North western Alps Holocene paleohydrology recorded by flooding activity in Lake Le Bourget, France and possible relations with Mont-Blanc glaciers fluctuations

Maxime Debret, Emmanuel Chapron, Marc Desmet, M. Rolland-Revel, O. Magand, Alain Trentesaux, Viviane Bout-Roumazeilles, Jérôme Nomade, Fabien Arnaud

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M., Debret[1, 2], E., Chapron[3, 2], M., Desmet[2], M., Rolland-Revel[4], O., Magand[5], A., Trentesaux[6], V., Bout-Roumazeille[6], J. Nomade[7], F., Arnaud[8]

1. **Laboratoire de Morphodynamique Continentale et Côtière**, Université de Rouen, UMR CNRS/INSU 6143, Department of Geology, 76821 Mont-Saint-Aignan Cedex, France
2. **ISTO** – Université d'Orléans, UMR 6113 1A rue de la Ferollerie 45071 Orléans Cédex 2, France and Université François Rabelais UMR 6113 Parc de Grandmont 37200 Tours, France.
3. **Geological Institute, ETH Zürich**, CH-8092 Zürich, Switzerland
4. **Géosciences Azur**, Université de Nice UMR6526, Parc Valrose, 28 Av. de Valrose, BP2135 06108 Nice cedex 2, France.
5. **LGGE**, Université de Grenoble, UMR 5183, 54, rue Molière, 38402 - Saint Martin d'Hères cedex, France
6. **PBDS Laboratory**, UMR 8110 CNRS, University of Lille 1, 59 655 Villeneuve d'Ascq, France
7. **LGCA Laboratory**, Université Joseph Fourier, Maison des géosciences BP 53, 38041 Grenoble cedex 9
8. **EDYTEM Laboratory**, UMR 5204, University of Savoie, CISM, Campus Scientifique F-73376 Le Bourget du Lac Cedex, France.

Correspondance Address

Now at:

Laboratoire de Morphodynamique Continentale et Côtière
UMR CNRS 6143 - Bâtiment IRESE A
Département de Géologie - Université de Rouen
76821 Mont Saint Aignan Cedex, FRANCE

Telephone(s):

Email: maximedebret@yahoo.fr

Abstract

A 14-meter long piston core was retrieved from Lake Le Bourget, NW Alps (France), in order to provide a continuous record of flooding events of the Rhone River during the Holocene. The selection of the coring site was based on high resolution seismic profiling, in an area with limited mass wasting deposits and accumulated proximal Rhone River inter- and under-flow deposits. The age-depth model of this core is based on (i) 14 AMS radiocarbon dates, (ii) radionuclide dating (^{137}Cs) and (iii) the identification of historical data (flood events, eutrophication of the lake). The sedimentary record dates back to 9 400 cal BP, and includes a thin mass wasting event deposited around 4500 cal BP. A multi-proxy approach was used to track the evolution and origin of clastic sedimentation during the Holocene, in order to identify periods of higher hydrological activity in the catchment area. Spectrophotometry was used to detect fluctuations in clastic supply and the study of clay minerals (especially the Illite cristallinity index) allowed locating the main source area of fine grained clastic particles settling at the lake after flood events. This dataset highlights up to 12 periods of more intense flooding events over the last 9 400 years in Lake Le Bourget and shows that the main source area of clastic particles during this period is the upper part of the Arve River drainage basin. This part of the catchment area drains several large glaciers from the Mont Blanc Massif, and fluctuations in Rhone River flood supply in Lake Le Bourget is interpreted as resulting essentially from Mont Blanc Glacier activity during the Holocene. The comparison of clastic sedimentation in Lake Le Bourget with periods of increasing land use and periods of Alpine glacier and mid-European lake level fluctuations, suggest that the core LDB04 clastic record in Lake Le Bourget is a continuous proxy of the Holocene hydrological history of the NW Alps.

Keywords: Holocene, Flooding events, lake sediment, Alps, detritism, Glacier fluctuations

Introduction

The magnitude of temperature fluctuations in Central Western Europe over the last 8,000 years is thought to have been within a range of +/- 1°C (Davis et al., 2003). However, there is growing evidence that suggests significant changes of atmospheric circulation patterns driven by marked decadal- to millennial-scale Holocene climate variability (Nesje et al., 2000; Six et al., 2001; Chapron et al., 2002; Magny et al., 2003; Rimbu et al., 2003). In and around the NW Alps, dating of glacier advances (Holzhauser et al., 2005) and proxy-records of lake level changes (Magny, 2004) have been used to track past hydrological conditions. While they are particularly robust, those approaches have not produced the continuous high-resolution series needed to reconstruct rapid Holocene climate variability.

Lake sediment records of detrital fluxes in glacier-covered watersheds have also been used to reconstruct past hydrological conditions (Nesje et al., 1991). Such an approach has been extensively applied to several Scandinavian glacier-lake systems, but at present only a few sites have been studied in the European Alps (Leeman and Niessen, 1994; Arnaud et al, 2005; Chapron et al., 2007). This is partly due to morphological differences between the ice-cap glaciers found in Scandinavia and the valley glaciers typical of the Alps, which limit the occurrence of coupled glacier-lake systems favourable to the sedimentary record of glacier activity (Dahl et al., 2003).

Lake Le Bourget receives a fraction of the discharge of the Rhone River when it leaves its partly-ice-covered alpine watershed (Chapron et al., 2002; Revel-Rolland et al, 2005). The abundance of the detrital fraction in Lake Le Bourget sediments was therefore used to reconstruct the past flooding activity of the Rhone River during the Little Ice Age (Chapron et al., 2002) and over the last 7500 years (Arnaud et al., 2005). Two limitations can be identified in this latter study performed on distal Rhone River flood deposits: 1) the magnetic susceptibility (MS) signal used to track the mineral discharge was very low in Mid-Holocene sediments, precluding a fine interpretation of the detrital signal; and 2) this study did not allow disentangling the relative contributions of climate and land-use on the terrigenous signal. In the present paper, we address both those problems by studying a new longer core retrieved in more proximal Rhone River flood deposits with a new proxy subjected to spectrophotometry, which gives better resolution than MS; and through the discrimination of the source area of the detrital fraction of sediment by performing a mineralogical study of lacustrine, fluvioglacial and fluvial sediments.

Colorimetric measurements are commonly used in palaeoceanographic studies as a rapid, high resolution tool of sediment characterisation (Chapman and Shackleton, 2000). In

Lake Le Bourget, the sediment was shown to be a two-phase mixture made of autochthonous bio-induced calcite and allochthonous mostly silicate-bearing minerals (Chapron 1999, Arnaud et al., 2005; Arnaud, 2005). In such a case, the L* parameter, *i.e.* the gray-scale value of the sediment colour, can be used as a simple proxy of the carbonate / silicate ratio (Chapman and Shackleton, 2000) and therefore as a marker of detritism. The direct relationship between the carbonate / silicate ratio and the L* value is further confirmed and calibrated based on a low-resolution series of major element measurements.

Reconstructing the intensity of detritism can yield information about the drainage basin's hydrological activity and therefore about variations in precipitation regimes, provided proof can be found that no change occurred through time in the source of clastic particles. This underscores a major uncertainty concerning the causes of changes in detrital fluxes which may be simplified into "climate" vs. "human" impact on erosion (Desmet et al, 2005) To control this over simplication, we still take care that internal processes, like lake level variations, did not affect the detritism record. We address this problem by looking at the origin of Lake Le Bourget's fine grained detrital fraction from the angle of its mineralogical fingerprint and comparing it to the suspended sediment load of the main tributaries and the evolution of detrial input during the time. We test the regional significance of our paleohydrological record by comparing it with the reconstructed Holocene paleo-hydrological framework of the NW Alps based on Alpine glacier and lake level changes. As Lake Le Bourget is located more than 150 km downstream from its glacier-covered watershed, we discuss the potential causal link between glacier fluctuations and paroxysmal phases of Rhone River flooding activity.

2. Setting

Lake Le Bourget, (45°45' N, 5°52' E) is a north-south glacial basin, 19 km long and 2.8 km wide located at an altitude of 231.5 m (Figure 1). The permanent catchment area of Lake Le Bourget (600 km^2) is composed predominantly of carbonated sedimentary rocks: the Upper Jurassic to the Cretaceous formations of the subalpine range and Jura mountains. Some Tertiary molasses and Quaternary glacial deposits are also present locally. The lake basin is composed of two sub-basins: a northern (-146 m) and a southern (-112 m) basin separated by a threshold at 110 m water depth formed by the Sierroz delta. The so-called Savières canal is the natural outlet of the lake flowing towards the Rhone River. The vertical drop between the lake level (231.5m) and the mean level of the Rhone River (231m) is presently only 50 cm. Hence during severe flooding of the Rhone River, the current in the canal is easily reversed, the Chautagne marsh is partly flooded (Bravard, 1981) and the Rhone River can develop strong hyperpycnal (underflow) or mesopycnal (interflow) currents in the lake, depending on the density contrast between the inflowing waters and the lake waters (Chapron et al, 2004). During such flood events, the catchment area of Lake Le Bourget extends from 600 km^2 to ca. 4600 km^2 and includes tributaries draining both part of the Jura Mountains and the Inner Alps (Fig. 1). Since all the sediments transported by the Rhone River in Switzerland are trapped in Lake Geneva (Moscariello et al., 1996), most of suspended sediment supply of the Rhone River downstream of the city of Geneva comes from the Arve River (Bravard, 1987). This large alpine river drains up to 1984 km^2 of the French NW Alps and the catchment culminates at 4810 m in the Palaeozoic Mont Blanc External Crystalline massif. Several large glaciers in the Mont Blanc massif and smaller ones in the Aiguilles Rouges massif cover up to 6% of the Arve River catchment area. The hydrological behaviour of the Arve River is nival to pluvio-nival and characterized by large flood events in spring (when storms cause abundant snowmelt), but also in autumn and in winter (during heavy cyclonic rains) according to Bravard (1987).

Former studies have shown that the permanent (Leysse and Sierroz rivers) and the sporadic (Rhone River) watersheds of Lake Le Bourget provide clastic particles characterized by different clay minerals (Chapron, 1999; Chapron et al., 2002) and specific Sr and Nd isotope compositions (Revel-Rolland et al., 2005). In particular, these measurements revealed that the Rhone River provides predominantly illite in the northern sub basin of the lake and mainly reworks particles transported by the Arve River that were eroded in the Palaeozoic Mont Blanc External Crystalline massifs.

The location of core LDB04 (45° 47'N; 5° 50'E; 100 m water depth) was selected in the northern part of the lake (at 3 km from the Savière canal) based on a high-resolution seismic survey (Figure 1, 2 and 3), The Holocene lacustrine drape at the coring site is 10 m thick and sensitive to proximal Rhone River flood events (Chapron et al. 2005). At this specific location (Figures 1 and 2, 3) the Holocene sequence drapes the northern part of the Hautecombe Disturbed Unit (HDU, Figures 2 and 3), a large earthquake-triggered mass wasting deposit that remoulded the Late-glacial Rhone River lacustrine fan delta (Chapron et al., 1996; Chapron et al., 2004). The lacustrine drape itself is only locally interrupted by a thin mass wasting deposit (labelled S in Figures 2 and 3) occurring at 650 cm below the lake floor. Periods of enhanced Rhone River flooding activity developed several high amplitude reflections (labelled A, B, C and D) in the northern sub-basin resulting from accumulations of more frequent Rhone River inter- and underflow deposits during the Holocene (Chapron et al., 2005).

3. Material and methods

3.1. Lacustrine sediment cores

Core LDB04 was retrieved in 2004 at 100 m water depth in Lake Le Bourget with a 3 m long UWITEC piston coring device operated from a platform. A 14 m continuous composite series was established from two series of overlapping 3 m long sections, as illustrated in Fig. 2 according to 1) sedimentological properties measured every 5 mm with a GEOTEK multi sensor track at ETH Zurich (gamma density, P wave velocities and magnetic susceptibility) and 2) the identification of several marker horizons (thick flood deposits; mass wasting deposits) on spilt cores. Sediment water content and undrained peak shear strength were punctually measured at the same depths in the core by weighing 2 cm^3 of sediment before and after drying in an oven at 105°C, and using a pocket vane shear testing device (Wille Geotechnik) perpendicular to bedding.

In addition, recent lacustrine sediment samples were retrieved (Figures 4 and 5) in 2005 at the water sediment interface of a recent ice-contact lake in front of the Mer de Glace glacier (Mont Blanc massif) and at the top of a short sediment core from Lake Anterne (Aiguilles Rouges massif) retrieved in 1999 (cf. Arnaud et al., 2002).

3.2. Fluvial sediment samples

Recent fluvial sediment samples were collected in 2005 from flood deposits resulting from significant snow melt events at the end of the winter in the catchment areas of the Arve and Giffre rivers, as shown in Figures 4 and 5. These samples where taken from river oxbows and river bed depressions in areas trapping flood events with suspended sediment load. Four samples were also obtained from sediment filters installed at the outlet of subglacial streams directly at glacier fronts or at the outlet of recent proglacial lakes in the Mont Blanc massif. These samples therefore represent the fine grained suspended sediment load of the upper Arve River resulting from soil and bedrock erosion by heavy rainfall, snow melt events and high altitude warm based glaciers.

3.3. Clastic sediment analyses

The sediment magnetic susceptibility on this core was measured using a Bartington MS2E point sensor with a sampling interval of 5 mm. The precision was tuned at 10^{-5} S.I. unit in order to allow rapid and high resolution measurement. The sensor was set to zero every 2 measurements by measuring the ambient air in order to avoid any drift and thus preserve measurement accuracy.

Lacustrine and fluvial sediment clay mineralogy was documented by X-ray diffraction according to the protocol developed by Holtzapffel (1985), and based on the observations of Brown et al, (1961). Measurements were taken on a standard BRUCKER type D4 Endeavor diffractometer (anti-cathode of copper, 40Kv, 25 mA), with a sweep from 3 to 32.5° 2θ. The identification of argillaceous minerals was carried out from the basal reflection (mainly (001), but also (002) for chlorite) deduced by the MacDiff 4.2.5 software (Petschick, 1999). The error margin on the quantitative evaluation of minerals resulting from this interpretation is evaluated to 5%. Sampling for clay mineral determination was carried out every 25 cm in core LDB04. This protocol was also applied to the 26 samples taken within the catchment area of the Arve River. In addition to clay mineral identification, the illite crystallinity index (ICr) was documented. This index corresponds to the measurement of the illite peak width around the mid-height of the diffraction peak at 10A (Kubler, 1964) and gives an indication of the degree of bed-rock metamorphism: an ICr of 0.42° (Δ2θ Cu Ka) characterizes the boundary between anchizone and diagenesis, while an ICr of 0.25° (Δ2θ Cu Ka) characterizes the anchizone-epizone transition (Kübler, 1964, 1967; Kisch, 1983). These limits were calibrated with a Philips 40kV, 20 my, an Ni filter, an opening 2°-0,2 mm-2° and an angular velocity of 2°/min.

The major element content in core LDB04 was determined with a sampling interval of 25cm and each sample includes a sediment thickness of 1cm. The measurements were performed with the accuracy of 1.4%.

Finally, a Minolta CM 2600d spectrophotometer was used on core LDB04 to measure the sediment reflectance intensity of visible wavelengths between 400 and 700 nm, at 10 nm intervals. We used the Specular Component Excluded mode- CIE L* a* b* analyses in order to avoid biasing data with specular reflection. The L* a* b* mode covers the whole spectrum perceptible to the human eye and it includes every colour mode (RGB and CMYK). The illuminant chosen in this study was D65 (Minolta CM-2002 handbook) and corresponds to average daylight with a color temperature of 6504 K. The aperture of the instrument was 8 mm and measurements were taken at 5 mm intervals, thereby providing an almost continuous record of sediment changes in core LDB04. Contrary to the methodology of Chapman and Shackleton (1998), who recommend covering the instrument to be calibrated by the white standard with polyethylene film, we calibrated the spectrophotometer without the film as the instrument expects specific reflectance values that are stored in its internal memory (Balsam et al., 1997, Debret et al, 2006). Calibration was performed on a white calibration tile referenced according to an international standard, $BaSO_4$. The instrument was calibrated at the beginning of each 1.50 m section and after about 150 measurements, thereby accounting for any potential instrumental drift.

Laboratory descriptions of core lithologies are supported by laser diffraction grain size measurements using a Malvern Mastersizer at Savoie University.

4. Results

4.1. LDB04 lithology

The sediment macroscopic analysis coupled with granulometric, reflectance, clay mineralogy, MS measurements and the estimation of carbonate content in core LDB04, allowed defining three sedimentary units, as shown in Figure 6.

Unit 1 (from 0- to ca. 400 cm core depth) is composed of laminated silty clays and can be subdivided in two sub units (U1A and U1B). From 0 - 9 cm core depth, U1A, is characterized by an alternation of very dark grey and very light grey laminae that oxidized rapidly and contained low MS values. This unit has a mode of 12.25 µm and a mean grain size from 10 to 16 µm. Clay particles are predominantly illite (64 %) and chlorite (22 %). This unit is observed over the whole lake and is composed of biochemical varves (cf. Chapron et al., 2005) and results from the eutrophication of the lake initiated in the middle of the 20^{th} century. From 9 to ca. 400 cm core depth, U1B is characterized by a dark grey colour and frequent laminae. Sediment MS is irregular and gives the highest values of the record (7-$22*10^{-5}$ SI). The carbonate content varies in opposition to MS and follows the reflectance curve. Clay minerals are dominated by illite (33%) and smectite (38%). Numerous fine grained dark grey laminae and frequent silty layers are several millimetres thick and have the typical signature of the interflow and underflow flood deposits described by Chapron et al. (2002, 2005).

Unit 2 (from ca. 400 to 940 cm core depth) shows very low MS values that oscillate significantly. These variations are also clearly recorded by the sediment reflectance showing a signal of strong amplitude. The high reflectance values underline the high quantity of carbonates in the sediment and the limited occurrence of flood deposits. This unit is essentially composed of carbonate-rich silty clay material. Clays are dominated by smectite (from 40 to 60%). A mass wasting deposit occurring between ca. 640 and 675 cm core depth from a mixture of very light grey lacustrine chalk and light grey clayey silts with several sandy silt layers. The sediment geotechnical properties presented in Figure 7 allowed to clearly identify the signature of this thin mass wasting deposit and to distinguish it from in situ sediments: It is characterized by a significant drop in water content (50 %) and by cohesive sediments bearing the highest values of undrained shear strength (24.5 kPa) measured on core LDB04. On split core, this deposit is made of remoulded greyish to light grey sediments and some mud clasts are locally made of lacustrine chalk typical from littoral lacustrine environments (Figure 7). This facies is contrasting with laminated clayey silts and faintly laminated lake marls and correspond to a chaotic acoustic facies on seismic profiles that is getting thicker from LDB04 coring site towards the NNW (cf. Figures 2 and 3). Following the classification of Mulder & Cochonat (1996) this deposit retrieved in core LDB04 is interpreted as a distal slump deposit.

Unit 3 (from 940 cm to the base of the core) is characterized by a sharp variation of all the sediment characteristics: geotechnical properties, reflectance, magnetic susceptibility, particle mode and sorting, as well as carbonate content. This unit is poor in carbonates and in general darker than units 1 and 2. It consists from top to base of an alternation of light grey homogenous facies made of poorly cohesive sediments (down to 4.9 kPa) bearing a high water content (up to 80%) evolving downcore into several sequences of finely laminated dark grey more cohesive (9-14 kPa) sediments bearing a lower water content (30-40%). Below 1100 cm laminations are locally very well defined and highly variable in thickness. Sediment grain size is also highly variable in this unit, evolving from fine silt to coarse silts with localised areas of medium sands. The clay assemblage contains from 50 to 60 % of illite. This unit is correlated to a major mass wasting deposit (the Hautecombe Disturbed Unit, HDU) remoulding the proximal environments of a former lacustrine fan delta developed in the northern part of Lake Le Bourget and well documented on seismic profiles (Chapron et al., 1996, 2004, 2005). At the LDB04 coring site, this mass wasting deposit correspond to the upper part of the HDU identified on seismic profiles and is composed, at the base of the core, of tilted packages of stratified deposits typical of a slide deposit, and is evolving upward into liquefied and more homogenous sediments suggesting the development of a debris flow.

4.2. Age model

The age model in core LDB04 was established based on fourteen AMS ^{14}C radiocarbon dates (10 dates in Units 1 and 2; 4 dates in Unit 3) performed at the *Radiocarbon Laboratory* in Poznan (Figure 8; Table 1). Four additional dates were integrated in the age-depth model on the basis of stratigraphic correlations with the previously dated core LDB01 (Arnaud et al., 2005) retrieved in distal Rhone River flood deposits (Chapron et al., 2005). These ages were also obtained by AMS ^{14}C and their stratigraphic position in LDB01 was seen again in LDB04 in units 1 and 2, as shown in Figure 9, by comparing magnetic susceptibility and reflectance profiles measured with a 5 mm sampling step on both cores. All the calibrated ages were computed using Intcal version 5.0.2, with the calibration curve taken from Reimer et al. (2004). The resulting age model is illustrated in Figure 8.

Detailed dating was obtained over the historical period using radiometric markers (^{137}Cs peaks corresponding to the AD 1986 Chernobyl accident and the 1964 maximum fallout caused by atmospheric nuclear bomb tests), the onset of biochemical varve formation due to lake eutrophication in ca. AD 1943 +/-1 years (Guiguet-Covex et al, 2009) and the recognition of three thick underflow flood deposits corresponding to well-documented catastrophic floods events on the Rhone River between AD 1732 to 1734 (Chapron et al., 1999, 2002). The water-sediment interface is well preserved, as attested by the comparison with a short gravity core retrieved nearby.

Because of the deposition of a slump at ca. 4500 cal BP and of the HDU at 9400 cal BP (Figure 8), the LDB04 age-depth model was cut in two parts: 0-580 cm (i.e. from present to 4200 cal BP) and 690-940 cm (i.e. from 5450 to 9400 cal BP). These two continuous age depth models highlight contrasted mean sedimentation rates that fluctuate between 1 and 2.5 mm/yr above the Mid-Holocene slump, and a stable mean sedimentation rate of 1 mm/yr between the slump and the top of HDU remoulding early Holocene sediments.

4.3. Evolution of clastic sedimentation in LDB04

Different markers had been used previously in the sediments of Lake Le Bourget to track the evolution of clastic sedimentation over decadal, centennial and millennial time scales. While Chapron et al, (2002) have shown that the smectite / illite ratio is a good proxy of Rhone River flood deposits in the northern sub basin of the lake; Arnaud (2003) and Arnaud et al. (2005) successfully used sediment magnetic susceptibility to reconstruct changes in clastic sedimentation in core LDB01. Sediment MS in this distal core can be considered as a good proxy for Rhone River flooding activity, since it has a high coefficient of correlation (R = 0.92) with the percentage of aluminium in the sediment. However, the weak concentrations of ferromagnetic materials in carbonate rich sections, limit the use of sediment MS before the Mid-Holocene.

To solve this problem, we measured sediment reflectance (L*) from core LDB01 at high resolution in order to track the evolution of clastic clay particles that could be transported more easily towards distal environments than coarser magnetic minerals. All the changes in sediment MS documented by Arnaud et al (2005) below 4.50 m in core LDB01 are well defined with the sediment reflectance (Figure 9). In addition, the high correlation between major elements and L* measured in core LDB04 clearly shows that the sediment of Lake Le Bourget is composed of only two main components (Figure 10): one composed predominantly of carbonate and the other silicate minerals. There is an inverse relationship between SiO_2 and CaO is direct (-0.9974), confirming the existing links in core LDB04 (i) between L* and carbonate (R > 0.925) and (ii) between L* and silica (R > -0.932). Sediment reflectance (L*) in LDB04 can thus be considered as a high resolution proxy of Holocene fine grained clastic sedimentation in Lake Le Bourget sediments.

This result is in agreement with seismic stratigraphy and the dominant lithology of core LDB04: in Unit 1, characterized by frequent flood deposits (Figures 2 and 3) and fluctuating sedimentation rates (Figure 8), the L* values highlight a higher and more variable clastic supply than for Unit 2, which is comparatively enriched in carbonates (**Figure 6**). The sediments of Unit 3 (i.e the upper meters of the HDU) showing the lower reflectance values of core LDB04 are depleted in authigenic carbonates but dominated by illite and essentially composed of contorted and remoulded sediments from a former Rhone River lacustrine fan delta (Figures 2 and 3).

4.4. Clastic sediment source areas

Since severe Rhone River flood events have essentially provided illite to the northern sub-basin of Lake Le Bourget (Chapron et al., 2002) and mainly reworked the fine grained sediment suspension load transported by the Arve River (Revel-Rolland et al., 2005), the illite cristallinity index can be used to track the main source areas of clastic sedimentation of core LDB04.

In line with the studies by Kübler (1964), Aprahamian (1974) and Deconinck (1992) on rock metamorphism and diagenesis in the northern French Alps, the illite cristallinity index in core LDB04 shown in Figure 11 is typical of bedrocks located at the limit between the epizone (33% of samples) and the anchizone (66% of samples). The ICr in this sediment core is relatively constant throughout the record and oscillates between 0.18° and 0.35°, furthermore suggesting that the illite had the same origin during the Holocene.

The Late-Glacial and Holocene sediments of Lake Annecy (Figure 1) are characterized by clay minerals that essentially rework Tertiary Molasse formations or result from pedogenesis (Manalt et al., 2001) while the illite (35% of the assemblage) has a mean ICr > 4° during the Holocene. Since the Fier River drains Lake Annecy and a part of the Bauge Subalpine massif not belonging to the anchizone (Aprahamian, 1974; Deconinck, 1992), this tributary of the Rhone River cannot be the source area of the illite deposited in core LDB04. Similarly, the source area cannot be located in the catchment area of the Valserine River (Figure 1) since this river drains carbonate rocks from the Jura Mountains, which are neither in the epizone nor in the anchizone.

By contrast, the mean ICr from fluvial samples located in the Arve River upstream from its confluence with the Giffre River (Figure 12) is 0.273° and very similar to that measured in core LDB04 (0.27° on average). However, the ICr values of samples at two locations, i.e. from the Giffre (0.38°) and Sallanches (0.49°) rivers, are significantly higher than those measured in core LDB04. These results therefore indicate that the main source areas of illite in core LDB04 are located in the Arve River drainage basin upstream of the town of Sallanches, and in most of the Giffre River catchment area.

5. Discussion

5.1. Nature and origin of suspended sediment load in the upper Arve River

The upper Arve River catchment area (Figure 12 and 13) is characterized by contrasted lithologies, high altitude peaks and steep slopes that were frequently affected by mass wasting events (rock falls, ice falls, landslides, snow avalanches, debris flows) during the Holocene (Dorthe Monachon, 1988; Balandras & Jaillet, 1996; Deline & Orombeli, 2005). Together with glacier erosion (cf. Dahl et al., 2003 for a review), these processes provide large volumes of sediment to the fluvioglacial streams that drain the Mont Blanc and the Aiguilles Rouges massifs at the origin of the Arve River. Such clastic supply together with snow melt events affect the braided pattern of the upper Arve valley, which controls the amount of sediment load transported by the river. Frequent fluctuations in the regime of the Arve River and contrasted glacier activity in the last centuries significantly limited human activities in this high altitude valley until the 19^{th} century (Mougin, 1912; Bravard & Peiry, 1993). In the drainage basin of the Giffre River, however, a lack of glaciers, gentler slopes and better accessibility to high altitude plateaus may have favoured human land use such as pastoral and mining activities since at least the Roman period (Arnaud et al., 2006). Unfortunately further studies are still needed to document the Holocene evolution of land use (and erosion) at high altitude in the Mont Blanc and Aiguilles Rouges massifs. According to available studies in the surrounding massifs, human activities essentially affected the altitude of the tree line which reached about 2500 m during the Mid Holocene (David & Barbero, 1995; Talon et al., 1998).

In brief, clastic supply from the upper Arve valley appears to be mainly controlled by snow melt events, glacier erosion and slope stability processes during the Holocene. In this high altitude catchment area largely covered by glaciers (cf. Figure 13), the fluctuation of bedrock erosion and the substantial production of fine grained clastic particles therefore seems controlled mainly by climatic conditions and for the most part results from glacier activity. The impact of humans on vegetation cover since –at least- the Roman period may have been, in addition, a potential source of erosion in the drainage basin of the Giffres River. Since this tributary is smaller than the Arve River upstream of Sallanches and also characterized by a lower suspended sediment load, most of the illite produced in this part of the NW Alps is believed to result from natural changes in temperature and precipitations at high altitudes in the Mont Blanc massif.

The origin of the illite is in agreement with field observations carried out at the end of winter 2005 after large snow melt events, when the flow of the Arve River (approximately ten times larger than in the Giffre River) was characterized by a "milky" colour resulting from a high suspended sediment load, while neither the Giffre River, nor the other tributaries of the Arve River, had such a colour. On the contrary the smaller tributaries downstream of Sallanches were typically characterized by clear blue waters. These observations suggest that snow melt in these high altitude drainage basins of the Arve and Giffre rivers provides most of the water during flood events and that the glacier activity of the Mont Blanc massif in the upper Arve valley constitutes the main source of clastic sediments.

In conclusion, the ICr indicates that illite in Lake Le Bourget Holocene sediments essentially came from glacial and peri-glacial processes in the Mont-Blanc massif. To test this interpretation and to further investigate the relations between Lake Le Bourget clastic sedimentation, Mont Blanc glacier activity and climate changes, the MS and L* signals from core LDB04 are compared in the following sections to Alpine glacier and mid-European lake level fluctuations documented during the Holocene.

Possible anthropic impact on clastic sedimentation in Lake Le Bourget

The respective contribution during the Holocene of human impact *versus* climate forcing on the clastic sedimentation in Lake Le Bourget is an important issue. Here are some arguments supporting the dominating influence of climate on the clastic signal at site LDB 04:

- The clastic sediment source area remained constant over the last 9400 years. The Illite crystallinity shows that the detritism comes from the upper valley of the Arve River in the Mont Blanc Massif. Therefore the people living adjacent to the lake, or in alpine valleys did not contribute significantly to the clastic variations recorded in the lake at site LDB04.

- Due to their specific geomorphologic relationships, a Rhone River detrial supply in Lake Bourget requires that the Rhone River form a large flood event. Any Rhone River detrital supply in the lake since 9400 years is thus resulting from favourable hydrological conditions and can therefore be considered as a good paleohydrological proxy for the NW Alps. Human activities in the catchment area may, however, affect the amount of sediment released during a Rhone River flood event and therefore may amplify the suspended sediment load during a flood event. Consequently, human impact may impact the intensity of the Rhone River clastic supply in Lake Le Bourget, but won't affect the timing nor the triggering of a flood event.

5.2. Comparison with NW Alpine glacier and Mid-European lake level fluctuations

Instrumental and historical records of alpine glaciers: decadal scale.

Before AD 1870, glacier front positions in the northern Alps (France and Switzerland) were deduced primarily from paintings or historical writings on the damage caused by advancing glaciers (Mougin, 1912; Zumbühl et al, 1983; Schmeits and Oerlemans, 1997). These data show that alpine glaciers in the middle of the 19th century were from 0.8 to 1.6 km longer than today and underwent a major retreat during the 20th century (Figure 14).

During this period (150 years), the clastic record (MS) of Lake Le Bourget is compared in Figure 14 with the cumulative length of five large alpine glaciers documented by Vincent et al (2005): (i) 3 glaciers from the Mont Blanc massif (Bossons, Argentière and Mer de Glace, see location in Figure 13) draining into the Arve River; (ii) the Trient Glacier located in the Mont Blanc massif but draining into the Rhone River in Switzerland and (iii) the Grindelwald glacier in the Bernese Alps (Central Switzerland). The maximum extensions of these glaciers are generally contemporaneous but not perfectly synchronous because their length is not directly linked with climate, but also results from other specific parameters controlling their dynamics, such as size, exposure and geometry (Nye, 1965; Johannesson, 1989). Nevertheless, the general evolution of the length of these alpine glaciers highlights a similar pattern over the last 150 years.

Figure 14 shows that clastic sedimentation was higher in Lake Le Bourget when these glaciers were either increasing or decreasing from three periods of culminating length (i.e. at the end of 19th century; between AD 1920 and AD 1931; between AD 1983 and AD 1995). The MS signal in Lake Le Bourget shows three significant peaks around AD 1880, AD 1930, AD 1950 and a small plateau between the 1980's and the 1990's. This suggests that since AD 1870, clastic supply in Lake Le Bourget has resulted from bedrock erosion associated with Mont Blanc glacier fluctuations in the Arve River following the end of the Little Ice Age. If an anthropogenic imprint exist, it seems that it only impact the amplitude of the signal and not the timing. It seems that the flooding of the Rhone River into the lake results from climatic factors.

Alpine glacier and mid-European lake level fluctuations over 3 500 years: secular scale.

Holzhauser et al (2005) reconstructed the fluctuations of several large glaciers in the Swiss Alps (Aletsch, Gorner and Grindelwald glaciers) over the last 3500 years and compared this record with lake level changes in west-central Europe previously documented by Magny (2004). In this recent study, periods of glacier advances clustered between BC 800-400, AD 500-700, AD 800-950, AD 1100-1200 and AD 1300-1880, were contemporaneous (within dating uncertainties) with phases of high lake levels in the Jura Mountains, in the French NW Alps and/or on the Swiss Plateau. Short periods of lake level fluctuations around BC 1000 and between AD 0-250, however, were not clearly associated with glacier advances in the Swiss Alps.

Figure 15 compares Swiss glacier fluctuations and periods of higher lake levels in Western Europe with the continuous record of Rhone River flooding activity in core LDB04 (the magnetic suscpetibility signal) and highlights periods where increased flooding activity matches with periods when glaciers where near their maximum extent and higher lake levels: between 2800-2400 cal BP (period 5); 1500-1300 cal BP (period 4); 1200-1050 cal BP (period 3); 900-800 cal BP (period 2) and 700-220 cal BP (period 1). Periods of increased flood activity occurring between 2200-2000; 1950-1600 and 1050-950 cal BP, are, on the other hand, not contemporaneous to any clearly documented glacier or lake level fluctuations in the alpine range, but took place after wet periods associated with higher Rhone River torrential activity (cf. Arnaud et al., 2005): the so-called Iron Age Hydrological crisis (1200-1550 cal BP), the Roman Wet Period (between 2100 and 1900 cal BP) and the High Middle Age Wet Period (1500-1200 cal BP). Moreover, at coring site LDB01, Arnaud *et al* (2005) have shown that peacks in magnetic suscptibility were also matching several transgressive phases recognized over the last 3000 years by Magny & Richard (1985) at the archeological site of Conjux (NW littoral platform, cf Fig. 1) in Lake Le Bourget. These transgressive phases and enhanced clastic supply at site LDB01 coincided with periods of high water activity in the Upper Rhone River documented by Bravard (1996).

Figure 16 also compares the LDB04 ligthness signal (L*) with periods (i) of higher lake level phases in west Central Europe from Magny (2004), (ii) of Mont Blanc glaciers advances both in France (Argentiere glacier; Bless, 1984) and in Italy (Miage glacier, Deline & Orombelli, 2005), (iii) of glacier advances in the Swiss and Austrian Alps (Maisch et al., 2000; Holzhauser et al, 2005) and (iv) a synthesis of cooling events recorded in the Swiss and Italian Alps (Hass et al., 1998). In this figure, the L* signal is characterized by 12 phases of enhanced clastic supply from the Rhone River since 9400 cal BP (labelled from A to L).

Over the last 3500 years, phase A (end of the 19^{th} century to 695 cal BP) in L* (Fig 16) and periode 1 in magnetic susceptibility (Fig. 15) are corresponding to the well known Little Ice Age cooling period characterized by higher lake levels and glacier advances in the Alps. Phase B (1255-2120 cal BP) in L* includes periods 3 and 4 of higher lake level from Magny (2004), a dated advance of the Argentiere (ca. 1480 +/- 40 cal BP) and Miage (from 1200 to

1650 cal BP) glaciers (Bless, 1984; Deline & Orombelli, 2005) and the Goschenen II cooling period identified in the eastern and central Alps (Maisch et al. 2000) including an advance of the Aletsch glacier from 1350 to 1650 cal BP in the Valais (Holzhauser et al, 2005). Phase C (2530-2735 cal BP) in L* matches period 5 from Magny (2004), a dated advance of the Argentiere and Miage glaciers (Bless, 1984; Deline & Orombelli, 2005); the Goschenen I cooling period identified in the eastern and central Alps (Maisch et al. 2000 ; Holzhauser et al, 2005, Hass et al., 1998) and a period (ca. 2500-2700 cal BP) of enhanced flooding activity of the Rhine River in Lake Constance (Wessels, 1998). Phase D (3240-3500 cal BP) in L* similarly matches period 6 of Magny (2004), enhanced Rhine River flooding activity in Lake Constance between ca. 3300-3400 cal BP (Wessels, 1998), an increase in St Sorlin glacier activity in the French western Alps between 3600-3300 cal BP identified above 2500 m altitude in Lake Bramant (Guyard et al., 2007) and the Lobben cooling period identified in the eastern and central Alps (Maisch et al. 2000 ; Holzhauser et al, 2005).

Over the last 3500 years, it is also important to note that a trend toward increasing clastic supply in Lake Le Bourget since ca. 2800 cal BP (i.e. in Unit 1 of core LDB04 and during phases A, B and C) is also documented in the French pre-Alps (Lake Annecy; Nomade, 2005), in the French Western Alps (Lake Bramant, Guyard et al., 2007), in the Eastern Alps (Lake Constance, Wessels, 1998) and up to Scotland (Lake Lochnagar, Dalton et al, 2005). This period is in addition matching a transgressive trend in jurassian lakes (Mangy, 2003). A large number of archaeological studies performed in the alluvial plain of the Rhone River have also reported that hydrological activity was weak in the river valley from the Neolithic period (ca. 5000 cal. BP) to the 1st Iron Age (Salvador et al, 1993; Bravard, 1996).

These comparisons suggest that since the onset of the Iron Age (ca. 2800 cal BP), increased Rhone River flood activity in Lake Le Bourget has been above all sensitive to significant hydrological change, resulting in advances of Alpine glaciers, higher lake levels in mid-Europe and a higher torrential activity in the Rhone River.

Alpine glacier and lake level fluctuations during the Holocene: millennial scale

Few continuous reconstructions of glacier or hydrological activities during the Holocene are documented in the Alps and those available originate from western Europe lake level reconstructions (Magny, 2004) and proglacial environments from the French, Italian, Swiss and Austrian Alps (Dorthe-Monachon, 1988; Balandras & Jaillet, 1996; Wessels, 1998; Leemann and Niessen, 1994; Maisch et al., 2000; Hormes et al., 2001; Deline & Orombelli, 2005; Joerin et al., 2006; Holzhauser, 2007; Hass et al., 1998). The synthesis of environmental changes in the Alps describes the first part of the Holocene (until 6 000 cal BP) with very small glaciers. This period is known as the Holocene climate optimum. This implies that information on glacier activity during this period is limited and Holzhauser (2007) underlines the difficulties of establishing a continuous chronology, while Hormes et al. (2001) and Joerin et al (2006) suggested several periods with smaller glaciers than today, based on statistical studies of radiocarbon dates from wood samples found in glacial and proglacial deposits.

Nevertheless, between 3500 and 9400 cal BP the L* signal in core LDB04 highlight several periods of enhanced clastic supply (phases E to L, Figure 16).

Phase E (3780-4150 cal BP) in L* matches period 7 of higher lake level from Magny (2004) and enhanced Rhine River flooding activity in Lake Constance (Wessels, 1998). Phase F (5400-5950 cal BP) in L* corresponds relatively well to period 9 of Magny (2004), a glacier advance in the Swiss Alps between 5000 and 6000 cal BP (Holzhauser, 2007), the onset of proglacial sedimentation in Lake Silvaplana (Leemann and Niessen, 1994) and a cooling period between 5620 and 6150 cal BP (Hass et al., 1998; Magny & Hass, 2004). Phase G (6076-6415 cal BP) in L* from core LDB04 matches the period 10 of Magny (2004) and the cooling phase of Rotmmoss I (Maisch et al., 2000). Phase H (6540-7050 cal BP) in L* correspond to the end of period 11 from Magny (2004) and it matches enhanced torrential activity in the Upper Arve valley in front of the Tour glacier (Ballandras and Jaillet, 1996) contemporaneous from the end of the Frosnitz cooling period (Maisch et al., 2000). Phase I (7400-7770 cal BP) in L* correspond to the beginning of period 11 from Magny (2004) and of the Frosnitz period (Maisch et al, 2000) and it occurs just after a cooling phase between 7115 and 7480 cal BP identified by Hass et al. (1998). In the detail, period 11 from Magny (2004) contains a double peak and the two phases H and I of detritism in Lake Le Bourget, seems coherent (Magny, pers. com.) and could add more details to the hydrological activity reconstructed by Magny (2004). Phase J (7820-8250 cal BP) in L* correspond to period 12 of Magny (2004) and to a cooling event documented between 7700 and 8370 cal BP by Hass et al (1998). While phase K (8450-8700 cal BP) in L* is not matching any other reconstruction of environmental changes in the Alps, phase L (9100-9400 cal BP) in L* matches nicely with period 13 of Mangy (2004), with an enhanced torrential activity in the Upper Arve valley in front of the Tour glacier (Ballandras and Jaillet, 1996) and with a cooling event between 9060 and 9550 cal BP (Hass et al., 1998).

These comparisons suggest that Rhone River flood activity in Lake Le Bourget between 3500 and 9400 cal BP has been above all sensitive to wet (and often cooler) periods in the Alps (favouring higher lake levels in mid-Europe). These wet periods were contemporaneous to glacier fluctuations, especially after the Holocene Optimum (a period known as the Neoglacial). Only one period of higher lake level from Magny (2004) is not clearly documented in this study: it correspond to the period 8 dated between 4800-4850 cal BP, matching (within dating uncertainties) a glacier advance of the Miage glacier documented by Deline & Orombelli (2005) between 4600 and 4800 cal BP in the Mont Blanc Massif and the Rotmoss II phase of glacier advance in the Alps (Maisch et al., 2000). This period is not well documented at site LDB04 in Lake Le Bourget because of the occurrence of a slump deposit dated to ca. 4500 cal BP (cf. Figures 6, 9 and 16). The L* and magnetic susceptibility signals above this slump deposit (Figures 6 and 9) are, however, characterized by sharp but significant fluctuations (between 618 and 640 cm core depth, cf. Fig. 9), suggesting enhanced clastic supply between ca. 4375 and 4500 cal BP. As a working hypothesis, this slump deposit remoulding littoral sediments may have been triggered by abrupt lake level fluctuations during Mont Blanc glacier fluctuations. Since lake level reconstructions in Lake Le Bourget are only covering the last 4300 yrs (Magny and Richard, 1985) this hypothesis still need to be confirmed.

6. Conclusion

A multi-proxy study was used to analyse one of the longest sedimentary records of flood deposits in the Alps. The continuity of the cores sampled throughout the last 9400 years allowed tracking the sources of detritism and studying the Holocene climatic variability recorded by the lake.

The study of clay fractions made it possible to precisely locate the sources of detritism upstream of Sallanches, in the Mont-Blanc range. This source remained the only component of detritism recorded in the lake sediments throughout the Holocene. Thus, in spite of the distance (150 km), the lake record is closely linked to the glacier fluctuations in the Mont-Blanc massif, suggesting that they respond to the same hydrological forcing. Because of the specific geomorphological relationship between Lake Le Bourget and the Rhone River during the Holocene, human activities may have amplified the erosion of the catchment during periods of climate deteriorations, but could not affect the timing of the flood events.

Consequently, the evolution of clastic sedimentation recorded in core LDB04 represents a reliable proxy for Holocene paleohydrology.

Agreement between the 12 phases of detritism in Lake Le Bourget and different lake records, and with other Alpine glaciers, shows that the Mont Blanc range underwent climatic oscillations with significant variations in the hydrological cycle.

The variations of detritism recorded in Lake Le Bourget are in agreement with Alpine climatic oscillations, indicating that the hydrology of this part of the Alps reflects a regional climatic pattern.

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Figures captions

Figure 1 : General setting of LDB in the NW Alps and bathymétric map of LDB (isobaths 5 m) showing the location of sediment cores and seismic profiles presented in figures 2 and 3 (B).Towards the North, Lake Le Bourget is sporadically draining the catchment area of the Rhone River flowing out of Lake Geneva and three main tributaries: the Arve River originating from several glaciers in the Mont Blanc Massif; the Valserine River draining the SE part of the Jura mountains and the Fier River draining Lake Annecy and part of the Borne subalpine massif. During the Little Ice Age, frequent major Rhone River flood events, developed either interflow (light grey) or underflow (dark grey) flood deposits (after Chapron et al., 2002; 2004; 2005). Core LDB 04 was retrieved in an area submitted to proximal Rhone River inter- or under-flow deposits, while core LDB 01 was sampled in distal Rhone River flood deposits.

Figure 2: NE-SW orientated seismic section illustrating the coring site (left) and the seismic stratigraphy calibrated by core LDB 04 (right). Two way travel times (TWT) are converted into depth below lake floor (m. b.l.f.) using a P wave velocity of 1.5 km/s. Two drill sites with overlapped sections and the identification of marker horizons allow reconstructing the synthetic lithology of core LDB 04 as detailed in the text. This 14 m long core is made of dark grey lacustrine marls with frequent flood deposits (Unit 1) evolving down core into light grey marls (Unit 2) interrupted by a thin slump deposit (S) at 6.2 m. b.l.f. and covering, at ca. 9.5 m b.l.f., the upper part of large mass wasting deposit (the Hautecombe Disturbed Unit; HDU cf. Chapron et al. 1996; 2004). The HDU is consisting of dark grey intensively remoulded sediments (producing a transparent acoustic facies towards the top of the HDU) and of folded and disrupted pieces of greyish laminated mud (producing thrusted and contorted blocks of lake strata in the lower part of the HDU). *A lacustrine drape developed above the HDU is characterized by several high-amplitude reflections (labelled A,B,C and D) corresponding to periods of enhanced Rhone river flood deposits within lacustrine marls (Chapron et al., 2005) and is locally affected by a slump deposit*. On this NE-SW seismic section the slump deposit forms a lens-shape body with chaotic internal reflection to transparent acoustic facies. It is thicker towards the NE, gets thinner towards the SW and ends at ca. 160 m South-Westward from LDB04 coring site.

Figure 3: N-S orientated seismic section illustrating the coring site (left) and the seismic stratigraphy calibrated by core LDB 04 (right). On this N-S seismic section the slump deposit forms a lens-shape body with few chaotic internal reflections in a transparent acoustic facies. It is thicker towards the North and ends at ca. 50 m Southward from LDB04 coring site. The HDU is characterized by an upper transparent acoustic facies (corresponding to dark grey remoulded sediments in core LDB04) and a lower part made of thrusted and contorted blocks of lake strata (corresponding to pieces of greyish laminated mud).

Figure 4: Locations of samples in the watersheds of the Arve and the Giffre rivers taken from river beds, subglacial streams, outlets of recent proglacial lakes, the lake floor of an ice-contact lake facing the Mer de Glace glacier and from Lake Anterne.

Figure 5: List of samples in the watersheds of the Arve and the Giffre rivers taken from river beds, subglacial streams, outlets of recent proglacial lakes, the lake floor of an ice-contact lake facing the Mer de Glace glacier and from Lake Anterne.

Figure 6: LDB04 lithological description and measurements of sediment reflectance (L*), magnetic susceptibility, carbonate content, and clay minerals allow defining four sedimentary units: the Eutrophication Unit (Unit 1A), laminated marls rich in clastic sediments (Unit 1B), marls (Unit 2) interrupted by a thin slump deposit, and Unit 3 corresponding to the upper part of the Hautecombe Disturbed Unit (HDU) discussed in the text. Grey scale levels in the lithological description are indicative of the degree of lamination produced by Rhone River flood deposits: finely laminated (dark grey), laminated (grey), and faintly laminated (light grey). Sandy layers are indicated by black lines. The stratigraphic locations and the ages (cal BP) of radiocarbon samples are also indicated.

Figure 7: Sediment water content and undrained shear strength obtained on core LDB04 illustrating contrasting geotechnical characteristics of the slump, the HDU and the undistrubed lacustrine marls. The patchy and remoulded lithological facies of the slump deposit occurring at 620 cm below the lake floor in core section LDB04-02-C2 is also illustrated (right).

Figure 8: Age depth model of core LDB04 based on ^{14}C dates (from cores LDB04 and LDB01), on ^{137}Cs and on the identification of sedimentary events (lake eutrophication, historical Rhone River flood events and mass wasting deposits).

Figure 9: Comparison between SM and L* of LDB 01-I core and L* of LDB 04-I core allowed to use 4 datations from the previous work of Arnaud et al, 2005.

Figure 10: Correlation coefficients between sediment reflectance (L*) and two major element contents in core LDB04. CaO and SiO2 content estimated by XRF measurements are significantly correlated to parameter L* which can thus be used as a proxy to track variations in either clastic (SiO2) or authigenic (CaO) sediment supply. In these correlations, the eutrophic unit was not considered.

Figure 11: Evolution of the illite cristallinity index (ICr) in core LDB04. According to the ICr measured in fluvial samples (right panel) at the different localities shown in Figure 3 and in agreement with former mineralogical studies in the Northern French Alps described in the text, the illite deposited at the LDB04 coring site (left panel) during the Holocene and remoulded by the Hautecombe Disturbed Unit (HDU) originate from the Mont-Blanc massif.

Figure 12: The illite cristallinity index (ICr) of fluvial and lacustrine samples in the upper part of the Arve River drainage basin. The limits of the different gradations of bedrock metamorphism based on the ICr documented in the studies of Kubler (1964), Aprahamian (1974) and Deconinck (1992) are also indicated.

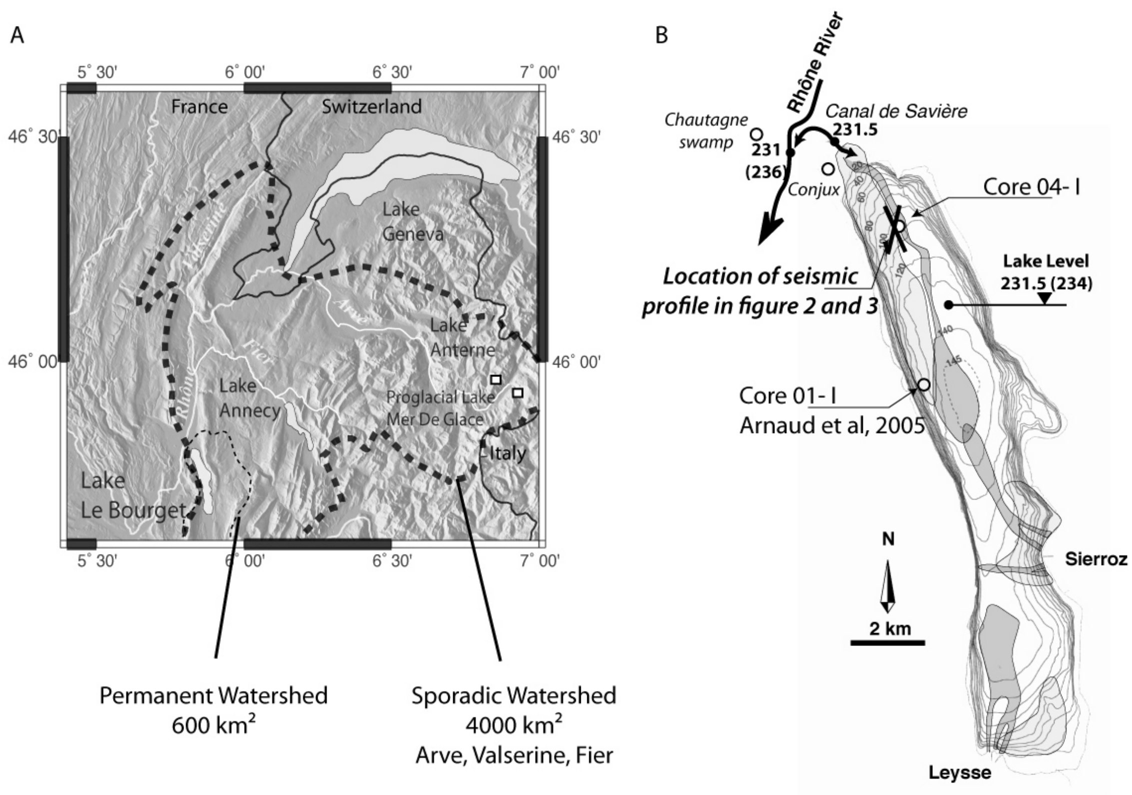
Figure 13: The main source area of clastic particles trapped in core LDB04. White squares are sampling locations in the two watersheds. Black points are the main cities. The dotted line is the 2500 m elevation and the bold lines are the Little Ice Age moraines. No. 1 is the Trient glacier, no. 2 Tour glacier, no. 3 Argentière glacier, no. 4 Mer de Glace, no. 5 Taconnaz glacier, no. 6 Bosson glacier, and no. 7 Miage Glacier.

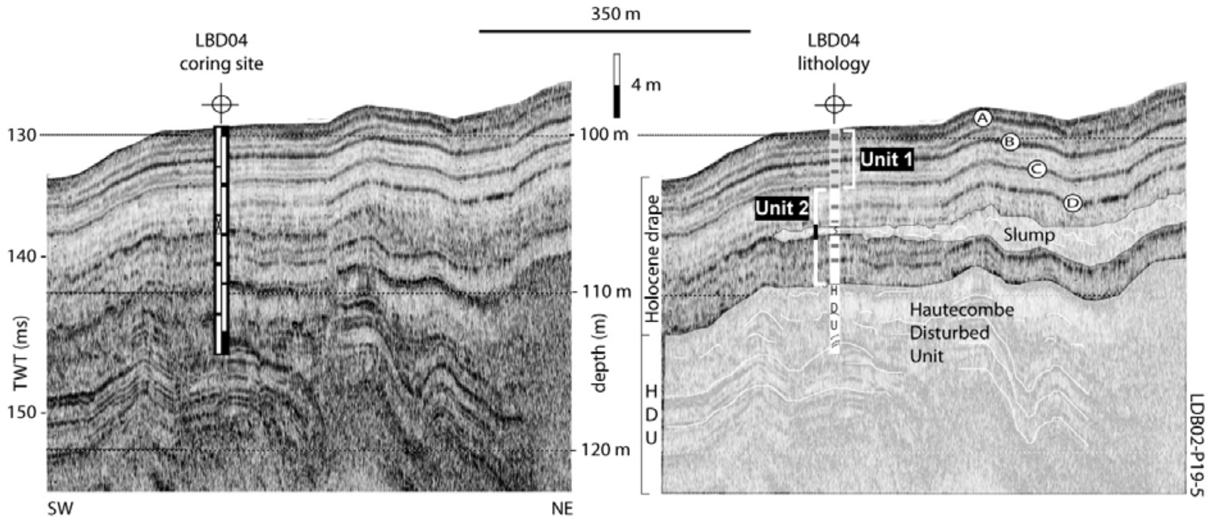
Figure 14: Comparison of clastic supply in core LDB04 with the cumulative length over the last 150 years of several alpine glaciers (after Vincent et al., 2005) in the Mont Blanc massif (Mer de Glace, Bosson, Argentière and Trient) and in Central Switzerland (Grindelwald

glacier). The chronology in core LDB04 is based on radionuclide dating and has decadal resolution due to the sampling interval.

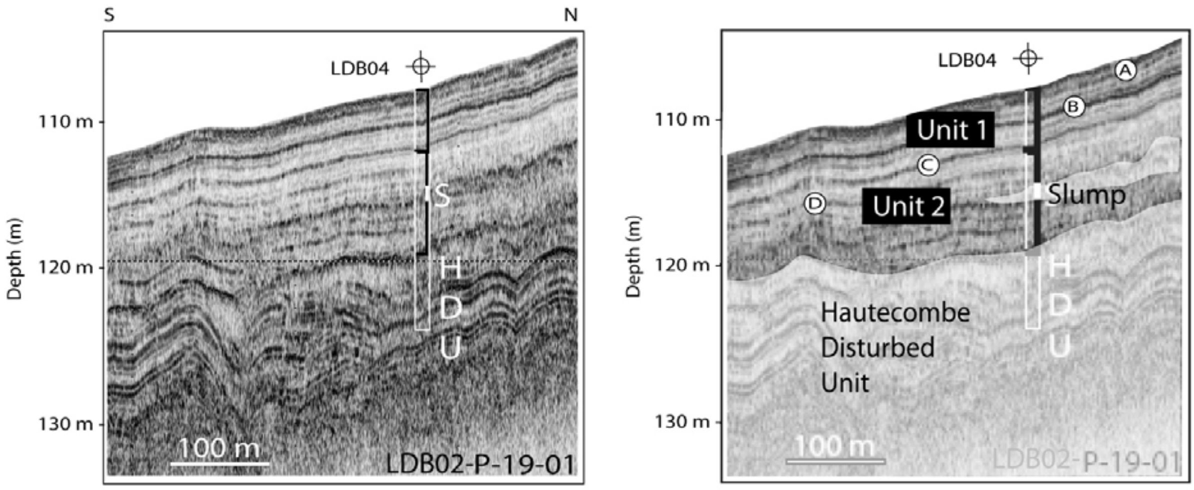
Figure 15: Comparison of Lake Le Bourget clastic sedimentation with the Great Aletsch glacier and mid-European lake level fluctuations during the last 3 500 years (modified after Holtzhauser et al., 2005).

Figure 16: Lake Le Bourget phase of detritism (L*) compared with a) Holocene higher lake levels from Jurassian lakes (Magny, 2004), b) Jaillet et Ballandras (1996), c) Arve valley landslide/torrentiality Bless (1984), d) Deline et al (2005), e) glacier fluctuation from Alps by Maisch (2000) and f) Haas et al, 1998. Dark levels are slumps.

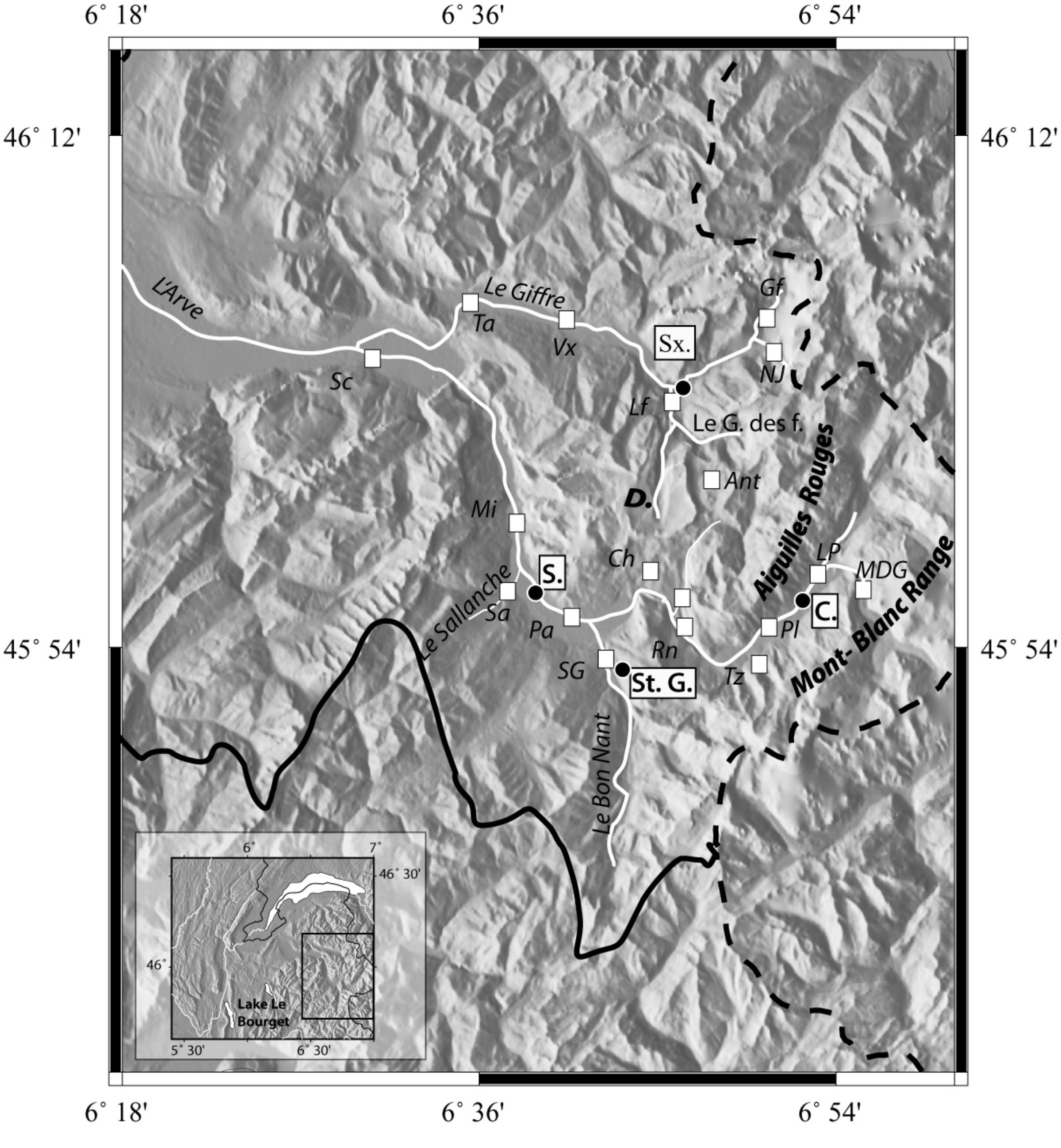




350 m
LBD04
coring site
LBD04
lithology
4 m
130
140
150
TWT (ms)
100 m
110 m
120 m
depth (m)
SW
NE
Holocene drape
H
D
U
Unit 1
Unit 2
A
B
C
D
Slump
Hautecombe
Disturbed
Unit
LDB02-P19-5



S
N
LDB04
110 m
120 m
130 m
Depth (m)
S
H
D
U
100 m
LDB02-P-19-01
LDB04
A
B
C
D
Unit 1
Unit 2
Slump
Hautecombe
Disturbed
Unit
100 m
LDB02-P-19-01

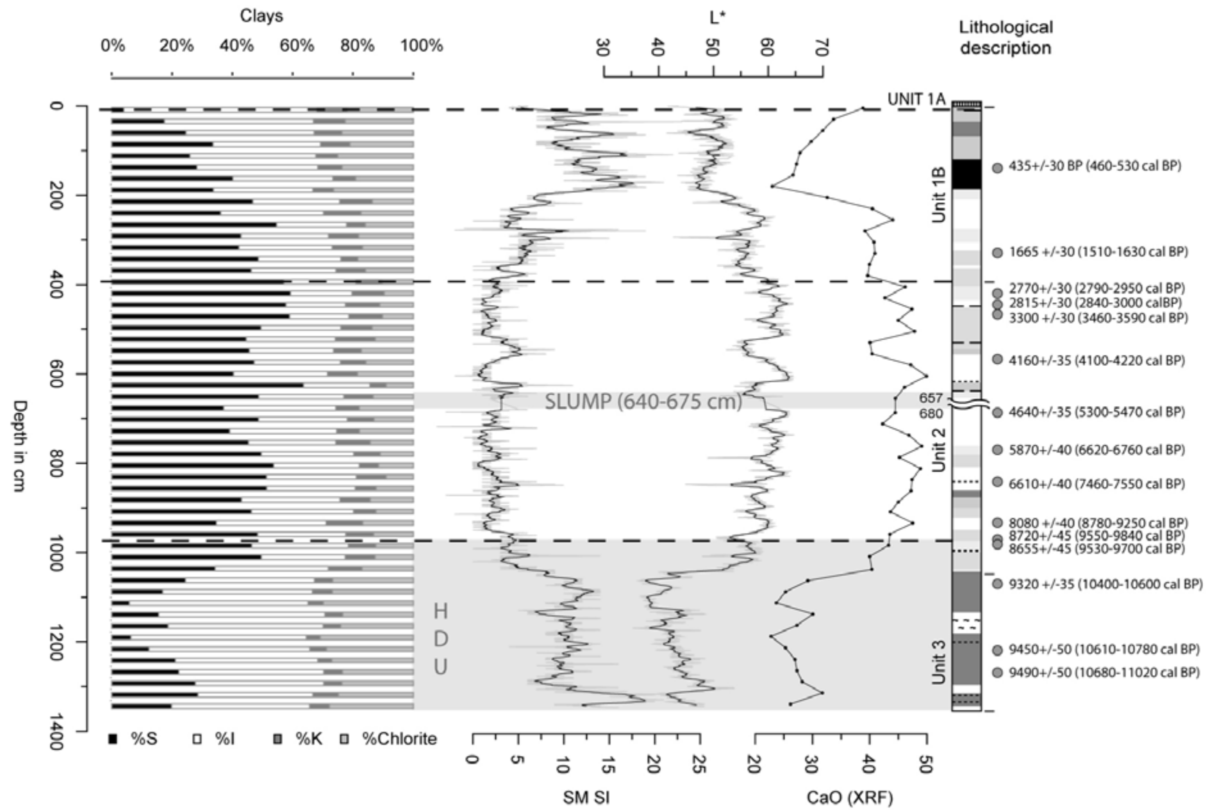

6° 18'
6° 36'
6° 54'
46° 12'
45° 54'
L'Arve
Le Giffre
Ta
Vx
Sx.
Gf
NJ
Sc
Lf
Le G. des f.
Ant
D.
Aiguilles Rouges
Mi
Ch
LP
MDG
S.
Le Sallanche
Sa
Pa
Rn
Pl
C.
Mont- Blanc Range
SG
St. G.
Tz
Le Bon Nant
6°
7°
46° 30'
46°
Lake Le Bourget
5° 30'
6° 30'

Arve watershed

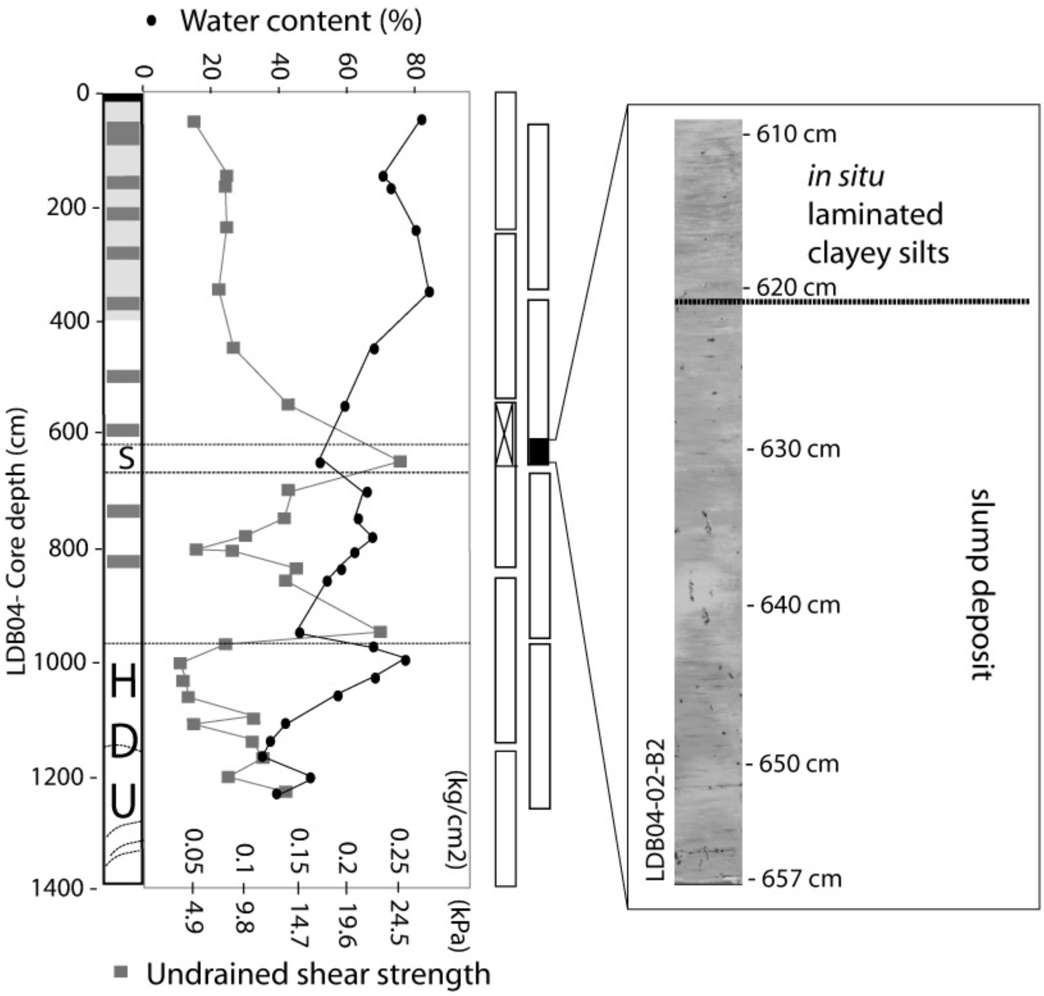
Samples	Location	River
LP 05	Les Praz de Chamonix	*Arve*
Pl 05	Les Pélerins	*Arve*
Tz 05	Le Bourgeat	*Taconnaz*
Dz 05 1	Le Bouchet	*Diosaz*
Dz 05 2	Le Bouchet	*Diosaz*
Rn 05	Museum Le Bouchet	*Arve*
Ch 05	Chedde-La motte	*L'Ugine*
SG 05 1	St Gervais - Le Fayet du Milieu	*Le Bon Nant*
SG 05 2	St Gervais - Le Fayet du Milieu	*Le Bon Nant*
Pas 05	Passy	*Arve*
SA 05	Sallanches	*La Sallanche*
Mi 05	Miribel - illettes Lake	*Arve*
MDG 02	Front Mer de Glace	*M. de G. Lake Ice contact*
MDG 00	Front Mer de Glace	*M. de G. Lake outlet*
MDG	Aval	*Proglacial Stream*
MDG	Between the 2 lakes	*Proglacial Stream*
MDG	Between the 2 lakes	*Proglacial Stream*
MDG	Outlet second lake	*Proglacial Stream*
Sc 05		*Arve*

Giffre watershed

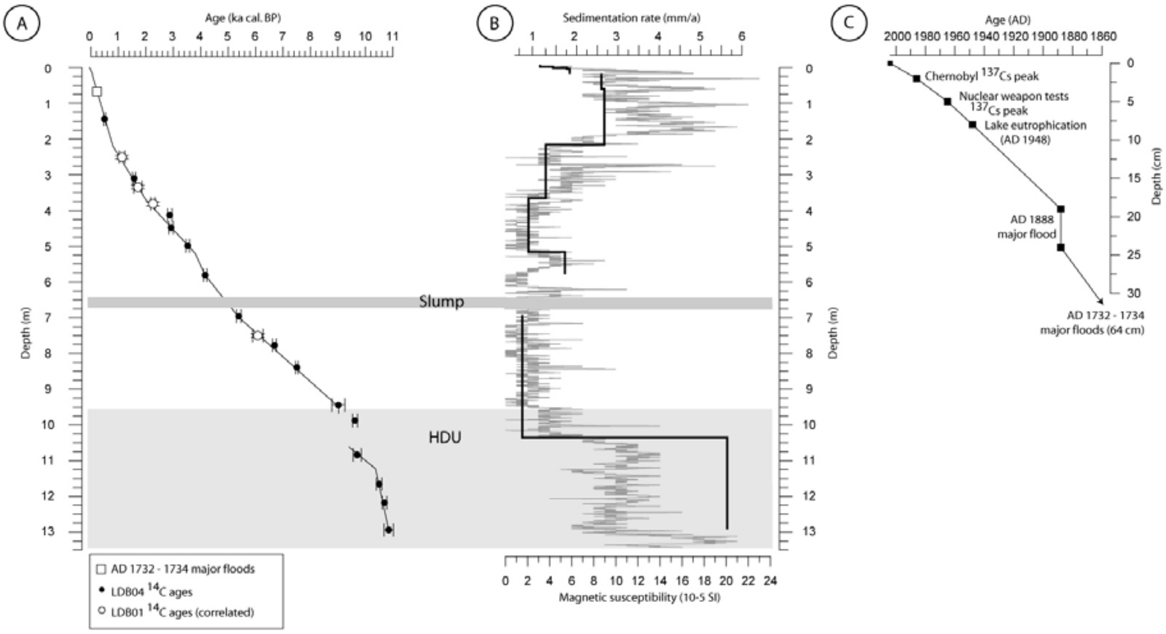
Samples	Location	River
TA 05	Tanninge	*Giffre*
Vx 05	Verchaix	*Giffre*
Le Fay 05	Pont des Nants	*Giffre des fonts*
NJ 05	Nant des Joathons - Plan des Lacs	*Nant des Joanthons*
Gf 05	cote 913	*Giffre*
Ant 01	Anterne Lake	*Anterne Lake*



Clays
0% 20% 40% 60% 80% 100%
L*
30 40 50 60 70
Lithological description
UNIT 1A
Unit 1B
Unit 2
Unit 3
Depth in cm
0 200 400 600 800 1000 1200 1400
SLUMP (640-675 cm)
657
680
H
D
U
435+/-30 BP (460-530 cal BP)
1665 +/-30 (1510-1630 cal BP)
2770+/-30 (2790-2950 cal BP)
2815+/-30 (2840-3000 calBP)
3300 +/-30 (3460-3590 cal BP)
4160+/-35 (4100-4220 cal BP)
4640+/-35 (5300-5470 cal BP)
5870+/-40 (6620-6760 cal BP)
6610+/-40 (7460-7550 cal BP)
8080 +/-40 (8780-9250 cal BP)
8720+/-45 (9550-9840 cal BP)
8655+/-45 (9530-9700 cal BP)
9320 +/-35 (10400-10600 cal BP)
9450+/-50 (10610-10780 cal BP)
9490+/-50 (10680-11020 cal BP)
%S %I %K %Chlorite
0 5 10 15 20 25
SM SI
20 30 40 50
CaO (XRF)



Water content (%)
0
20
40
60
80
LDB04- Core depth (cm)
0
200
400
600
800
1000
1200
1400
S
H
D
U
(kg/cm2)
0.05
0.1
0.15
0.2
0.25
4.9
9.8
14.7
19.6
24.5
(kPa)
Undrained shear strength
610 cm
in situ
laminated
clayey silts
620 cm
630 cm
640 cm
650 cm
657 cm
slump deposit
LDB04-02-B2



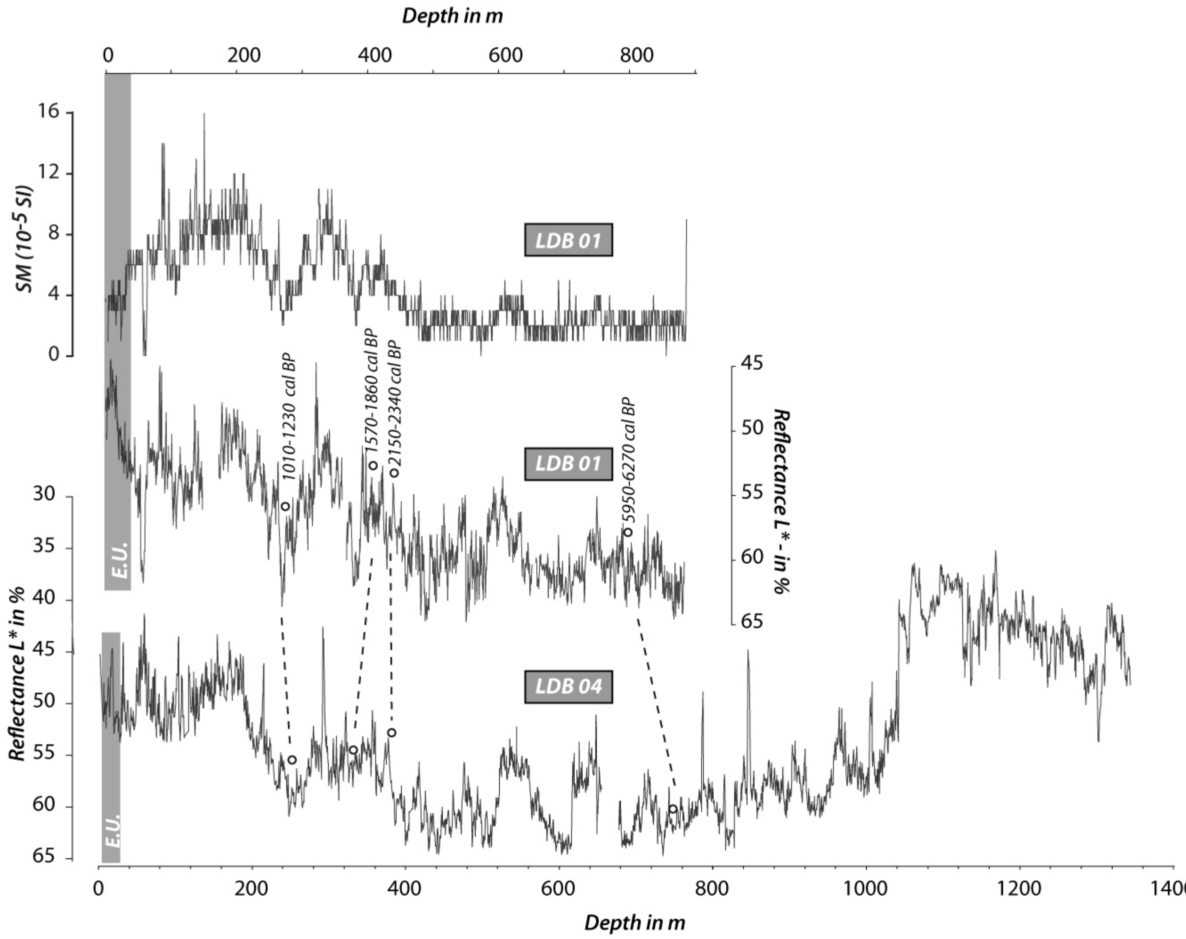
D

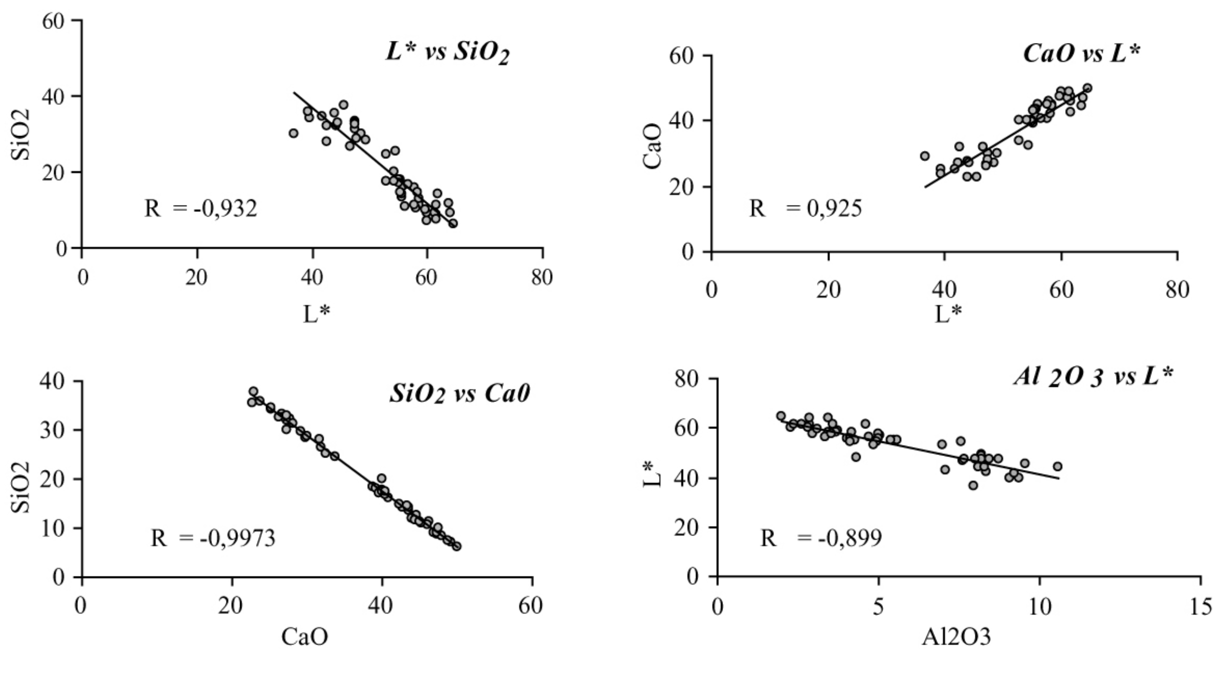
Non- ^{14}C age information

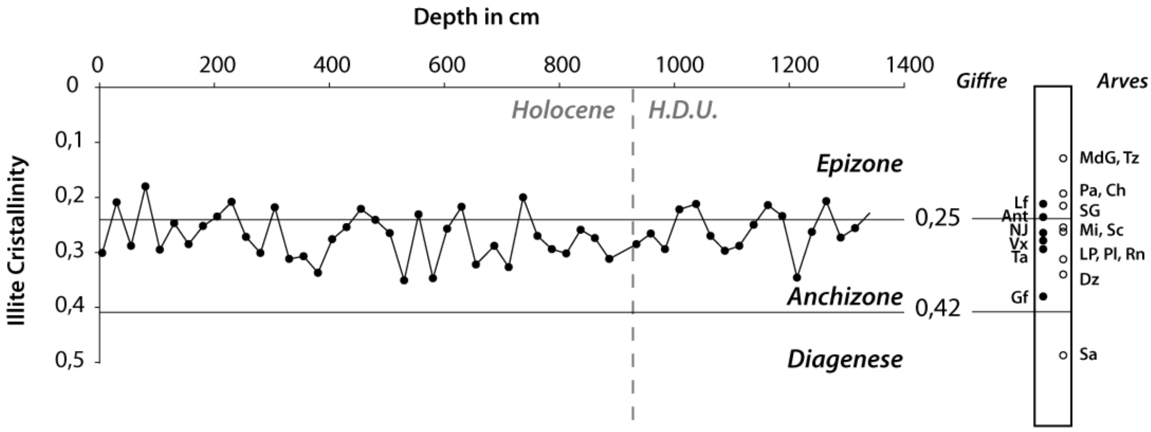
Historical event	Core	Depth (mm)	Age (yrs AD)	Age (yrs cal. BP)
Chernobyl accident (^{137}Cs)	LDB04-I	20	1986	−36
Atmospheric bomb tests (^{137}Cs and ^{241}Am)	LDB04-I	50	1965	−15
Eutrophication	LDB04-I	80	1948	2
Historical flood	LDB04-I	190	1888	62
	LDB04-I	240	1888	62
Historical flood	LDB04-I	640	1734	216

^{14}C age and calibration information

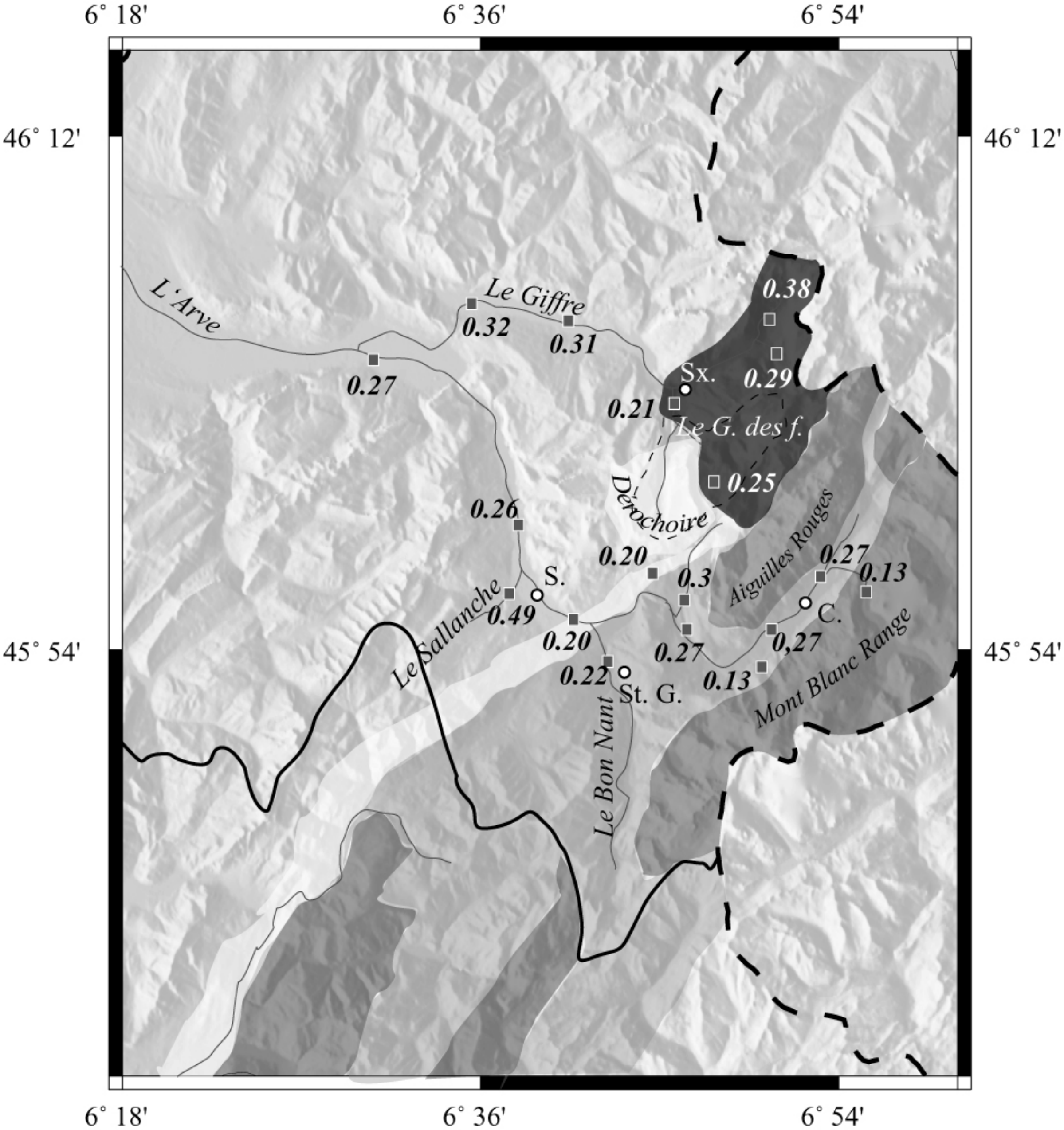
Laboratory code	Core	Depth (mm)	Correlated position on LDB04-I (mm)	^{14}C Age	+/- 2 s	2s probability range of calibrated ages (cal. BP)	
Poz-13986	LDB04-I	1440		435	30	460	530
Poz-710	LDB01-I	2710	2505	1200	30	1010	1230
Poz-13983	LDB04-I	3100		1665	30	1510	1630
Poz-718	LDB01-I	4070	3350	1800	45	1570	1860
Poz-716	LDB01-I	4405	3810	2250	30	2150	2340
SacA4834	LDB04-I	4128		2770	30	2790	2950
Poz-13984	LDB04-I	4480		2815	30	2840	3000
Poz-13985	LDB04-I	4990		3300	30	3460	3590
Poz-10562	LDB04-I	5810		4160	35	4100	4220
Poz-14033	LDB04-I	6960		4640	35	5300	5470
Poz-721	LDB01-I	7910	7500	5310	40	5950	6270
Poz-14032	LDB04-I	7770		5870	40	6620	6760
Poz-10563	LDB04-I	8400		6610	40	7460	7550
Poz-13987	LDB04-I	9440		8080	40	8780	9250
SacA4836	LDB04-I	10,835		8655	45	9530	9700
SacA4835	LDB04-I	9875		8720	50	9550	9840
SacA4837	LDB04-I	11,655		9320	35	10,400	10,600
Poz-10565	LDB04-I	12,180		9450	50	10,610	10,780
Poz-10566	LDB04-I	12,940		9490	50	10,680	11,020


Depth in m
SM (10-5 SI)
LDB 01
LDB 01
LDB 04
1010-1230 cal BP
1570-1860 cal BP
2150-2340 cal BP
5950-6270 cal BP
Reflectance L* in %
Reflectance L* - in %
E.U.
E.U.
Depth in m


L* vs SiO2
SiO2
L*
R = -0,932
CaO vs L*
CaO
L*
R = 0,925
SiO2 vs Ca0
SiO2
CaO
R = -0,9973
Al 2O 3 vs L*
L*
Al2O3
R = -0,899



Depth in cm
0
200
400
600
800
1000
1200
1400
0
0,1
0,2
0,3
0,4
0,5
Illite Cristallinity
Holocene
H.D.U.
Epizone
Anchizone
Diagenese
0,25
0,42
Giffre
Arves
Lf
Ant
NJ
Vx
Ta
Gf
MdG, Tz
Pa, Ch
SG
Mi, Sc
LP, Pl, Rn
Dz
Sa



Crystalline Range

Anchizone 0,4 > I Cr > 0,25

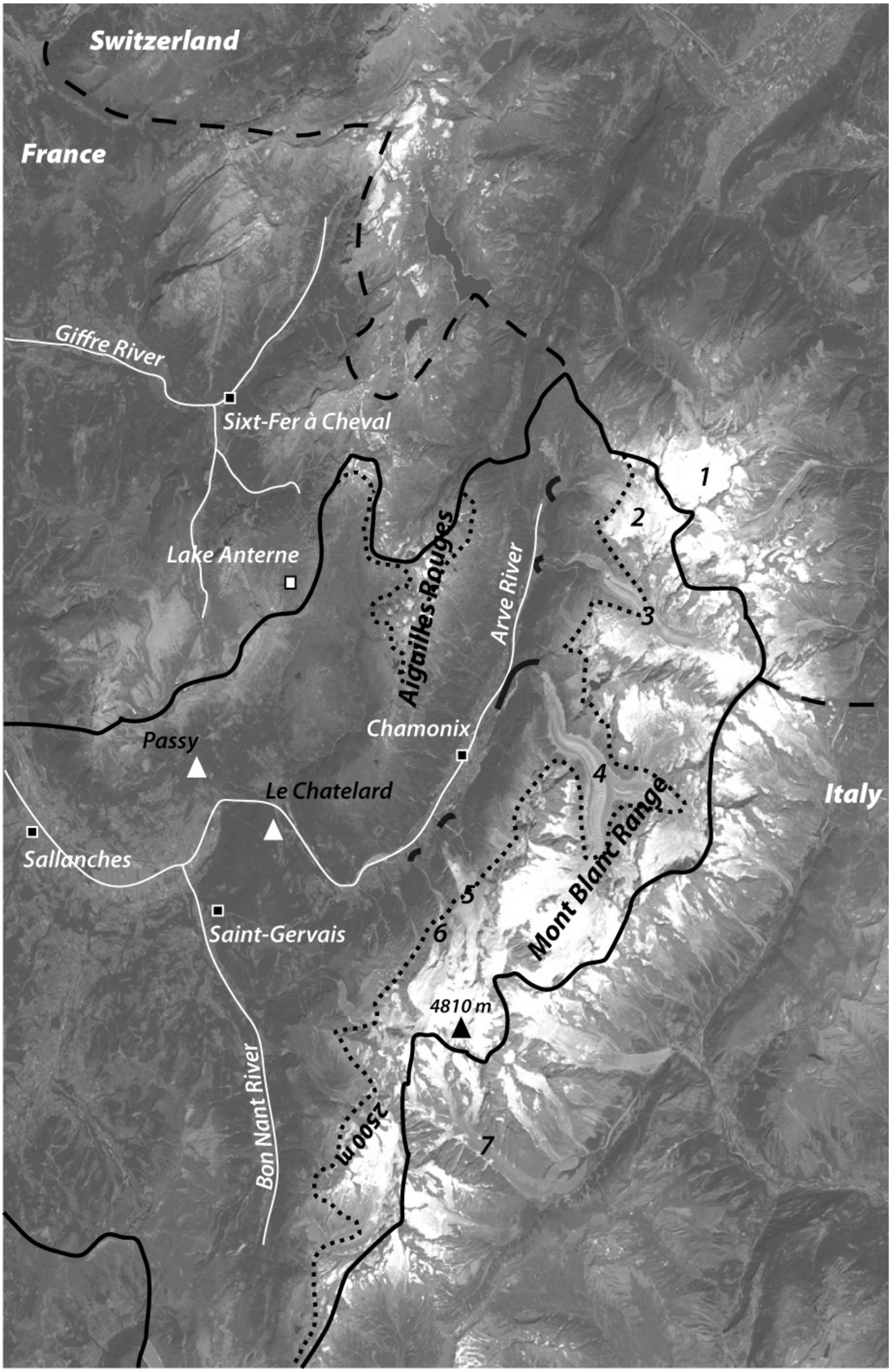
Giffre des Fonds Watershed

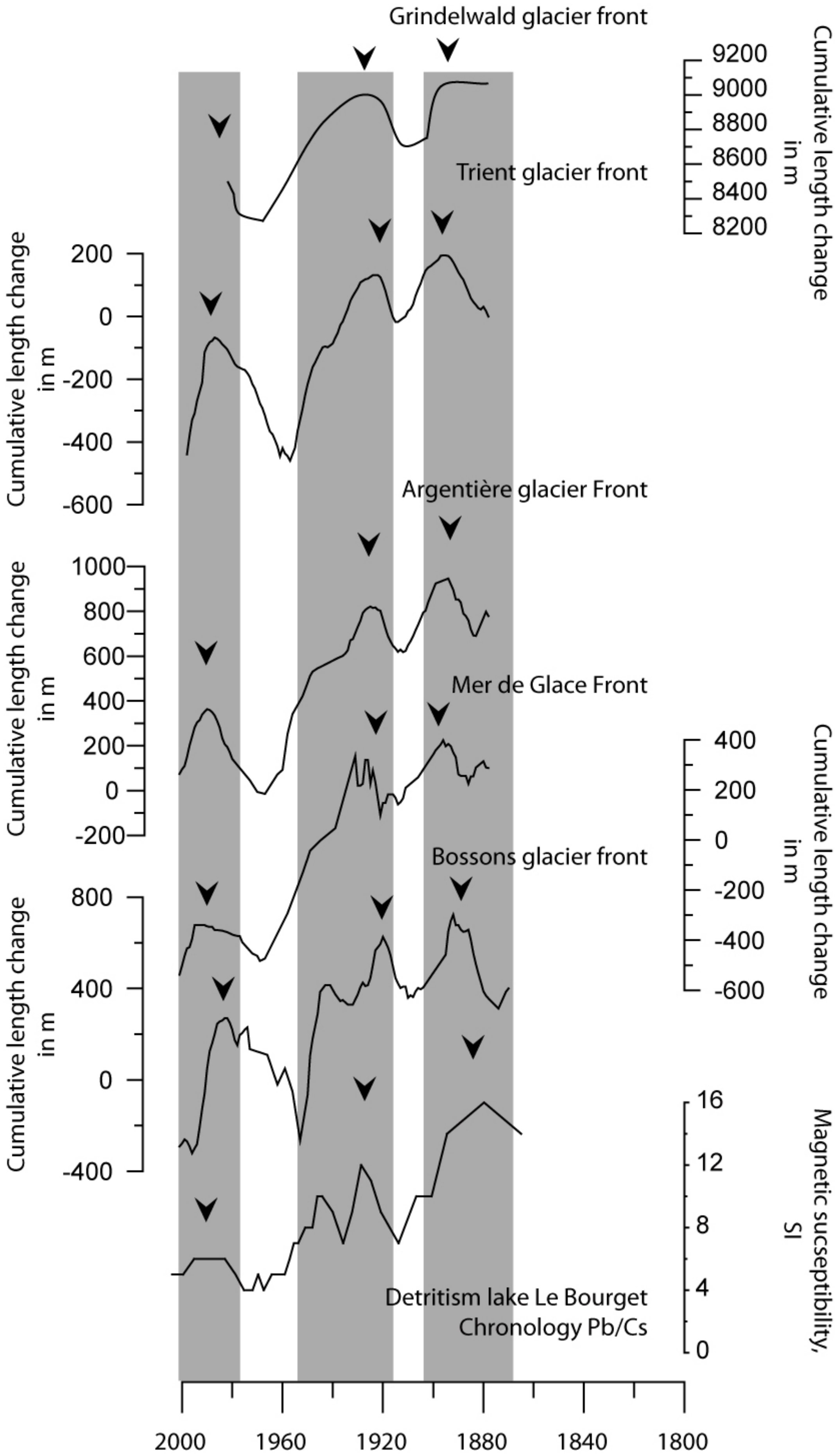
Epizone I Cr < 0,25

undescribed

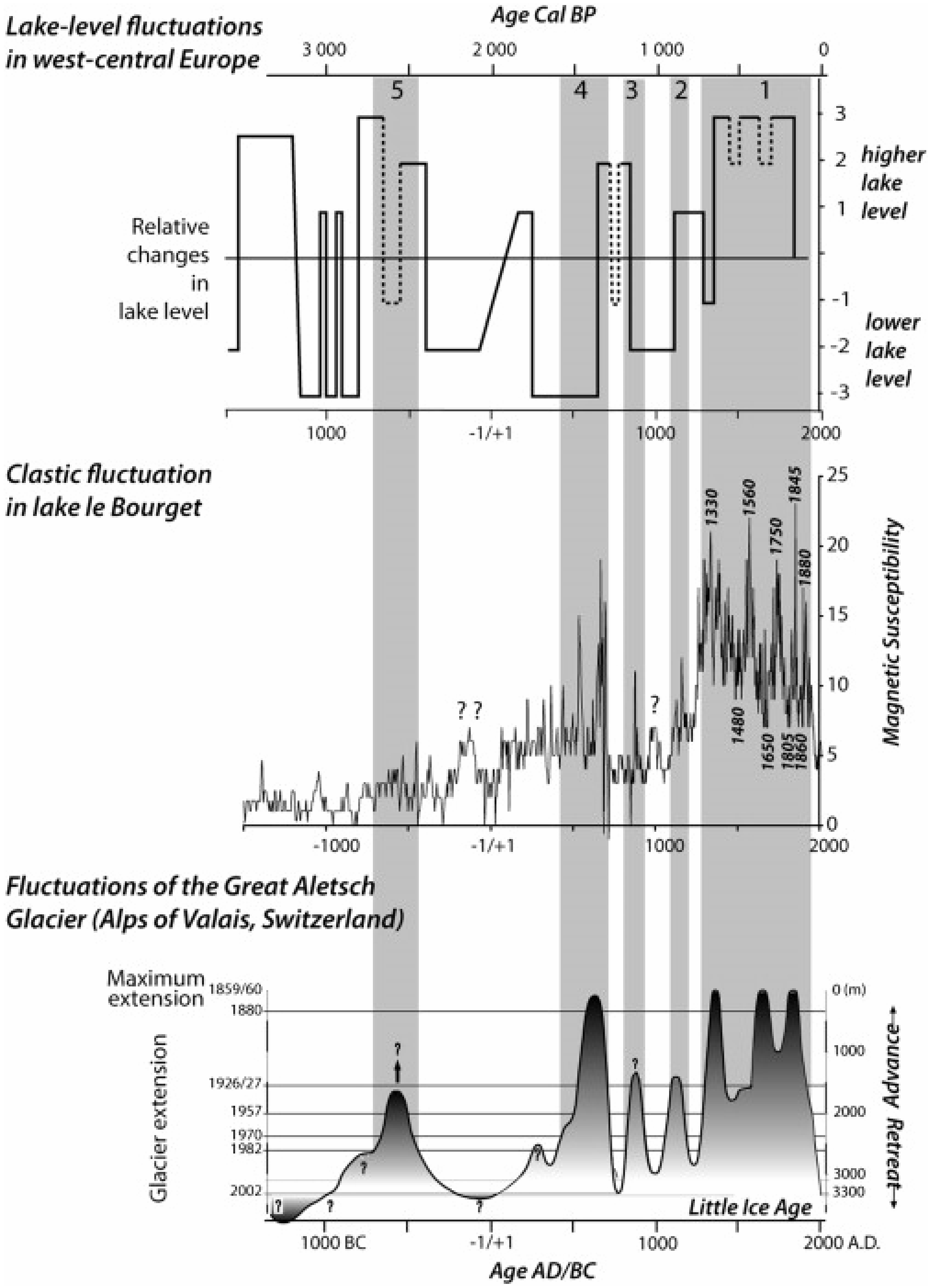
Samples Mai 2005

Main Localities C : Chamonix, St.G. : Saint Gervais, S : Sallanches, Sx. : Sixt-Fer à Cheval

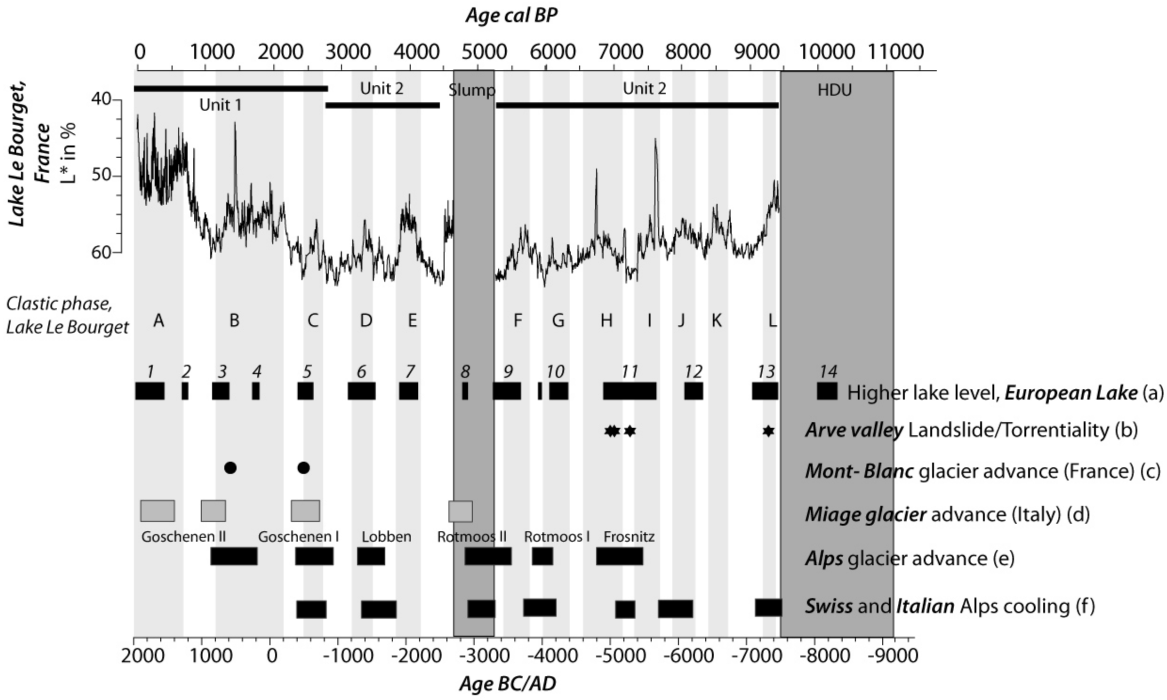

Switzerland
France
Giffre River
Sixt-Fer à Cheval
Lake Anterne
Aiguilles Rouges
Arve River
Passy
Chamonix
Le Chatelard
Sallanches
Saint-Gervais
Bon Nant River
Mont Blanc Range
Italy
4810 m
2500 m
1
2
3
4
5
6
7



Grindelwald glacier front
Cumulative length change in m
9200
9000
8800
8600
8400
8200
Trient glacier front
200
0
-200
-400
-600
Cumulative length change in m
Argentière glacier Front
1000
800
600
400
200
0
-200
Cumulative length change in m
Mer de Glace Front
400
200
0
-200
-400
-600
Cumulative length change in m
Bossons glacier front
800
400
0
-400
Cumulative length change in m
16
12
8
4
0
Magnetic susceptibility, SI
Detritism lake Le Bourget
Chronology Pb/Cs
2000
1960
1920
1880
1840
1800



Lake-level fluctuations in west-central Europe
Age Cal BP
3 000
2 000
1 000
0
5
4
3
2
1
Relative changes in lake level
higher lake level
lower lake level
1000
-1/+1
1000
2000
Clastic fluctuation in lake le Bourget
Magnetic Susceptibility
1330
1560
1750
1845
1880
1480
1650
1805
1860
-1000
-1/+1
1000
2000
Fluctuations of the Great Aletsch Glacier (Alps of Valais, Switzerland)
Maximum extension
1859/60
1880
1926/27
1957
1970
1982
2002
Glacier extension
0 (m)
1000
2000
3000
3300
Advance
Retreat
Little Ice Age
1000 BC
-1/+1
1000
2000 A.D.
Age AD/BC


Age cal BP
0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000 11000
Lake Le Bourget, France
L* in %
Unit 1
Unit 2
Slump
Unit 2
HDU
Clastic phase, Lake Le Bourget
A B C D E F G H I J K L
1 2 3 4 5 6 7 8 9 10 11 12 13 14
Higher lake level, European Lake (a)
Arve valley Landslide/Torrentiality (b)
Mont- Blanc glacier advance (France) (c)
Miage glacier advance (Italy) (d)
Goschenen II
Goschenen I
Lobben
Rotmoos II
Rotmoos I
Frosnitz
Alps glacier advance (e)
Swiss and Italian Alps cooling (f)
2000 1000 0 -1000 -2000 -3000 -4000 -5000 -6000 -7000 -8000 -9000
Age BC/AD