of these lakes as paleoclimatic (and/or neotectonic) archives, led different research teams to explore them through a combination of geophysical imagery and sampling (coring and drilling). Different Swiss and Italian lakes have been surveyed using continuous seismic reflection or refraction profiling (Vernet & Horn, 1971; Finkh et al., 1984; Curzi et al., 1992). More recently, the two largest French lakes (Le Bourget and Annecy) were investigated through high resolution seismic reflection

---

*This is the third in a series of eleven papers published in this special issue dedicated to Lac d'Annecy, France. Drs. Jacques-Louis de Beaulieu and Joel Casanova were the guest editors of this issue.

(Van Rensbergen et al., 1995; Van Chapron et al., 1996; Rensbergen, 1996). The different stages of post-Würm sedimentation detected for lakes Le Bourget and Annecy could be compared to the successions previously published for several other alpine lakes (Hsü & Kelts, 1984; Lister, 1984; Niessen & Kelts, 1989; Curzi et al., 1992).

Two surveys were conducted on Lake Annecy (1990 and 1993) within the frame of two research projects: a Belgian-French cooperation program dedicated to different large alpine lakes with a seismostratigraphic and neotectonic purpose, and the CLIMASILAC project concerning the recent evolution of Lake Annecy and its watershed. The 1990 survey used a very high-resolution system coupled to bathymetric mapping, and was specifically dedicated to the choice of a drilling/coring site. The 1993 survey – with lower resolution and greater penetration – was conducted for a seismostratigraphic study of the complete infill. The present paper deals with the results and interpretations of these two surveys (which respective data are complementary), and also represents a framework for different articles of this issue.

## Geological setting and data acquisition

Between the northwestern edge of the Outer Alps and the Jura Mountains (Figure 1), Tertiary siliciclastic sedimentation developed in the so-called 'Molassic Basin' (Deville et al., 1994). This relatively depressed part of the alpine foreland was particularly affected by Rissian and Würmian glacial erosion and sedimentation (Monjuvent & Nicoud, 1988; Campy, 1992) and includes most of the Swiss and French lakes (Neuchâtel, Léman, Annecy, Le Bourget) in overdeepened areas. In the southern termination of the Molassic Basin (see detail on Figure 2), Lakes Léman, Le Bourget, and Annecy occupy slightly different positions with respect to their pre-Quaternary substratum: the first is on the Tertiary molasse, the second is between the two innnermost Jurassian anticlines, and the third crosscuts the frontal boundary of the Outer Alps, generally represented by a main thrust-fault of Mesozoic series over Tertiary siliciclastics.

The northwestern termination of Lake Annecy (and the city of Annecy) are very close to the (visible) extremity of the Vuache Fault (Figure 2). The latter represents an important structural feature at a regional scale: it played a major role during Neogene tectonics as a transfer strike slip fault (Philippe, 1994). The Vuache fault is considered still active on account of a recent 5.3 (Richter magnitude) earthquake (Thouvenot et al., 1998) and present-day displacements detected by geodetic surveys (Jouanne et al., 1994).

Lake Annecy, which may be considered as a small 'fjord-lake' (Van Rensbergen, 1996), is 13 km long and 2–3 km wide (Figure 3) and surrounded (SW and NE sides) by 1500 to almost 2500 m-high relief. It is commonly divided into the 'Grand Lac' and 'Petit Lac' parts, connected by a 'strait' between Saint-Jorioz and Talloires. The maximum depth in the 'Grand Lac' subbasin is 67 m, although this does not represent the deepest site; a deep (85 m) conical hole, generally considered as a submerged karstic feature, is located in the north-western part of the lake, close to the city of Annecy.

As a revision of the bathymetric map of Lake Annecy was planned by regional authorities in 1990, the survey provided logistical support for coupling with a very high frequency seismic reflection source (2.5 kHz). Only a part of the navigation grid is presented on Figure 3 as the surficial sediments locally appear to contain gas (methane) which inhibited acoustic penetration. Gas blanketing (strong absorbtion beneath the water-sediment interface and lack of reflection) occurred in the entire 'Petit Lac' and at the extremities of the 'Grand Lac'. This first survey penetrated deep to about 90 milliseconds two-ways-time (msec t.w.t.) below lake floor, with an approximative 0.3 m resolution.

In order to penetrate the pre-Quaternary sub-stratum in the entire 'Grand Lac', a high resolution survey using a broad band source was performed in 1993. The new set of profiles was shot with a comb-type sparker, Renard Centre of Marine Geology (R.C.M.G.)'s CENTIPEDE, (fired at 500 J), and recorded through a single channel streamer. Unfiltered data were recorded on DAT-tapes and subsequently digitized with an ELICS Delph 2 system; processing was performed in R.C.M.G., using PHOENIX VECTOR sotfware on a SUN Sparc station. This processing involved:

- spiking deconvolution;
- high-pass filter (lower boundary at 300 Hz) to reduce low-frequency noise in the seismic signal;
- a Butterworth filter (800–2500 Hz for the uppermost 250 msec; 300–2500 Hz for the remaining 350 msec);
- and automatic gain control (A.G.C.).

This survey penetrated 300–400 msec below the lake floor, with an approximate 0.8 m resolution. A few deep reflections could be obtained through the surficial gas

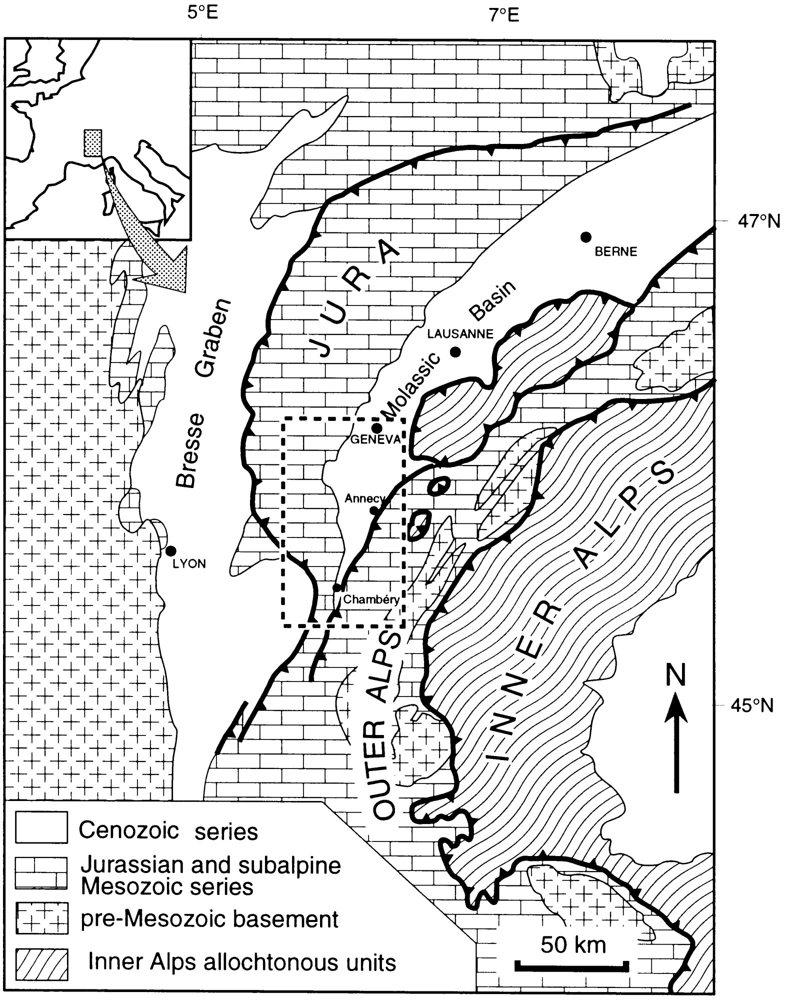

*Figure 1.* Geological and structural sketchmap of northwestern Alps.

between Talloires and Saint-Jorioz (Figure 3). Positioning of seismic tracks was done using a AXYLE radio-navigation system and onshore reference geodetic benchmarks; due to software problems, some of the tracks had to be re-positioned using cross points of profiles.

In terms of acoustic velocities, no measurement using refraction was done during our own survey; seismic-refraction data had been previously published by Finckh et al. (1984) and Curzi et al. (1992) for alpine lakes (Table 1). We used the values obtained by these authors, and especially the ones calculated by Finckh et al. (1984) for Lakes Le Bourget and Annecy.

## Acoustic facies and seismostratigraphic subdivisions

Due to the high density and the good quality of data acquired for the 'Grand Lac' part, the seismostratigraphic investigations were conducted on the latter (Van Rensbergen et al., 1995). The R.C.M.G. sparker survey was dedicated to this approach which was developed in parallel (same tools and processing) with the study of Lake Le Bourget (Chapron et al., 1996; Van Rensbergen, 1996) and, more recently, Geneva Lake (Moscariello, 1996; Wildi et al., 1997; Moscariello et al., 1998).

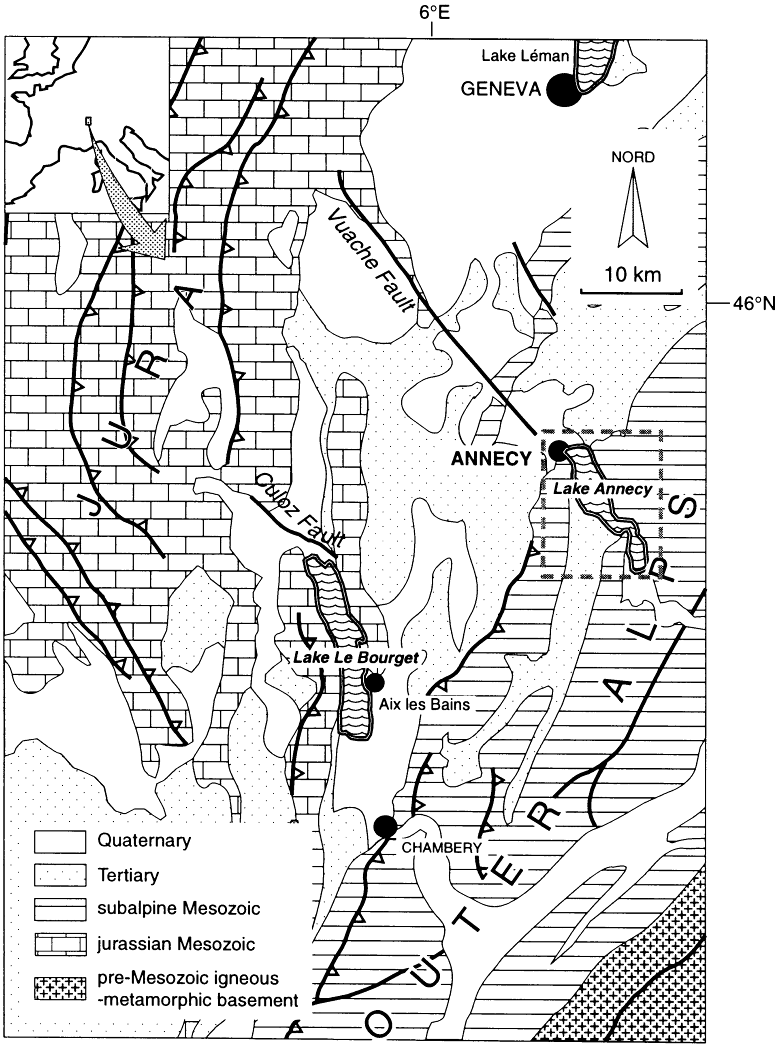

*Figure 2*. Geological and structural setting of Lakes Annecy and Le Bourget. Lake Le Bourget lies between two jurassian anticlines, partly on the southern termination of the Savoie Molassic Basin (Tertiary siliciclastics). Lake Annecy developed upon the outer boundary of the subalpine realm, at the south-eastern termination of the (still active) Vuache Fault.

### *General statement*

The whole infill appears elongated and trending parallel to the WSW and ENE edges with a 180 msec t.w.t. thickness in the axial part , representing about 150 m, using a 1.65 km/sec mean velocity. In front of Veyrier-du-Lac (Figure 3), the infill cross-section is roughly symmetrical; its eastern half is presented on Figure 4 which shows a framed portion that is interpreted on Figure 5. The infill thickness decreases towards the basin edges (ENE and WSS) either progressively or by means of two of three steps (Figure 4) related to the morphology of the underlying erosion surface and to the top of irregularly-shaped sedimentary bodies (SMU 1 on Figure 5).

According to surface geological data around the lake (Charollais et al., 1986; Doudoux et al., 1992) the basin substratum may consist of:

- Mesozoic limestones and marls;
- Tertiary siliciclastics (sandtones and marls) regionally called ‘molasse’ (Deville et al., 1994);
- late Quaternary Riss-Würm interglacial deposits: lacustrine varved silts and clays.

The Tertiary siliciclastics represent the major part of the acoustic substratum, indicated by high-amplitude

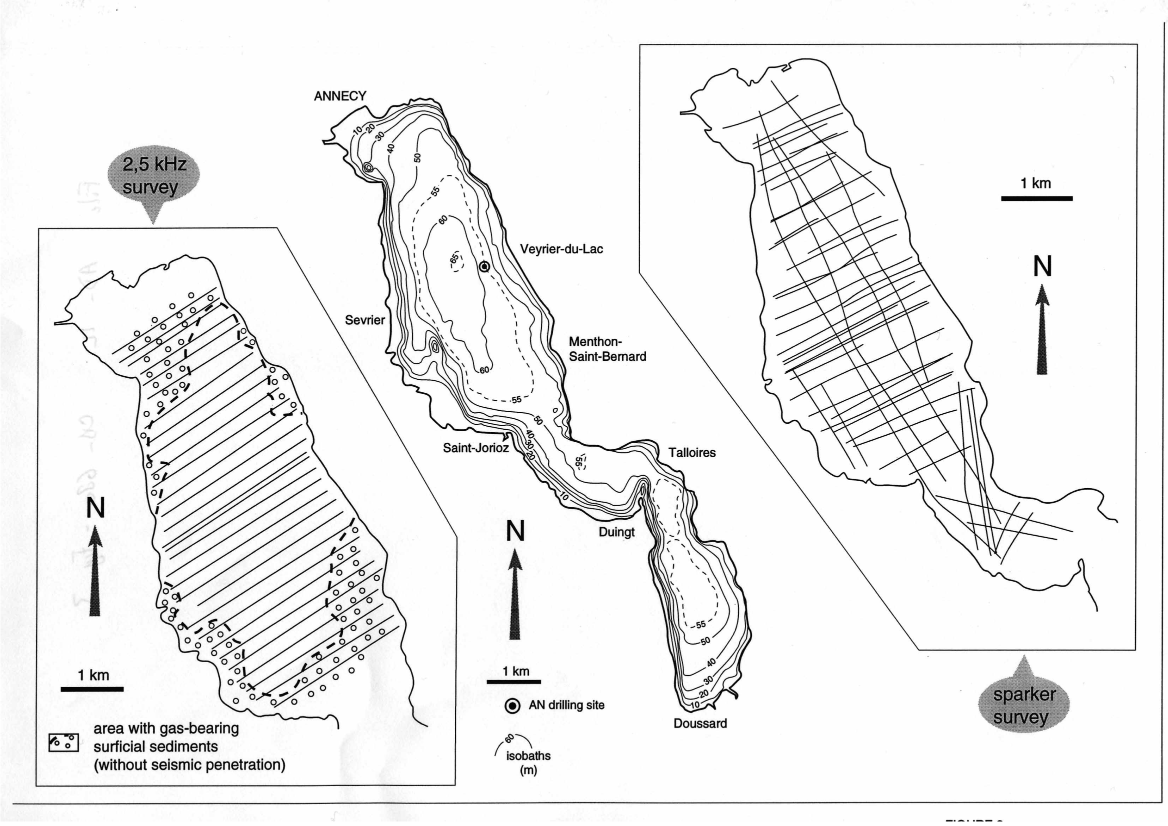

*Figure 3.* Simplified bathymetry and seismic grids. Gas blanketing was evidenced by the very high resolution (2.5 kHz) survey; this lack of acoustic penetration was slightly lower during the high resolution (sparker) survey. In both cases, the southern part (called the 'Petit Lac') did not yield seismic information.

reflections dipping southeastward often masked by many diffractions (see left-bottom part of Figure 4 unmigrated profile). Older Quaternary lacustrine deposits (horizontal) were preserved from Würmian glacial erosion in the south-western part of the 'Grand Lac' in the Sevrier/Saint-Jorioz area, especially below a NNW-SSE elongated high (see bathymetric map on Figure 3). We did not detect the top of the Mesozoic substratum (especially the Urgonian massive limestone which produces a very high amplitude reflection on deep investigation seismic lines performed for petroleum exploration; Deville et al., 1994; Philippe et al., 1994).

*Table 1.* Acoustic velocities ($V_p$) deduced from seismic-refraction studies of two perialpine lakes. Data from Finckh et al. (1984) and Curzi et al. (1992)

| Lake Annecy | Finckh et al. (1984) | |
|---|---|---|
| water | 1.45 km/sec | |
| 0–20 m blf | 1.55 km/sec | lacustrine |
| 20–113 m blf | 1.71 km/sec | sediments |
| tills | 2.21 km/sec | |
| bedrock | 3.93 km/sec | |
| Lago Di Garda | Curzi et al. (1992) | |
| water | 1.45 km/sec | |
| 0–20 m blf | 1.66 km/sec | lacustrine |
| tills | 2.24 km/sec | sediments |
| bedrock | 3.09–3.78 km/sec | |

blf = below lake floor.

A cursory view of seismic profiles transverse to lake elongation (Figure 4) clearly distinguishes a two-part subdivision of the stratigraphic section of late Quaternary infill:

- a lower part, non or poorly acoustically stratified (partly masked by multiples; Figure 4);
- an upper part, very thinly and regularly stratified, with good lateral continuity (longitudinal and tranverse). This subdivision roughly corresponds to: (i) initial phases of sedimentation still related to glacier dynamics; (ii) posterior phases of

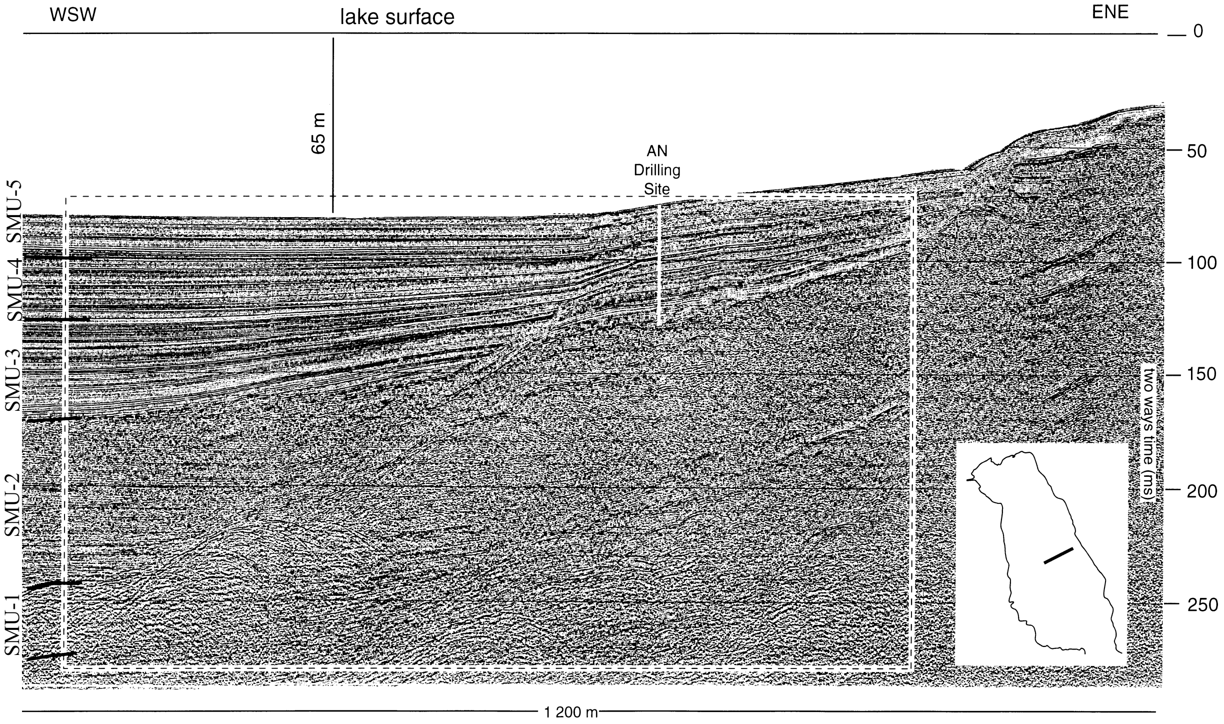

*Figure 4.* Selected portion of a transverse high resolution seismic-reflection profile across northern Lake Annecy. (High resolution sparker survey; processing described within text) The framed portion is interpreted on Figure 5.

lacustrine sedimentation (lake open and disconnected from glaciers). Both can be subdivided with more details as follows.

### *Seismostratigraphic facies and subdivisions*

The whole infill has been subdivided into 5 seismostratigraphic units (SMU on Figures 5 & 6) according to their internal configuration and seismic facies.

#### *The basal units*

Unit 1 (maximum thickness: 50 msec) is irregular and chaotic, developed both in the axial deeper part of the infill and higher on the basin edges; on longitudinal profiles (after migration), Unit 1 appears as several ridges with progradational and vertical aggradational internal configuration (Figure 6) underlined by weak reflectors. These banks, better defined on longitudinal profiles, end as chaotic wedges interbedded within the faintly stratified Unit 2.

Unit 2 (maximum thickness: 100 msec) has an axial distribution with two depocenters (northern and southern ends of the 'Grand Lac'); this unit is reflection-free in the deeper axial part of the infill and gets progressively acoustically stratified towards the basin ridges (Figure 4); there, reflectors are subparallel to hummocky (Figure 5) with variable amplitude. Geometrical relationships between Units 1 and 2 indicate that they are partly coeval.

#### *The lacustrine units*

Units 3–5 (Figures 4, 5 & 6) are well-developed and acoustically stratified in the entire lake, with good lateral continuity. We consider they were deposited in a lake with a size equivalent (or even larger) to the present one (dashed contour on Figure 7).

Unit 3 (maximum thickness: 40 msec) is a divergent fill, thinning towards the basin edges; low-amplitude reflectors show a good to high continuity with slight divergence towards the lake axis. High-amplitude reflectors seem to have a more limited extent (onlap towards the basin edge) and to characterize the axial deeper part of the basin fill.

Unit 4 (maximum thickness: 80 msec) differs from underlying Unit 3 both for its internal configuration and for its general geometry. On a tranverse profile (Figure 5), all reflectors show a good continuity from the axis onto the edges (no onlap); a slight divergence (less than for Unit 3) also appears. Unit 4 is char-

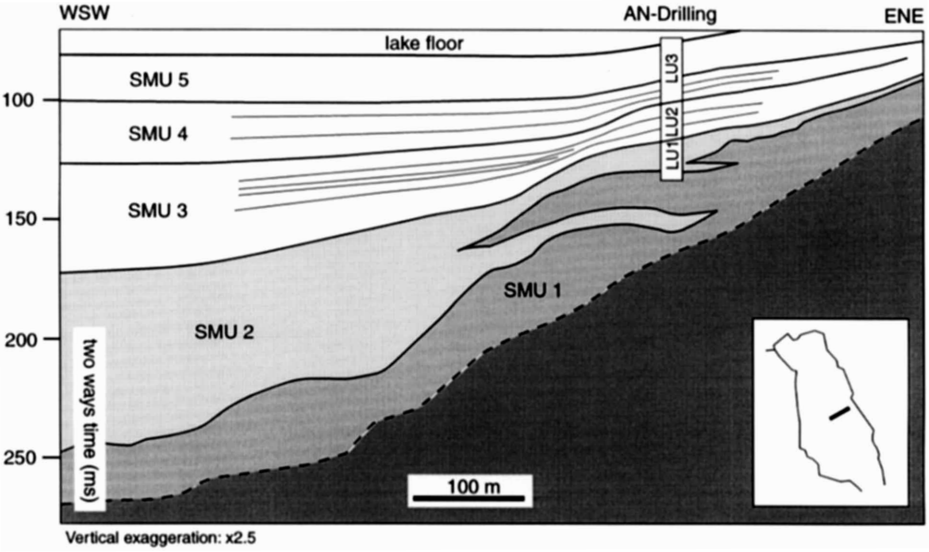

*Figure 5*. Interpreted seismostratographic profile across northeastern Lake Annecy. (SMU: seismostratographic unit; LU: lithostratigraphic unit (data from coring)). This section corresponds to the framed portion of the seismic line shown on Figure 4; acoustic basement is in dark grey. SMU 1 and 2 corresponds to the poorly or non acoustically stratified basal part; SMU 3 to 5 are acoustically well stratified and represent the lacustrine *s.s.* upper par of the infill. The difference between SMU3's and SMU4's internal configurations is underlined.

acterized, too, by a single northwestern depocentre close to the city of Annecy (Figure 8).

Unit 5 (thickness: 10 msec) is a concordant sheet drape with parallel very continuous low-amplitude reflectors. Its lower part thickens (up to 30 msec) at the northwestern margin. The top of Unit 4 (and locally Unit 5) contains chaotic lenses with contorted and disrupted reflections. These features, well imaged by the 2.5 kHz tool, are detailed on Figure 9.

*Interpretation*

Part of Unit 1, irregularly overlying the Würm erosion surface, consists of a series of four, longitudinal or transverse, small ridges, which appear on the detailed isopach mapping done by Van Rensbergen (1996). They were built in episodic pulses; in terms of glacio-lacustrine dynamics, they may be related to episodic outwash, building so-called 'esker deltas' (Banerjee &

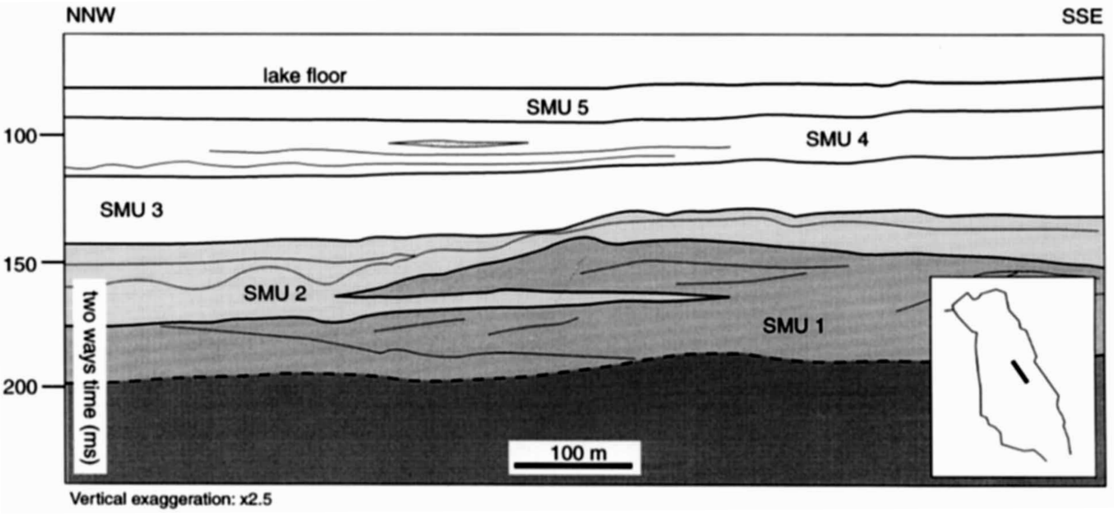

*Figure 6*. Interpreted seismostratigraphic profile across northeastern Lake Annecy. (same legend as for Figure 5). This section is orthogonal to Figure 5 section and crosses the drilling area.

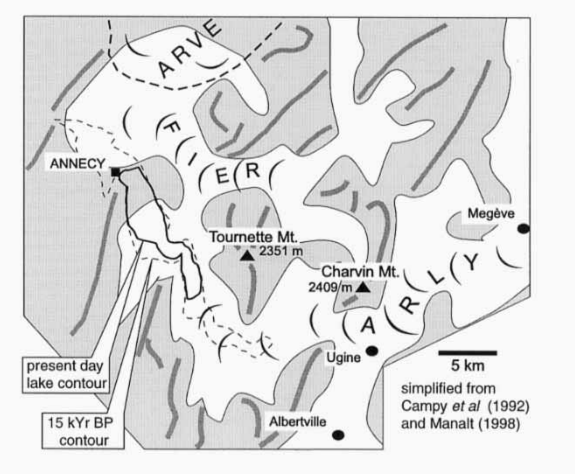

*Figure 7*. Occupation of Lake Annecy depression by valley glaciers during the beginning of the last deglaciation. Simplified from Campy (1992) and Manalt (1998).

McDonald, 1975; Rust & Romanelli, 1975). This succession is interpreted (Van Rensbergen, 1996) as forming in the contact zone between the front of a glacier and a pro-glacial lake. We tentatively compare these structures with the well documented '*grounding-line fans*' observed in glacio-marine setting (Boulton, 1986; Powell & Molnia, 1989; Belknap & Shipp, 1991); according to Syvitski & Praeg (1989), they could represent either ice-contact fans or dump moraine. Notwithstanding the scale difference, the ridges observed in Lake Annecy's Unit 1 are also similar to '*till tongues*' (King et al., 1991; Anderson et al., 1992). Here, a glacio-lacustrine setting is postulated; the inferred lake may represent the very beginning of deglaciation; its size was reduced with respect to the present situation, and valley glaciers was ending in it at both extremities. Apart from these specific features, Unit 1 contains, below the ridges, chaotic sediments which we do not interpret in terms of depositional processes (preserved or *in situ* reworked morainic bodies?).

Due to its acoustic transparency laterally grading into irregular stratification, Unit 2 is interpreted as pro-glacial to subglacial sedimentation in the initial lake stage. Transparent portions correspond to unsorted

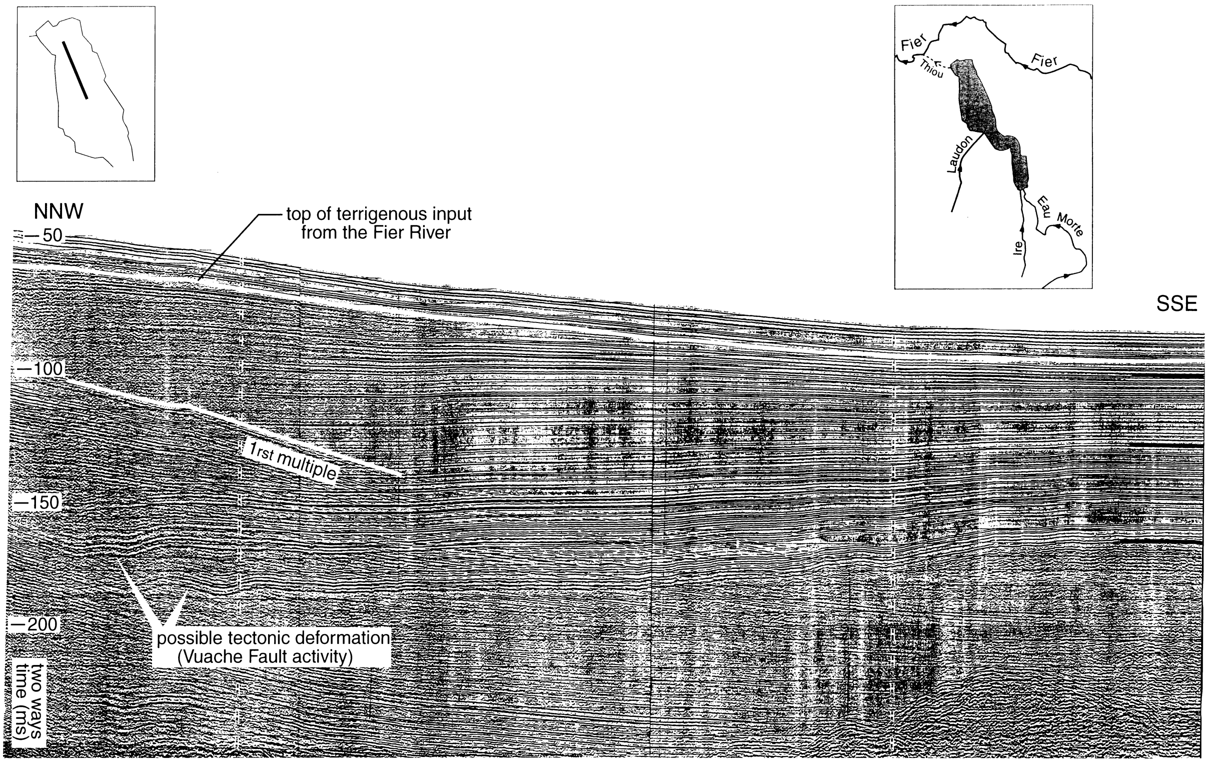

*Figure 8*. Selected portion of a longitudinal seismic-reflection profile across northern Lake Annecy. (High resolution sparker survey; processing described within text) The divergent configuration visible on the left part corresponds to the terrigenous input of the Fier River, when the latter was a (northern) tributary of Lake Annecy. The end of this feeding is marked by the transition to a drape configuration (above white line).

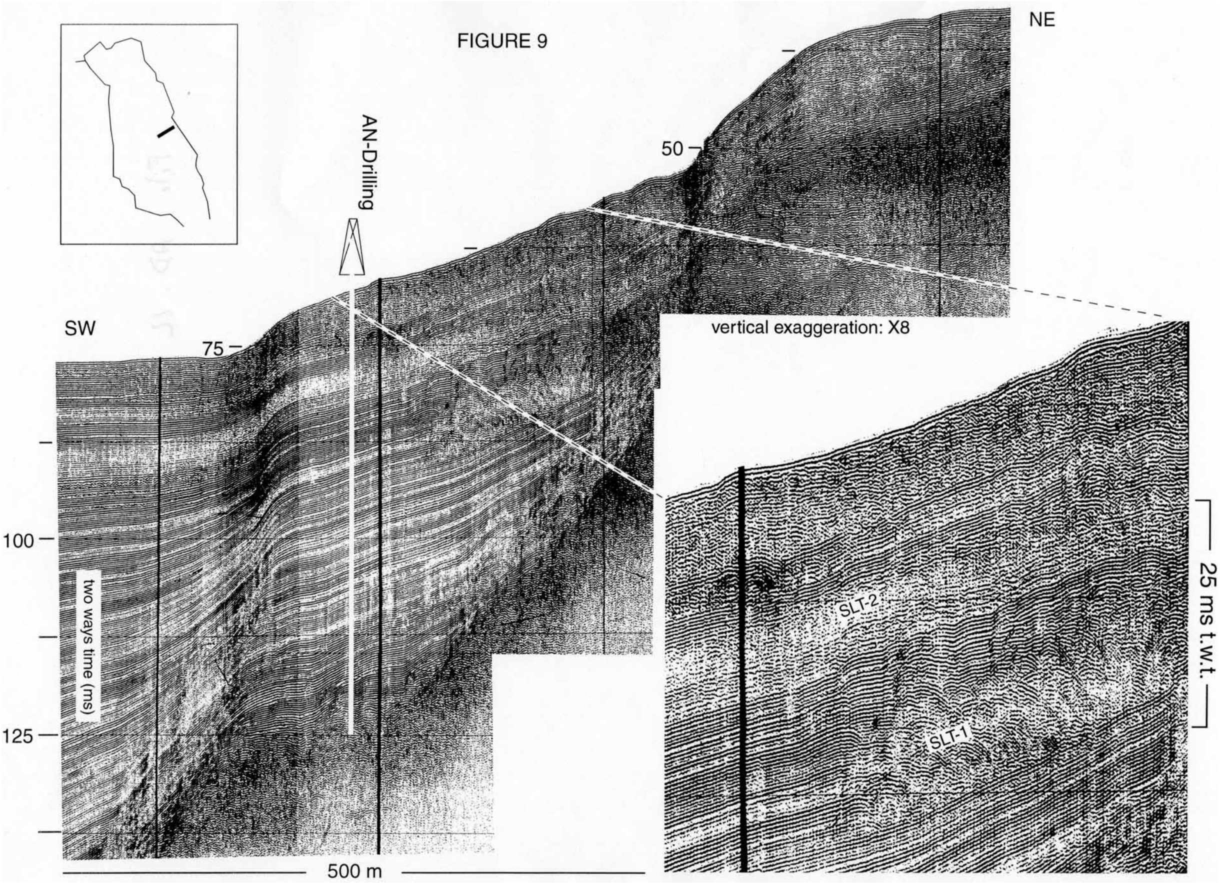

*Figure 9*. Selected portion of a transverse very high resolution seismic-reflection profile across northern Lake Annecy. (2.5 kHz survey). Different episodes of slumping are visible on the enlarged portion. The drilling site was chosen west of this gravity reworking zone.

coarse (sand, gravels?) deposits related to high gradient streams, while stratified lateral portions are more ice-distal, sediment-laden, underflows. We do not have direct information on Unit 2 in the axial deep part of the lake, but this unit was drilled on the basin edge (Figure 5) and, there, consists of silt and clay (Manalt et al., this volume). The general distribution of Unit 2 (Van Rensbergen et al., 1998) argues for a moderate southern source and a major northern source. Unit 2 may be compare to sediments described in perialpine lakes (Müller & Gees, 1970; Vernet & Horn, 1971; Hsü & Kelts, 1984; Curzi et al., 1992) or in glacio-marine setting (Eyles et al., 1991). In Unit 2, initial stratification may be disturbed (Figure 6) by grounding dead ice. Lateral interpenetration of Units 1 and 2 (Figures 5 & 6) reflects the complexity of this sedimentation at the front, or below the front, of glaciers with successive short retreats or re-advances, and melt-out of englacial sediment.

Both the general shape and the internal configuration of Unit 3 point out a divergent structure towards the axis of the basin fill (Figures 4 & 5); this tendency is particularly strong in the deepest part of the basin fill. The low amplitude reflectors are continuous from the axial part onto the edges (the lateral 'steps') while the high amplitude ones are concentrated in the axial part and onlapping on the lateral slopes (see Figure 4). This configuration can be related to axial bottom currents with variable density contrast with respect to the lake bottom water. The thickness and the horizontal distribution of these layers depend on sediment load, and temperature and duration of the incoming flows. In case of high density, typical underflows developed in the deeper part; at the difference, meltwater flows with finer-grained load, may induce a thicker turbiditic water layer and subsequent settling in the whole lake. This process should be favoured by a still cold lake, following the model proposed by Sturm & Matter

(1978). The transition from Unit 2 to Unit 3 represents a major change: increase of the lake size (larger than the present one; Nicoud et al., 1987; Van Rensbergen, 1996), with glaciers' fronts out of the lacustrine realm. The sediment-laden meltwater is supposed to enter the lake at an upslope margin. According to the complete seismostratigraphic study (Van Rensbergen, 1996) main fluxes have an axial provenance, northern and southern.

For Unit 4, a slight divergence towards the axis is still present (Figure 5); if observing longitudinal profiles, a strong divergence appears towards the North (Figure 8), related to a northern main tributary: the Fier River. Van Rensbergen (1996) underlined this pattern, a consequence of a lower suspended sediment load with respect to Unit 3. This lower buoyancy effects may also, at least partly, be explained by an increased temperature contrast between surficial and deep water (seasonal thermocline). Thus, the coarser fluxes could be distributed *as underflows on shorter distances*; the fined-grained fluxes could be deposited through *interflows* or *overflows* deflected by possible currents and Coriolis effect (Sturm & Matter, 1978; Smith & Ashley, 1985). This process may explain the occurrence of thick sedimentary cover in shallow areas in the southwestern 'Grand Lac' (between Sevrier and Saint-Jorioz; Figure 3). We interpret the transition from Unit 3 to Unit 4 as the conversion from a glacier-fed lake to an alluvial-fed lake, even if the tributary streams are fed by glacier-front melting more distant from lake. This transition has also been observed in neighbouring Lake Le Bourget (Van Rensbergen, 1996).

Large lenses of disrupted or contorted sediments occur at the top of Unit 4; they are interpreted as slumping effects and are present on both sides on the lake slopes; similar features have been observed in Lake Le Bourget at an equivalent stratigraphic level (Chapron et al., 1996).

Almost perfectly isopachous and acoustically transparent, Unit 5 covers the whole lake floor; in many peri-alpine lakes a similar unit is observed (Finckh et al., 1984). This sheet drape corresponds to *settling of bio-induced* ('*authigenic*') *particles generated in surficial water*. This implies an almost complete disappearance of terrigenous inputs, related to important changes in the lake watershed, and especially the restoration of vegetation cover and pedogenesis. A detailed study of the long AN core (44 m below lake floor, 57 m water depth; location on Figures 3 and 5) confirms this interpretation (Manalt et al., 2001).

### *The paleo-fan of the Fier River*

As already mentioned, *Unit 4* strongly thickens towards the northwestern termination of the lake (Figure 8), and is interpreted as the distal part of an outwash fan. The proximal and coarser part of the latter should be found onland in the subsurface of the city of Annecy. The *lower part of Unit 5* shows the same divergent tendency and the ending of this northern feeding (underlined on Figure 8 seismic profile) is located within Unit 5. According to the topography and to the present day hydrographic pattern at the northern edge of the lake, the Fier River (sketchmap on Figure 8) represents this past terrigenous flux. Two paleogeographies may be postulated: either the river course was closer to the present northern lake termination, or the river course was roughly at the same place and the lake itself was much more extended towards the North. The second hypothesis is more in agreement with onland surface and subsurface data (Nicoud et al., 1987; Nicoud & Manalt, 1994). At present, the Fier River bed – a few tens of meters lower than the mean lake surface – is a tributary of the Usses River, a tributary of the Rhône River; the shallow Thiou canal (sketchmap on Figure 8) connects Lake Annecy to the Fier River.

We are suggesting that the Fier River previously delivered sediment to Lake Annecy, but has since established a different course that bypasses the lake. This hydrographic change could be due to changes in sediment load and channel form, or it could be partly influenced by neotectonic deformation along the (active) Vuache fault. During the upper part of the Holocene, the Fier River eroded a few tens of meters within its own alluvium, and neotectonics may also have influenced this final evolution of Lake Annecy sedimentary filling.

## Gravity reworking phenomena

The 2.5 kHz survey, as well as the sparker survey, imaged numerous stratification disturbances both on the eastern and western margins of the lake basin. The lateral lake basin edges (more specifically the eastern one) consist of two or three 'steps' (see also Figure 4); reworking phenomena are concentrated on the lower one. The initial stratification may still be visible and contorted, or it appears completely destroyed on seismic profiles (Van Rensbergen, 1996). We present these gravity reworking features on the eastern slope of the lake. Figure 9 shows the eastern portion of Figure 4 sparker profile studied with the 2.5 kHz tool.

The enlarged portion illustrates the two situations:

- at the bottom, a massive slump with still visible stratification (SL-1);
- at the top, an acoustically chaotic unit (SL-2).

The second case may represent a debris-flow stage, with higher stratal disruption and possible water incorporation and transition to turbidites or grain-flows.

In terms of *chronology*, these large-sized disturbances appear concentrated in Unit 4 (Van Rensbergen, 1996), if checking the entire seismic grid. Nevertheless, several recent disturbances have a morphological expression on the lake floor and are presently being investigated using a side scan sonar. A detailed study of sedimentation through the deep AN core revealed the occurrence of sediment intervals containing several tens of silty-sandy turbidites and grain flows (few mm- to few cm-thick) interlayered within the fine-grained lacustrine sedimentation (Beck et al., 1996). The thickest of these layers may represent fluidized basinward prolongations of some larger-sized debris-flows imaged by 2.5 kHz seismic. These small-sized gravity deposits are also concentrated within Unit 4, top of Unit 3 and base of Unit 5. We suggested (Beck et al., 1996) that this time-concentration of gravity reworking phenomena (at both scales) is related to an episode of increased seismic instability – due to the post-glacial rebound (cf. Mörner, 1991, 1996) – rather than to consequences of unique sedimentary loading of the lake basin slopes. However we are unable to directly associate these interval with tectonic deformation features; alternately, these grouping of turbidites may be a result of climate-induced change in sedimentary load or flood frequency.

With respect to the choice of a drilling/coring site for purposes of lake and watershed evolution studies, the discovery of these stratification disturbances led the CLIMASILAC group to avoid the sampling of a too discontinuous sedimentary signal.

## Interpretation and conclusion: main stages of Lake Annecy infilling with relation to the last deglaciation

The seismic information provided essentially data from the 'Grand Lac' part, but the recorded different stages of the last deglaciation concern the whole basin and its catchment area.

The first stages of the evolution (Units 1 and 2) developed in the glacial environment, with progressive creation of a subglacial – and then aerial – lake, as previously described by Lister (1984) for Lake Zürich. The study of Lake Lugano by Niessen & Kelts (1989) pointed out a similar evolution. These early stages of post-Würmian evolution resulted in a sub-glacial to pro-glacial complex sedimentation with pulses, discontinuities, building and erosion of ridges (eskers deltas or 'till tongues'). The existence of northward and southward progradations and fluxes are in agreement with the activity of two major valley glaciers, Arve (north) and Arly (south-east) (Figure 7), as proposed by Nicoud et al. (1987) and Nicoud & Manalt (1994). A succession of grounding line deposits marks the retreat (with hesitations) of the glaciers fronts and *the gradually increasing lake*. The most overdeepened parts were rapidly filled with coarse to clayey material.

Sedimentation rates have been very high during the earlier phases (Unit 1 to 3) and strongly decreased in the final stages (Unit 4 to 5) (Beck et al., 1996; Manalt et al., 1998); in parallel, the *northern provenance of terrigenous feeding* became predominant as represented by the paleo-Fier delta. As underlined by Van Rensbergen et al. (1995, 1998), the main change in seismostratigraphic configuration occurring between Units 2 and 3 is related to the retreat of the glaciers fronts from the lake basin; during Unit 3, axially distributed sediment-laden meltwater was progressively replaced by prograding alluvial fluxes; a major remaining (climatic) question is the relative importance of precipitation-related flux with respect to glacier meltwater flux.

The last stage – Unit 5 sheet drape – is the decrease of erosion through the stabilisation of sediment in soils; as terrigenous input dropped, *bio-induced production* developed, favoured by better climatic conditions.

The changes of terrigenous fluxes provenance, as deduced from seimostratigraphy, is in agreement with mineralogical and geochemical data from Lake Annecy watershed formations and from AN core study (Négrel et al., 1997; Manalt et al., 2001). Taking in account chronological data (Beck et al., 1996), the late episode of sedimentation (Unit 5) should represent more than 12,000 yrs, with a 1 mm/yr mean sedimentation rate. If considering that the whole infill is posterior to the last Würm glacial pulse (around 20,000 yrs. BP), thus 90% of the infill was deposited in less than 8,000 yrs. Seismostratigraphic Unit 3, which corresponds to Lithologic Unit 4 (LU 2, Figure 5) defined in AN core, may represent less than 700 yrs. (Beck et al., 1996).

In summary, Lake Annecy's internal seismic configurations illustrate the main stages of the last deglaciation and the inferred climatic evolution:

- a glacial phase: grounding-line and glaciolacustrine deposits;
- a post-glacial phase: proglacial system evolving into an alluvial system;
- an interglacial phase, free of direct glacier influences, with dominant bio-induced ('authigenic') production.

*Corollary: choice of a lacustrine drilling site*

The very high resolution (2.5 kHz) seismic survey was dedicated to image the upper part of the lake fill and, overall, to choose a convenient site for offshore drilling and coring. This choice was guided:

- by logistical/technical constraints: the available maximum pipe-assemblage length, and the need of a well stabilized platform; both implied a moderate water depth;
- by the scientific purpose: to core the longest and most continuous sedimentary succession in order to analyse the last deglaciation with high resolution.

Thus, the lower part of the eastern slope was preferred to the deep central basin (see Figures 5 & 9). Seismostratigraphic results indicated that SMU Units 1–5 are represented there with a lower mean sedimentation rate. Furthermore the drilling was located immediately west of the disturbances imaged by the 2.5 kHz survey (see Figures 4 & 9). With respect to the time distribution of these reworkings, the chosen site could cross possible thin distal signatures of gravity instabilities (Beck et al., 1996) or earthquake-induced seiche deposits (Sieghenthaler et al., 1990).

## Acknowledgments

We are grateful to the Syndicat Intercommunal du Lac d'Annecy (SILA) and the Haute Savoie Department Council for providing logistical support for the seismic surveys. MDB is senior research assistant of the Fonds voor Wetenschappelijk Onderzoek-Vlaanderen (FWO); the analysis of the RCMG survey data was part of PVR' s Doctorate within a grant of IWON/IWT. Our first manuscript was greatly improved thanks to the detailed and pertinent review made by Professor Spencer H. Wood to whom we are grateful.

## References

Anderson, J. B., S. S. Shipp, L. R. Bartek & D. E. Reid, 1992. Evidence for a grounded icesheet on the Ros Sea continental shelf during the late Pleistocene and preliminary paleo-drainage reconstruction. In Eliot, D. H. (ed.), Contribution to Antarctic Research III. American Geophysical Union, Washington, 39–62.

Banerjee I. & B. C. McDonald, 1975. Nature of esker sedimentation. In Jopling, A. V. and B. C. McDonald (eds), Glaciofluvial and Glaciolacustrine Sedimentation. Soc. Econ. Paleont. Miner., Spec. Publ. 23, 132–154.

Beck C., F. Manalt, E. Chapron, P. Van Rensbergen & M. De Batist, 1996. Enhanced seismicity in the early post-glacial period: evidence from the post-Würm sediments of Lake Annecy, northwestern Alps. J. Geodynamics 22: 155–171.

Belknap D. F. & R. C. Shipp, 1991. Seismic stratigraphy of glacial marine units, Maine inner shelf. In Anderson, J. B. & G. M. Ashley (eds), Glacial Marine Sedimentation; Paleoclimatic Significance. Geol. Soc. Am., Spec. Paper 161: 137–147.

Boulton G. S., 1986. Push-moraines and glacier contact fans in marine and terrestrial environments. Sedimentology 33: 677–698.

Campy M., 1992. Paleogeographical relationships between Alpine and Jura glaciers during the two last Pleistocene glaciations. Paleogeogr. Palaoclim. Paleoecol. 93: 1–12.

Chapron E., P. Van Rensbergen, C. Beck, M. De Batist & A. Paillet, 1996. Lacustrine records of brutal events in Lake La Bourget (northwestern Alps-southern Jura). Quaternaire 7: 155–168.

Charollais J., C. Ruchet, C. Ginet, C. Müller, J. P. Lombard, D. Dondey & J. Rosset, 1986. Carte Géologique de France au 1:50 000. Feuillle d'Annecy-Bonneville, Ed. B.R.G.M.

Curzi P. V., A. Castellarin, M. Ciabatti & G. Badalini, 1992. Caratteri morfostrutturali, sedimentologici del Lago di Gardi. Boll. Soc. Torricellana Sc. Lett. Faenza 43: 1–111.

Deville E., E. Blanc, M. Tardy, C. Beck, M. Cousin & G. Ménard, 1994. Thrust propagation and syntectonic sedimentation in the Savoy Tertiary Molasse Basin (Alpine Foreland). In Mascle, A. (ed.), Hydrocarbon and Petroleum Geology of France. Europ. Assoc. Petrol. Geol., Spec. Publ. 4: 269–280.

Doudoux B., G. Nicoud, B. Colletta, S. Rivano-Garcia, M. Tardy, E. Deville, F. Guerin, J. Rosset, J. C. Barfety, J. L. Pairis, J. C. Carfantan & J. Rochet, 1992. Carte Géologique de France au 1:50 000. Feuillle d'Annecy-Ugine, Ed. B.R.G.M.

Eyles N., H. T. Mullins & A. C. Hine, 1991. The seismic stratigraphy of Okanagan Lake, British Colombia; a record of rapid deglaciation in a deep 'fjord-lake' basin. Sed. Geol. 73: 13–41.

Finkh P., K. Kelts & A. Lambert, 1984. Seismic stratigraphy and bedrock forms in perialpine lakes. Geol. Soc. Am. Bull. 95: 1118–1128.

Hsü K. J. & K. Kelts, 1984. Quaternary geology of Lake Zürich: an interdisciplinary investigation by Deep Lake Drilling. Cont. to Sed. 13: 210 pp.

Jouanne F., G. Menard & D. Jault, 1994. Present-day deformation of the french northwestern Alps/southern Jura mountains: comparison between historical triangulations. Geophys. J. Int. 119: 151–165.

King L., K. Rokoengen, G. Fader & T. Gunleiksrod, 1987. Till tongue stratigraphy. Geol. Soc. Am. Bull. 103: 637–659.

Lister G. S., 1984. Deglaciation of the Lake Zürich area: a model based on the sedimentological record. In Hsü, K. J. & K. R. Kelts (eds), Quaternary Geology of Lake Zürich: an Interdisciplinary Investigation by Deep-Lake Drilling. Schweitzerbart'sche Verlagsbuchhandlung, Stuttgart, 177–186.

Manalt F., 1998. Enregistrement lacustre de la dernière déglaciation dans les Alpes Nord-Occidentales. Le remplissage sédimentaire du Lac d'Annecy (Haute Savoie). Unpublished Thesis, Universite de Savoie, 227 pp.

Manalt F., C. Beck, J.-R. Disnar, J.-F. Deconinck & P. Recourt, (2001) Evolution of clay mineral assemblages and organic matter in the Late glacial-Holocene sedimentary infill of Lake Annecy (northwestern Alps): paleoenvironmental implications. J. Paleolim. 25: 179–192.

Monjuvent G. & G. Nicoud, 1988. Modalités et chronologie de la déglaciation würmiennedans l'arc alpin occidental et les massifs français: synthèse et réflexions. Bull. Assoc. Fr. Quat. 2/3: 147–156.

Mörner N.-A., 1991. Intense earthquakes ans seismotectonics as a function of glacial isostasy. Tectonophysics 188: 407–410.

Mörner N.-A., 1996. Liquefaction and varve deformations as evidence of paleoseismic events and tsunamis. The autumn 10 430 BP case in Sweden. Quat. Sci. Rev. 15: 939–948.

Moscariello, A., 1996. Quaternary geology of the Geneva Bay (Lake Geneva, Switzerland): sedimentary record, paleoenvironmental and paleoclimatic reconstruction since the Last Glacial Cycle. Terre et Environnement, Publ. Sc. de la Terre, Univ. de Genève 4: 230 pp.

Moscariello A., A. Pugin, W. Wildi, C. Beck, E. Chapron, M. De Batist, S. Girardclos, A.-M. Rachoud-Schneider, C. Signer & T. Van Cauwenberghe, 1998. Déglaciation würmienne dans des conditions lacustres à la terminaison occidentale du bassin lémanique (Suisse occidentale et France). Eclog. Geol. Helv. 91: 185–201.

Müller G. & R. A. Gees, 1970. Distribution and thickness of Quaternary sediments in the lake Constantz. Sed. Geol. 4: 81–87.

Négrel P., J. Casanova & G. Nicoud, 1997. Caractérisation isotopique (O, C, Sr) des fluxs glaciaires du bassin versant du lac d'Annecy (E. France). Bull. Soc. Géol. France, vol. 168, 2: 243–254.

Nicoud G. & F. Manalt, 1994. L'évolution du bassin versant du lac d'Annecy depuis le retrait glaciaire würmien. Doc.t CLIMASILAC, S.I.L.A. Annecy.

Nicoud G., G. Monjuvent & G. Maillet-Guy, 1987. Contrôle du comblement quaternairedes vallées alpines du Nord par la dynamique lacustre. Géol. Alpine Mém. h.s. 13: 457–467.

Niessen F. & K. Kelts, 1989. The deglaciation and Holocene sedimentary evolution of southern perialpine Lake Lugano – implications for Alpine paleoclimate. Eclog. Geol. Helv., vol. 82, 1: 235–263.

Philippe Y., 1994. Transfer zones in the southern Jura belt (eastern France): geometry, development and comparison with analogue modelling experiments. In A. Mascle (ed.), Hydrocarbon and Petroleum Geology of France. Europ. Assoc. Petrol. Geol., Spec. Publ. No. 4: 269–280.

Powell R. D. & B. F. Molnia, 1989. Glacimarine sedimentary processes, facies and morphology in the south-southeast Alaska shelf and fjords. Mar. Geol. 85: 359–390.

Rust B. R. & R. Romanelli, 1975. Late Quaternary subaqueaous outwash deposits near Ottawa, Canada. In Jopling, A. V. & B. C. McDonald (eds), Glaciofluvial and Glaciolacustrine Sedimentation. Soc. Econ. Paleont. Mineral., Spec. Publ. 23: 22–100.

Siegenthaler C., W. Finger, K. Kelts & S. Wang, 1987. Earthquake and seiche deposits in Lake Lucerne, Switzerland. Eclog. Geol. Helv. 80: 241–260.

Smith N. D. & Ashley G., 1985. Proglacial lacustrine environment. In Ashley G., J. Shaw & N. D. Smith (eds), Glacial Sedimentary Environments. Soc. Econ. Paleont. Miner., Short Course 16: 135–216.

Sturm M. & Matter A., 1978. Turbidites and varves in Lake Brienz (Switzerland): deposition of clastic detritus by density currents. Int. Assoc. Sed., Spec. Publ. 2: 147–168.

Syvitski J. P. M. & D. B. Praeg, 1989. Quaternary sedimentation in the St. Lawrence estuary and adjoining areas, Eastern Canada: an overview based on high resolution seismo-stratigraphy. Géogr. Phys. et Quat. 43, 3: 291–310.

Thouvenot F., J. Fréchet, P. Tapponnier, J.-C. Thomas, B. Le Brun, G. Ménard, R. Lacassin, L. Jenatton, J.-R. Grasso, O. Coutant, A. Paul & D. Hatzfeld, 1998. The ML-5.3 Epagny (French Alps) earthquake of 15 July 1996: a long-awaited event on the Vuache fault. Geophys. J. Int. in press.

Van Rensbergen P., F. Manalt, M. De Batist & C. Beck, 1995. Seismic expression of glacial and post-glacial sedimentation in Annecy Lake, northwestern Alps. Int. Assoc. Sed. 16th Reg. Meet., p. 148.

Van Rensbergen P., 1996. Seismic stratigraphic study of the glacial and lacustrine infill of Lakes Annecy and Le Bourget. Unpublished Thesis, University of Ghent, 2 vol.

Van Rensbergen P., M. De Batist, C. Beck C & F. Manalt, 1998. High-resolution seismic stratigraphy of Late Quaternary fill of Lake Annecy (northwestern Alps): evolution from glacial to interglacial sedimentary processes. Sed. Geol. in press, 26 pp.

Vernet J. P. & R. Horn, 1971. Etudes sédimentologiques et structurales de la partie occidentale du lac Léman par la méthode sismique à réflexion continue. Eclog. Geol. Helv. 64, 2: 291–317.

Wildi W., A. Moscariello, A. Pugin, C. Beck, E. Chapron, M. De Batist, S. Girardclos & T. Van Cauwenberghe, 1997. Deglaciation of the Geneva basin in lacustrine conditions in response to rapid climatic change. Abstract E.U.G. IX, Strasbourg, 9, p. 627.