

Rhone River flood deposits in Lake Le Bourget: a proxy for Holocene environmental changes in the NW Alps, France

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The Holocene evolution of Rhone River clastic sediment supply in Lake Le Bourget is documented by sub-bottom seismic profiling and multidisciplinary analysis of well-dated sediment cores. Six high-amplitude reflectors within the lacustrine drape can be correlated to periods of enhanced inter- and underflow deposition in sediment cores. Based on the synthesis of major environmental changes in the NW Alps and on the age-depth model covering the past 7500 years in Lake Le Bourget, periods of enhanced Rhone River flood events in the lake can be related to abrupt climate changes and/or to increasing land use since *c.* 2700 cal. yr BP. For example, significant land use under rather stable climate conditions during the Roman Empire may be responsible for large flood deposits in the northern part of Lake Le Bourget between AD 966 and 1093. However, during the Little Ice Age (LIA), well-documented major environmental changes in the catchment area essentially resulted from climate change and formed basin-wide major flood deposits in Lake Le Bourget. Up to five 'LIA-like' Holocene cold periods developing enhanced Rhone River flooding activity in Lake Le Bourget are documented at *c.* 7200, 5200, 2800, 1600 and 200 cal. yr BP. These abrupt climate changes were associated in the NW Alps with Mont Blanc glacier advances, enhanced glaciofluvial regimes and high lake levels. Correlations with European lake level fluctuations and winter precipitation regimes inferred from glacier fluctuations in western Norway suggest that these five Holocene cooling events at 45°N were associated with enhanced westerlies, possibly resulting from a persistent negative mode of the North Atlantic Oscillation.

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Palaeoenvironmental and palaeoclimate reconstructions in the French NW Alps are commonly presented for the last glaciation and deglaciation (Nicoud *et al.* 1987; Van Rensbergen *et al.* 1998, 1999; Moscariello *et al.* 1998; Manalt *et al.* 2001; Girardclos *et al.* 2005), but relatively little is known about Holocene glacier fluctuations. Millennial-scale Holocene climate fluctuations have been documented by lake level fluctuations, archaeological and palynological records for many small lakes in the Jura Mountains and several larger peri-alpine lakes (Magny *et al.* 2003; Magny 2004). However, such reconstructions may be complicated in the alpine foreland, where large fluvial systems such as the Arve and the Rhone rivers (Fig. 1A) are draining large and contrasting areas, including alpine glaciers. The Holocene geomorphic evolution of these large fluvial systems with respect to climate, land use or an active seismo-tectonic setting is still to be further documented, but may be key to reconstructing detailed Holocene environmental changes in these mid-latitude mountain ranges.

Lake Le Bourget (45°45'N, 5°55'E; Fig. 1) is an 18-km-long narrow and over-deepened basin of glacial

origin situated along an active fault zone next to the Subalpine front (Chapron *et al.* 1999). Its sedimentary infill (Fig. 2), intensively studied by high resolution seismic reflection surveys since 1991, is characterized by well-developed lacustrine fan deltas (seismic stratigraphic Units 3 and 4) in front of each tributary (Sierroz, Laysse and Rhone rivers; Figs 1, 2) and by numerous stacked mass wasting deposits (MWD) (the so-called Hautecombe Disturbed Unit (HDU) or Unit 4R) in the main basin (Chapron *et al.* 1996; Van Rensbergen *et al.* 1999; Chapron *et al.* 2004). During the last deglaciation, the Rhone has been the main tributary of this periglacial lake, and the progradation of the Rhone fan delta has gradually filled up the sub-basin north of the present lake (Fig. 2). During the Preboreal chronozone (11 500–10 200 cal. yr BP), the Rhone delta progradation induced (i) the formation of Lavour and Chautagne swamps north of the present lake (Fig. 2), (ii) a drastic reduction in the sedimentation rate in Lake Le Bourget, as the Rhone River shifted its course westward and bypassed the lake (Bravard 1981), and (iii) the development of a large alluvial plain downstream from the palaeolake

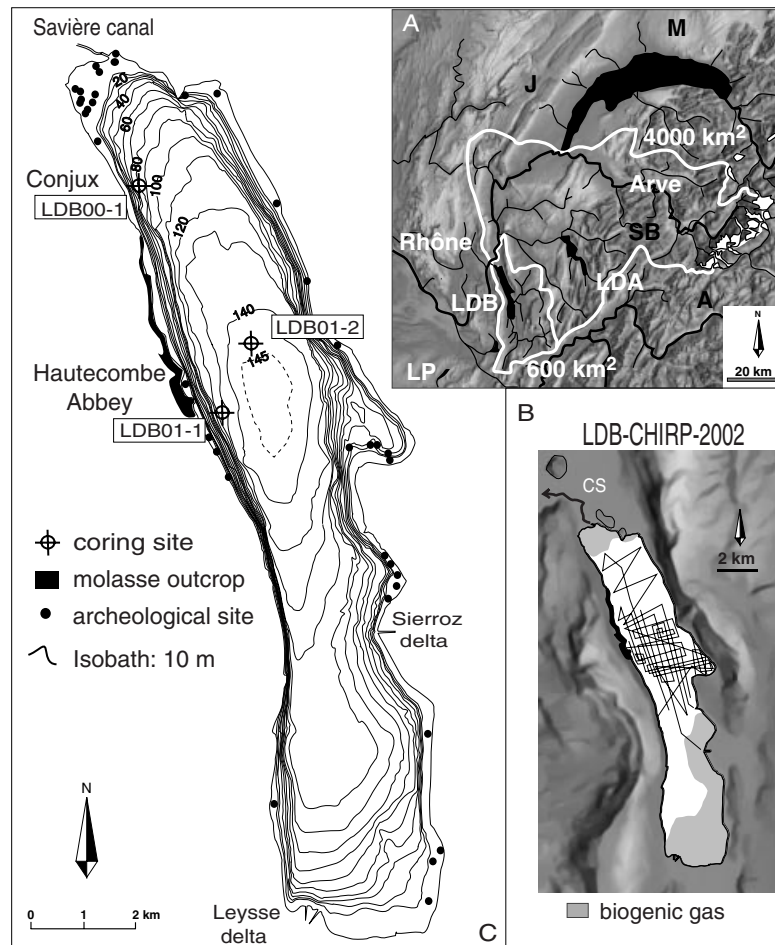


Fig. 1. General setting of Lake Le Bourget. A. Its catchment area in the NW Alps and the present-day extension (in white) of Mont Blanc massif glaciers in the Arve valley. These glaciers represent 15% of the Rhone catchment area between Geneva and Lake Le Bourget (4000 km²). B. Seismic grid of the survey performed in June 2002 with a Chirp device. C. Bathymetric map of Lake Le Bourget indicating the location of piston cores and archaeological sites discussed in the text. LDB: Lake Le Bourget, LDA: Lake Annecy, LP: Lake Paladru, A: Alpine chain, SB: Subalpine massifs, J: Jura mountains, M: Molasse basin, CS: Chautagne swamp.

(Salvador *et al.* 2004). Since this major change, mainly autochthonous Holocene sedimentation (marls) has been favoured in Lake Le Bourget (Van Rensbergen *et al.* 1999) and a lacustrine drape formed (Unit 5, Fig. 2).

In this article, we describe the signatures of Rhone River flood deposits in Lake Le Bourget sediments, the main evolution of lacustrine sedimentary environments during the Holocene and discuss their palaeoenvironmental and palaeoclimatic implications.

Holocene geomorphological and archaeological settings

The catchment area of Lake Le Bourget is characterized by a local watershed related to the Leysse and Sierroz rivers (600 km², with a maximum elevation at

1845 m a.s.l.; Fig. 1) and a sporadic regional watershed only during major flooding events of the Rhone River (a catchment of 4000 km², culminating at 4808 m and mainly related to the Arve river supply). During the Little Ice Age (LIA), Rhone River flood waters entering Lake Le Bourget were more frequent, more powerful and sometimes catastrophic (Chapron *et al.* 2002), until efficient embankments were built on the floodplain north of the lake (the Chautagne swamp, Figs 1, 2) in the mid-19th century (Bravard 1981). Coarse particle size distributions of the levees between the braided Rhone River bed and the Chautagne swamp in the 18th century (Fig. 2A), together with the extension of catastrophic flood deposits in the lake basin during the LIA (Fig. 2B), highlight the high energy of floods entering into the lake during the LIA.

Like many peri-alpine lakes, prehistoric human settlements in the study area were closely related to periods of low lake levels (Magny 2004). The main

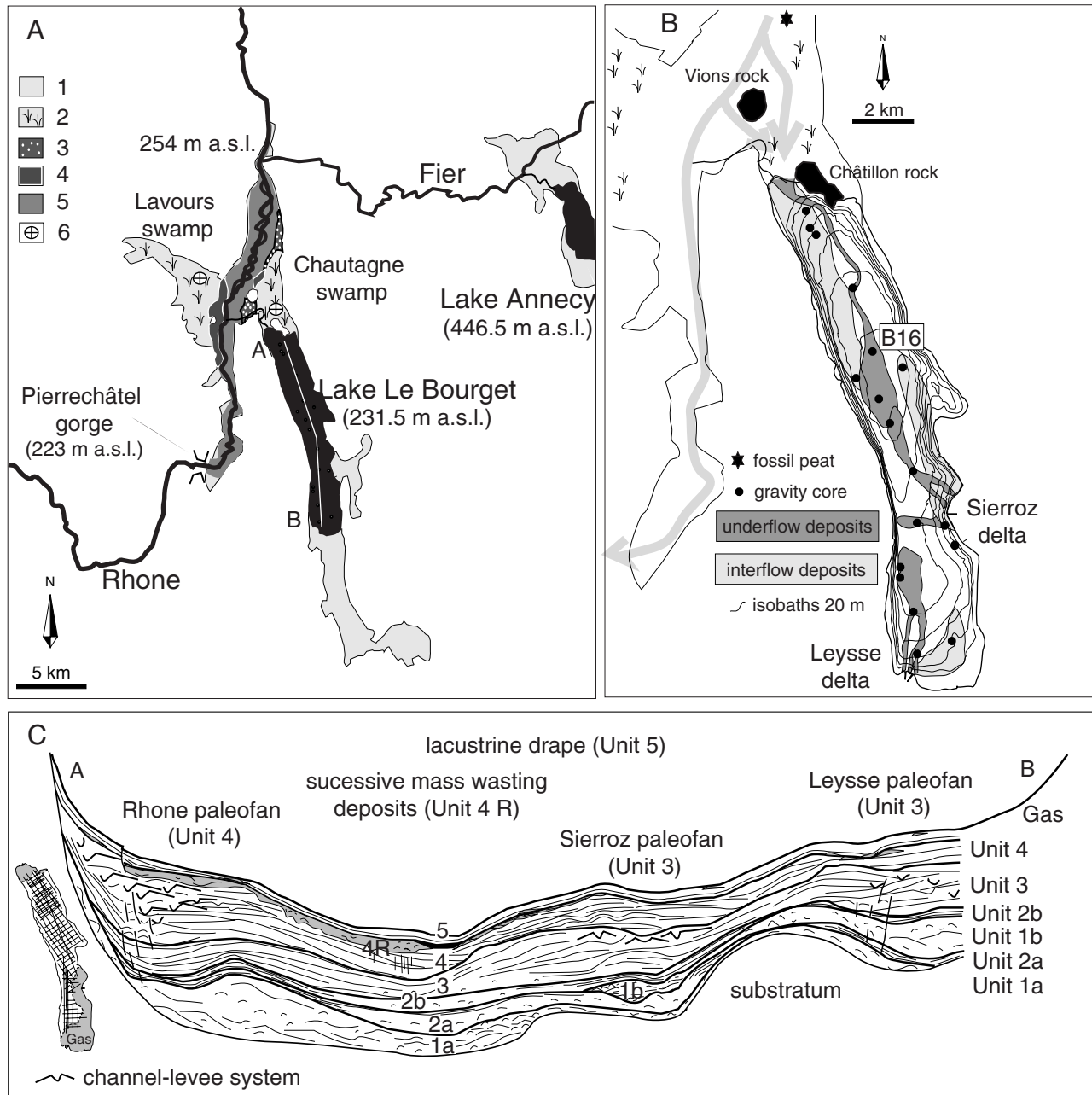


Fig. 2. Relation between the Rhone River and Lake Le Bourget. **A.** Sedimentary environments in the 18th century associated with the Rhone River, the Lavours and Chautagne swamps. 1: Lateglacial palaeolake (after Nicoud *et al.* 1987), 2: back swamps and flood plains, 3: gravel-dominated alluvial plain, 4: silt-dominated alluvial plain, 5: river bed, 6: location of old drill-sites discussed in Bravard (1981). **B.** Extension of subaqueous flood deposits in Lake Le Bourget related to the Rhone, Sierroz and Laysse rivers in the 18th century (after Chapron 1999) and location of Chautagne buried peat sample dated by radiocarbon. **C.** Synthetic seismic stratigraphy of Lake Le Bourget sedimentary infill since the last glaciation (Chapron 1999) across A–B profile in (A) based on a dense grid of sparker seismic data shown in (C) and detailed in Chapron *et al.* (1996) and Van Rensbergen *et al.* (1999). Note the extension of the Rhone River fan delta in Unit 4 largely remoulded by Unit 4R.

archaeological sites in Lake Le Bourget are located in shallow waters within littoral platforms in bays or close to the lake outlet (Fig. 1). These sites are essentially of Neolithic and Late Bronze Age (from 5500 BC to 850 BC), but evidence for settlements in the

Antiquity (700 BC–AD 500), Gallo-Roman period and High Middle Age (AD 500–1000) exists (Billaud & Marguet 1997; Marguet 2002). Since the Preboreal, the water level of Lake Le Bourget has been essentially controlled by the altitude of the Rhone River bed in

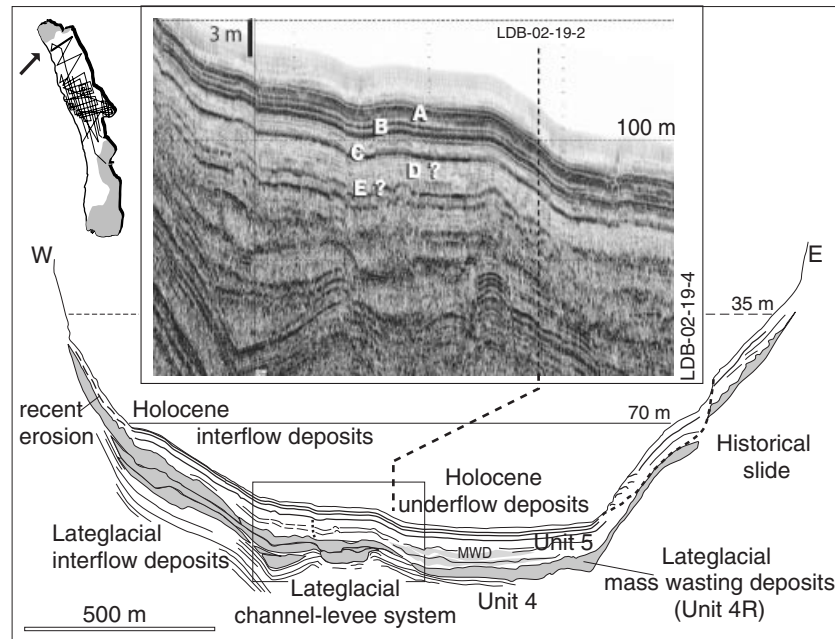


Fig. 3. Seismic section in proximal Rhone River flood deposits and its interpretation. Note the Lateglacial channel levee system of the Rhone fan delta in Unit 4 and strong amplitude draping reflections in Unit 5. Reflectors A, B and C can be clearly correlated from proximal to distal clastic environments, but the occurrence of several mass-wasting deposits (MWD) is limiting the correlation of reflectors D and E in these proximal environments.

the Chautagne swamp, where the lake outlet reaches the Rhone. According to Bravard (1981), the rise in the level of Lake Le Bourget since the Neolithic records a progressive aggradation of the Rhone River profile. Within this transgressive trend, Magny & Richard (1985) have distinguished minor but abrupt lake level fluctuations over the past 4500 years at archaeological sites offshore of Conjux (Fig. 1). These reconstructions highlight regressive phases during the Neolithic (4000–3700 cal.yr BP), the Bronze Age (3000–2800 cal.yr BP) and the Gallo-Roman time (1700–1500 cal.yr BP).

Material and methods

High-resolution seismic profiling

Over 90 km of very high-resolution seismic reflection digital profiles were acquired using a BATHY2000P device with a chirp seismic source in June 2002 (Fig. 1). With this seismic source, a modulating frequency centred at 12 kHz allowed imaging of up to 30 m of sediments with a 0.2 m vertical resolution. The seismic grid based on G.P.S. positioning acquired during the survey, and its visualization using BATHY2000W software, provides a detailed stratigraphic record of Holocene sediments in the main basin of Lake Le Bourget (Figs 3–5).

Sediment cores

Using a Benthos device, 17 short gravity cores (~1 m long) were retrieved in 1997 from the main lacustrine sedimentary environments (Fig. 2B). The coring sites were previously selected based on side scan sonar mapping calibrated by grab samples. Based on this data set, the short cores were correlated across the lake (Chapron 1999; Chapron *et al.* 2002). Three piston cores were then retrieved (Fig. 1) with an UWITEC coring device from a barge in 2000 (LDB00-1) and 2001 (LDB01-1 and LDB01-2). These coring sites were selected on the basis of the available seismic data set (cf. Van Rensbergen *et al.* 1999; Chapron *et al.* 2004) and on the sedimentary record of the LIA in short gravity cores, in order to extend back in time the evolution of proximal and distal Rhone River flood deposits. LDB00-1 (2.9 m long) was recovered from 80 m water depth offshore of Conjux in Rhone River proximal interflow deposits (Chapron *et al.* 2004). LDB01-1 (9 m long) was sampled at 129 m water depth in distal Rhone river flood deposits (essentially interflows, Arnaud *et al.* 2005). Near the B16 short coring site (Fig. 2A), LDB01-2 (7.4 m long) was retrieved from 142 m water depth in distal Rhone River underflow deposits, but this coring site consists of three sections without a complete coverage (0 to 1.4 m; 1.6 to 4.4 m and 4.6 to 7.4 m).

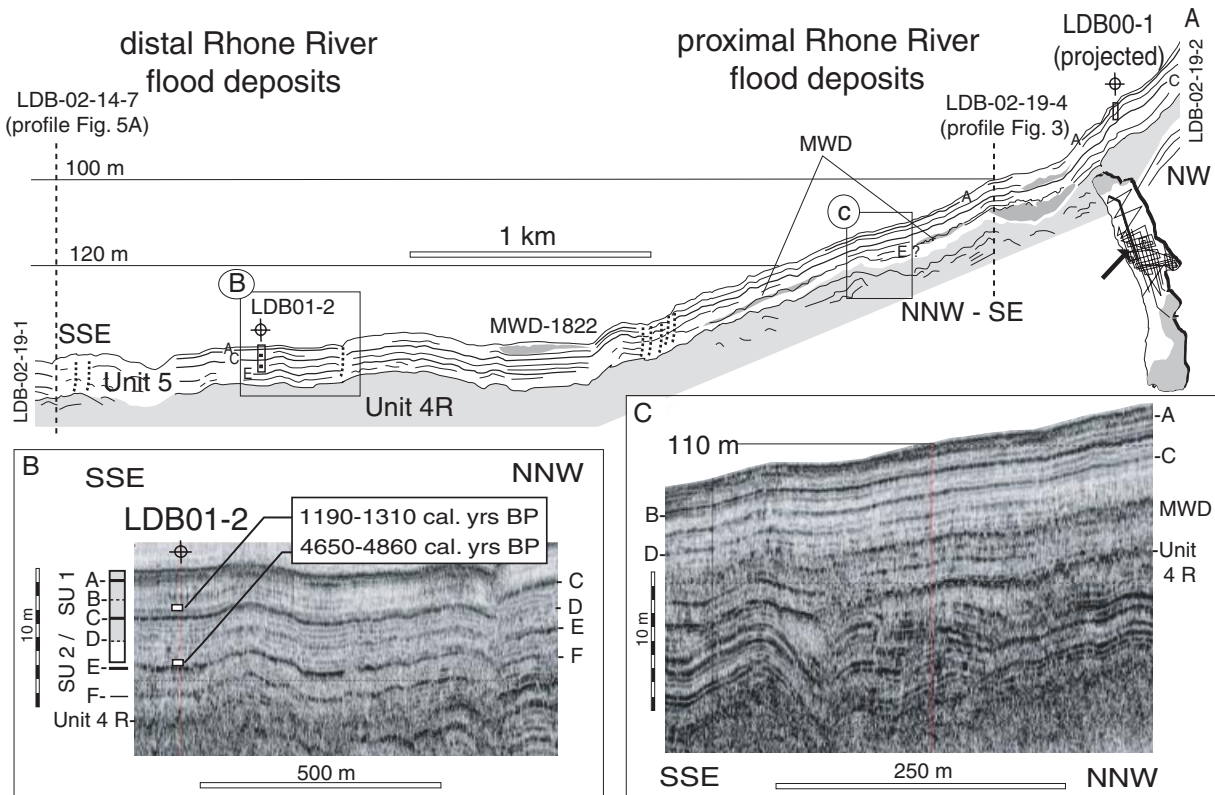


Fig. 4. Unit 5 seismic stratigraphy in the northern part of Lake Le Bourget (A) showing the extension of strong amplitude reflections (labelled A to E) and of mass-wasting deposits (MWD), as well as the location of piston cores and seismic sections in distal (B) and more proximal (C) Rhone River flood deposits. Also indicated are the depth locations of radiocarbon samples in core LDB01-2 and the synthetic lithology of this core based on the correlation of strong amplitude reflections and magnetic susceptibility profile (SU: sedimentary units). Note that Unit 5 draping Unit 4R is locally affected by ongoing listric faulting.

Sedimentary analysis

Laboratory descriptions of core lithologies (Figs 7, 8) are supported by laser diffraction grain-size measurements using a Malvern Mastersizer at Savoie University (Chapron *et al.* 1999; Arnaud *et al.* 2005; Revel *et al.* in press). Sediment magnetic susceptibility (MS) was measured with a Bartington loop sensor every 0.02 m on short cores and every 0.01 m on piston cores in order to correlate overlapping sections sampled in 2001. On LDB01-1 and on the upper section of LDB01-2, a detailed evolution of MS was measured every 5 mm (Fig. 8) with a Bartington MS2E1 surface scanning sensor (Arnaud *et al.* 2005). Total organic carbon (TOC) was documented by the thermal cracking of the organic matter between 200 and 600°C with a Rock-Eval 6 at Orléans University (Noël *et al.* 2001) every 0.05 m on selected short cores (Fig. 6) and every metre on LDB01-1 (Fig. 7). Carbonate content was also documented every metre on LDB01-1 by the Rock-Eval 6 pyrolysis/oxidation method (see Lafargue *et al.* (1998) for details). Bulk density was measured on a GEOTEK multi-sensor track at ETH Zürich every 5 mm on U-channels from

one drill at LDB01-1 coring site and converted into dry density by 98 measurements at Savoie University on 1 cm³ samples.

Age–depth models

Chronology in Lake Le Bourget sediments was established using ²¹⁰Pb, ¹³⁷Cs dating and by correlation of sedimentary events with historical chronicles (Fig. 7), such as strong local earthquakes, LIA tributary floods and the lake eutrophication (Chapron *et al.* 1999). On LDB01-1 the age–depth model (Fig. 8) is based on: (i) the recognition of key historical chronological markers (the lake eutrophication in 1940, the AD 1822 earthquake-triggered MWD (MWD-1822) and the oldest historical flood of the Rhone River in AD 1732) and (ii) six AMS ¹⁴C dates summarized in Table 1 (and further detailed in Arnaud *et al.* 2005). On LDB01-2, the age–depth model (Figs 4, 7) is based on: (i) recognition of the AD 1822 megaturbidite and the AD 1732 flood deposit in the lithology and on the MS profile, (ii) the correlation of the MS profile with the

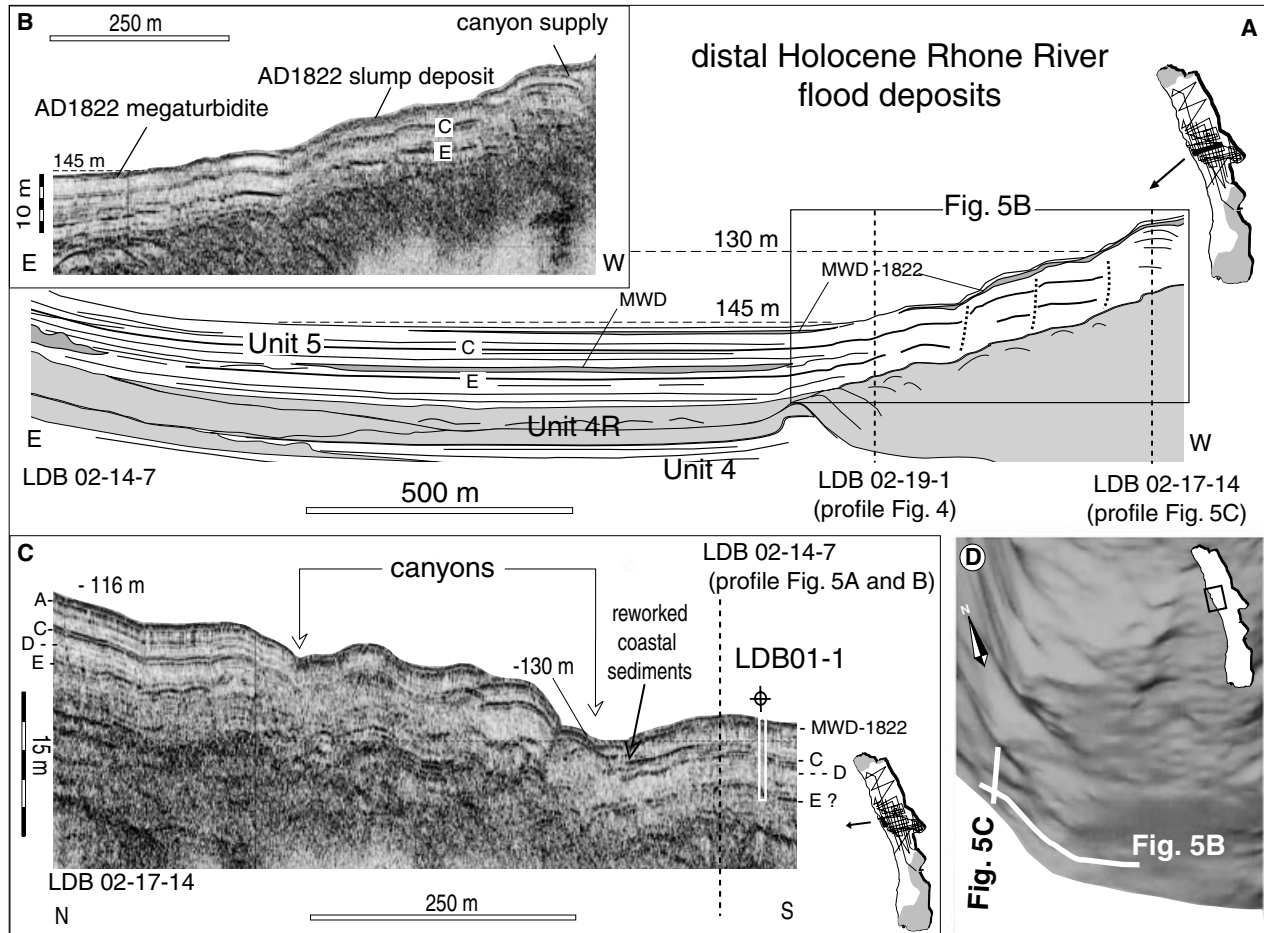


Fig. 5. Sedimentary environments near LDB01-1 coring site. Seismic stratigraphy of Unit 5 in the deep basin (A) and section of the profile (B) illustrating strong amplitude reflectors C and E. Seismic section across site LDB01-1 (C) illustrating the influence of canyons on sedimentation near the coring site, and mass-wasting deposits (MWD) triggered by the AD 1822 earthquake (MWD-1822). Location of seismic sections B and C on a selected part of the digital elevation model of the lake floor morphology (D) discussed in Chapron *et al.* (1996) and illustrating the development of canyons along the steep western edge of the deep basin. Note the irregular lake floor morphology in the deep basin due to the occurrence of Unit 4R now draped by c. 15 m of sediments (Unit 5).

one of LDB01-1, and (iii) two AMS ^{14}C dates (Table 1).

Sedimentary environments

Seismic stratigraphy

Only the top of Unit 4 is visible on our chirp data where Unit 4R is not too thick. This is the case in the northern part of the basin (Fig. 3), where the geometry of the Rhone fan delta in this proximal setting clearly illustrates two different depocenters: a channel-levee system made of underflow deposits and well-stratified interflow deposits developing continuous reflections draping the western flank of the basin (Chapron *et al.* 2004). Unit 4R consists of a complex succession of stacked MWD remoulding Lateglacial sediments from Unit 4 and developing megaturbidites in the deep basin

(Figs 3–5). Unit 5 forms a lacustrine drape 8 to 15.5 m thick across the lake, although its thickness near deltas is poorly constrained because of gas-rich sediments preventing acoustic penetration (Figs 1, 2). Besides its draping geometry, Unit 5 is characterized by: (i) the development of several parallel strong amplitude reflections in the northern part of the lake (labelled reflector A to F in Figs 3–5), some of them extending down to the deeper basin (A, C and E) and (ii) the occurrence of MWD that are essentially remoulding Rhone River interflow deposits and sometimes transforming into megaturbidites toward the deep basin (i.e. MWD-1822 in Figs 4 and 5). In the main basin of Lake Le Bourget, Unit 5 is locally affected by ongoing listric faulting, which, together with the occurrence of gravity reworking phenomena, limits correlations of strong amplitude reflections (Figs 4, 5). Along the western edge of the basin near the coring site of LDB01-1 Unit 5 is also punctuated by pulses of clastic

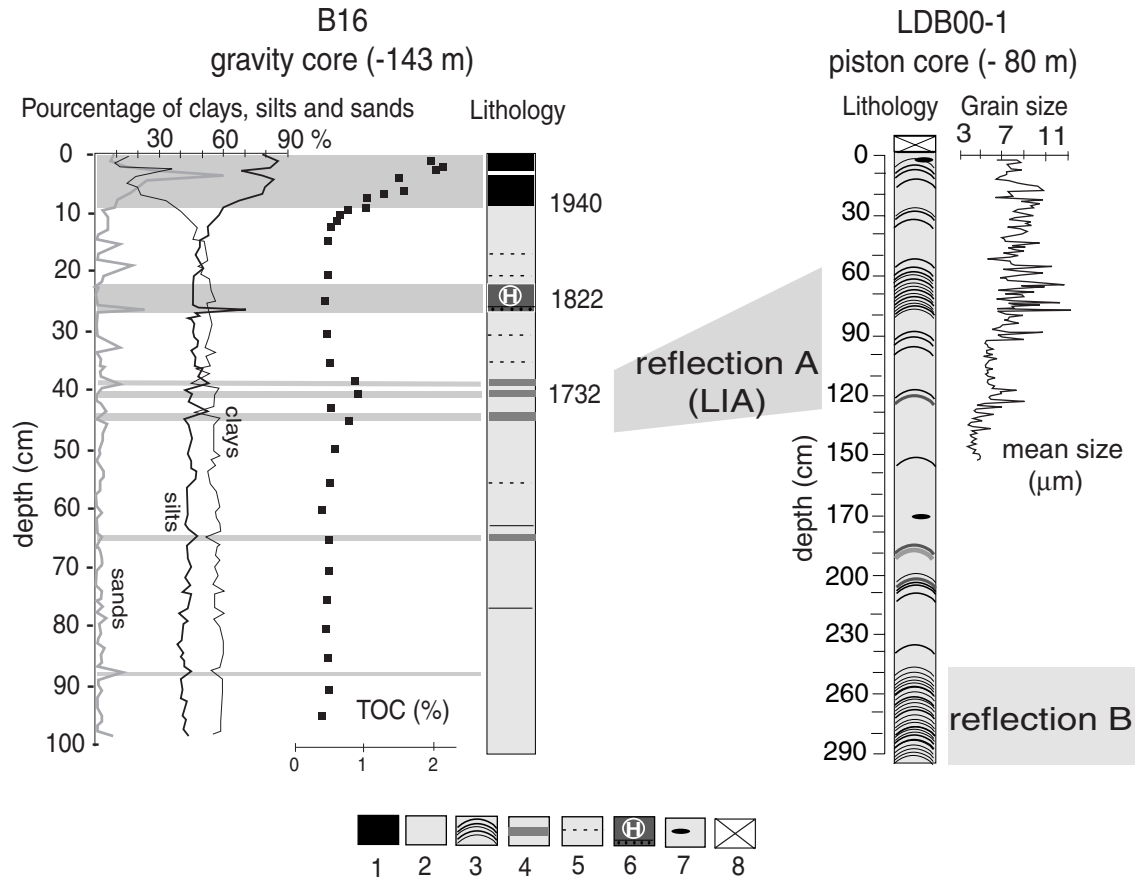


Fig. 6. Lithological signatures of Rhone River flood deposits from sediment cores retrieved in proximal (LDB00-1) and distal (B16) environments. Flood deposits are characterized by slightly coarser particles and higher content in total organic carbon (TOC). Also indicated is the correlation of seismic reflections A and B with periods of more intense flood deposits. The difference in the depths of flood deposits resulting from the Little Ice Age (LIA) in cores B16 and LDB00-1 is essentially related to the compaction of uppermost water-saturated sediments during gravity coring operations (B16). 1: post-1940 eutrophicated unit (biochemical varves), 2: carbonate-rich lacustrine marls, 3: interflow deposits, 4: catastrophic underflow deposits, 5: organic debris, 6: AD 1822 megaturbidite, 7: wood debris, 8: missing uppermost sediments (~20 cm, cf. Chapron *et al.* 2004).

sediments funnelled through canyons (localized stacked high amplitude reflections; Fig. 5). These steep canyons drain several small bays and a littoral platform next to the Hautecombe Abbey where Tertiary Molasse bedrock outcrops (Figs 1, 5).

Rhone River flood deposits

The strong amplitude reflectors A and B south of the lake outlet (Fig. 3) correspond to periods of enhanced Rhone River proximal interflow deposits sampled in the core LDB00-1 and characterized by successive dark coloured clayey silt layers (Fig. 6) coarser than the carbonate-rich background sedimentation (Chapron *et al.* 2004). Toward the deep basin, in cores B16 and LDB01-2, reflector A can also be correlated to the last occurrence of successive catastrophic underflow deposits (Fig. 6). These flood deposits are associated with high MS values in LDB01-2 (Fig. 7) and in LDB01-1 even if their signatures in this core are

affected by one of the MWD-1822 (Figs 5, 7). These flood deposits in core B16 have a coarser mean grain size due to higher silt and sand abundances (Fig. 6) and are systematically associated with an increase in SiO_2 , Al_2O_3 , Fe_3O_4 , MgO and Ti , but a decrease in CaO contents (Revel *et al.* in press). Organic debris characterizes the base of these catastrophic underflow deposits, reflected by a slightly higher TOC content (Fig. 6). Moreover, their enrichment in illite clay minerals (Chapron *et al.* 2002) and the Sr/Nd isotopic signature (Revel *et al.* in press) confirms that the sediments originate from the Mont Blanc massif and were transported by Arve and Rhone rivers during flood events. The strong amplitude reflector C clearly recognized across the northern part of the lake (Figs 3–5) corresponds in the deep basin to a period of enhanced Rhone River distal flood deposits (inter- and underflow deposits) associated with high MS values in LDB01-1 and LDB01-2, as well as denser sediments with a higher organic content than the host mud in

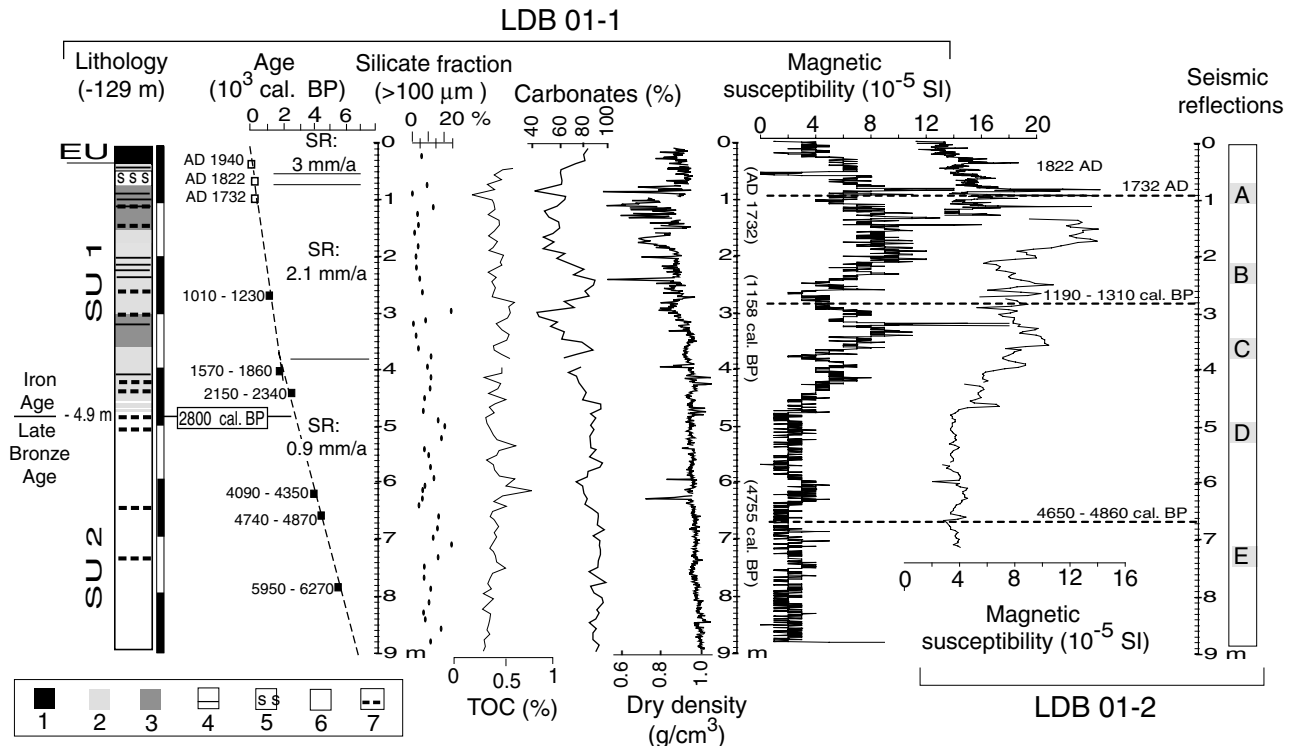


Fig. 7. Lithological signatures of distal Rhone River flood deposits in long piston cores from the deep basin and location of historic events and calibrated radiocarbon dates used to establish the age–depth model discussed in the text. This age–depth model is based on five radiocarbon dates in LDB01-1 and two in LDB01-2 (summarized in Table 1). Ages in parentheses next to the magnetic susceptibility profile on LDB01-1 show the consistency of the age–depth model established by Arnaud *et al.* (in press), when compared to radiocarbon dates in LDB01-2 and the correlation of strong amplitude reflections A to E near LDB01-2 coring site. 1: eutrophicated unit, 2: interflow deposits (lamination index <3), 3: interflow deposits (lamination index >3, cf. Arnaud *et al.* 2005), 4: catastrophic underflow deposits, 5: AD 1822 slump deposit, 6: lacustrine marls poor in silicates, 7: sandy layers originating from the nearby canyon and reworking Tertiary Molasse outcrops (after Arnaud *et al.* in press and Chapron *et al.* in press).

LDB01-1 (Fig. 7). Reflector B becomes less continuous toward the axis of the deep basin and its amplitude decreases in distal Rhone River flood deposits (Fig. 4), but this horizon is still associated in LDB01-2 with small peaks in MS matching several catastrophic underflow deposits in LDB01-1 that bear higher TOC values (Fig. 7). Reflector B thus probably reflects Rhone River floods of lower energy than those that produced reflector C, and was not clearly recorded at the LDB01-1 coring site, where a prevailing clastic supply was originating from the canyons (Fig. 5) draining the steep western edge of the basin (cf. Arnaud *et al.* 2005; Chapron *et al.* in press). Reflector D is characterized by a rather weak and variable amplitude in the study area and corresponds in LDB01-1 to the transition from sedimentary unit 2 (SU2, with low MS values and higher carbonate content) to sedimentary unit 1 (SU1, with higher MS values due to higher silicate content; Arnaud *et al.* 2005). On the contrary, reflector E is well developed in the axis of the deep basin, but was not sampled in LDB01-2 and in LDB01-1, where it is just beyond the depth reached by coring (Figs 4, 5). Its ponded geometry suggests the development of enhanced

Rhone River underflows during this period (Van Rensbergen *et al.* 1999). Reflector F is also characterized by a ponded geometry, but its lower amplitude (Fig. 4) is interpreted as resulting from underflows less powerful than the ones producing reflector E.

Chronology of Holocene clastic pulses

Based on a synthetic age–depth model in the deep basin of Lake Le Bourget resulting from 8 AMS ^{14}C dates, the recognition of three historical events and the correlation of MS profiles in cores LDB01-1 and LDB01-2 (Fig. 7), it is possible to estimate the age of reflectors A, B, C, D and E at LDB01-2 coring site (Fig. 4B). The resolution of this chronology is based on: (i) the resolution of the seismic data (0.2 m), (ii) the application of a 1500 m/s P-wave velocity in the sediments (Finckh *et al.* 1984), (iii) the depth of the top of the reflections below the lake floor (b.l.f.), and (iv) the application of a mean sedimentation rate of 3 mm/yr from 0 to 0.5 m, of 2 mm/yr from 0.5 to 4 m and of 1 mm/yr from 4 m down to the base of seismic Unit 5.

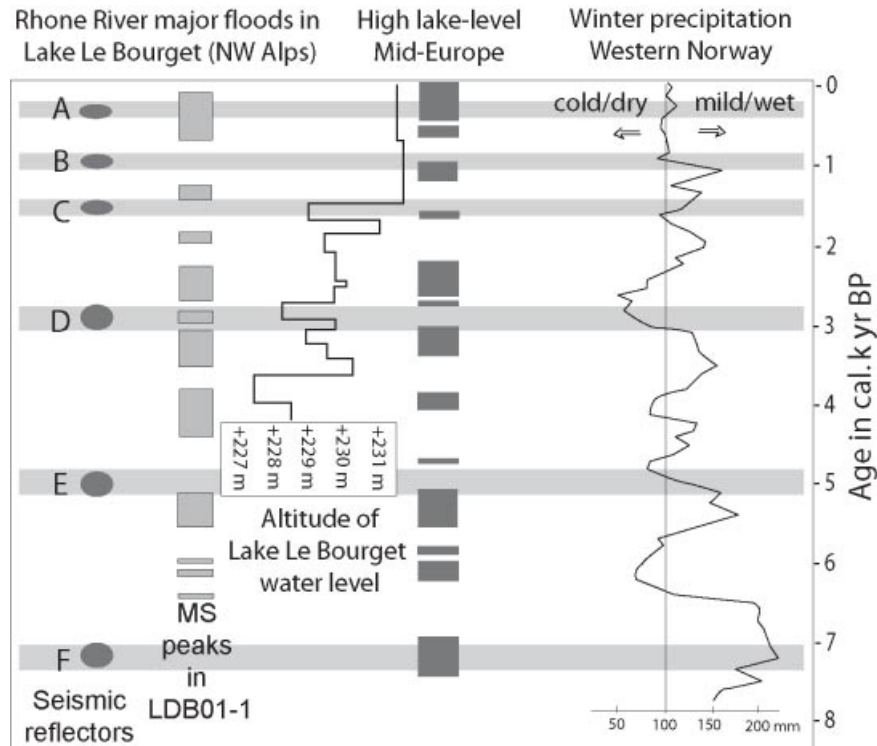


Fig. 8. Comparison from right to left of winter precipitation reconstructions in western Norway (after Nesje *et al.* 2001) with high lake-level phases in mid-Europe (Magny 2004), lake-level reconstruction since the Neolithic in Lake Le Bourget (Magny & Richard 1985) and Rhone River flooding activity in Lake Le Bourget inferred (i) from magnetic susceptibility (MS) curve in LDB01-1 (Arnaud *et al.* 2005) and (ii) from calculated age of seismic reflectors in Unit 5 (this study).

The calculated ages of these reflectors are: AD 1780 ± 100 years for reflector A (at 0.6 m b.l.f.); AD 966 ± 100 years for reflector B (at 2.1 m b.l.f.); AD 384 or 1616 ± 100 cal. yr BP for reflector C (at 3.4 m b.l.f.); 3016 ± 200 cal. yr BP for reflector D (at 5.1 m b.l.f.) and 5016 ± 200 cal. yr BP for reflector E (7.1 m b.l.f.). The extrapolation of a constant sedimentation rate of 1 mm/yr down to the base of seismic Unit 5 at LDB01-2 coring site gives an age of approximately 7000 ± 200 cal. yr BP for reflector F (at

9.1 m b.l.f.) and places the base of the undisturbed Unit 5 (10.1 m) in the centre of the basin at around 8000 ± 200 cal. yr BP.

Following the key reflections A and C from the deep basin toward more proximal Rhone River flood deposits we estimate a mean sedimentation rate of 2 mm/yr for the first 3.5 m of Unit 5 in Fig. 4C and of 2.6 mm/yr for the first 4.1 m of Unit 5 in Fig. 3. Since reflector E is not clearly identified in this more proximal part of the basin because of the occurrence of several MWD, it is not yet possible to estimate the age of deeper reflections in Unit 5. The estimated sedimentation rate of 2 mm/yr gives an age of AD 1065 ± 100 years to reflector B in Fig. 4C (at 1.87 m b.l.f.), while a sedimentation rate of 2.6 mm/yr in the upper part of Unit 5 in Fig. 3 gives an age of AD 1093 ± 100 years to reflector B at 2.36 m b.l.f.

Table 1. Accelerator mass spectrometry ^{14}C dates and calibrated ages (calibration after Stuiver & Reimer 1993) of the samples selected in cores LDB01-1 and LDB01-2.

Laboratory code	Depth (m)	^{14}C age	Median calibrated age yr BP (+/-2s)		
LDB01-1					
POZ 710	2.71	1200 ± 30	1010	1130	1230
POZ 718	4.07	1800 ± 45	1570	1710	1860
POZ 716	4.41	2250 ± 30	2150	2260	2340
POZ 717	6.19	3820 ± 30	4090	4200	4350
POZ 715	6.68	4280 ± 40	4740	4840	4870
POZ 721	7.91	5310 ± 40	5950	6080	6270
LDB01-2					
POZ 723	2.80	1350 ± 30	1190	1290	1310
POZ 711	6.68	4230 ± 40	4650	4830	4860

Discussion

Significance of reflections in Unit 5

Considering the resolution of our chronology, together with the sedimentary signatures of enhanced periods of Rhone River flood deposits, and the geometries of the

strong amplitude reflections in Unit 5, we interpret reflectors A, B, C, E and F as resulting from a contrasting acoustic impedance between deposits of frequent powerful inter- and underflows triggered by Rhone River floods, and background sedimentation (lacustrine marls). Thus these reflectors may form at the onset or at the end of a period of enhanced Rhone River flooding activity.

Flood deposits clustering around AD 966–1093 and producing reflector B seem to have resulted from less powerful events than the ones producing reflector A during the LIA, reflector C during the Gschenen I period, reflector E at the time of the Alpine Iceman and reflector F during the Boreal. However, these five reflections contrast with reflector D, which is attributed to a period of progressive increase in clastic versus autochthonous ratios in sedimentary environments receiving Rhone River supply after the Late Bronze–Iron Age transition. This horizon thus reflects an important change from deep sedimentation that is essentially calcareous (SU2) to deep sedimentation (SU1) influenced by fluctuating discharges of distal Rhone River flood suspended load.

These interpretations are in general agreement with the correlation of MS peaks in LDB01-1 (Arnaud *et al.* 2005) with periods of higher Rhone River water discharge and abrupt transgressive phases in Lake Le Bourget during the Late Bronze–Iron Age transition (*c.* 2800 cal.yr BP), during the transition from the Roman period to the High Middle Age (*c.* 1600 cal.yr BP) and during the LIA (Fig. 8). This is further supported by the correlation of reflectors A, B, C, D, E and F in Unit 5 with documented Rhone River discharge fluctuations or geomorphological changes upstream or just downstream from Lake Le Bourget during Holocene environmental changes in the NW Alps, outlined below.

Holocene environmental changes in the NW Alps

The catastrophic impact of the AD 1732 Rhone River flood over the Chautagne swamp reported by Bravard (1981) and the induced major underflow deposit retrieved by several short cores in Lake Le Bourget (Chapron *et al.* 2002) illustrate the downstream consequences of disastrous floods related to the development of larger glaciers in the Mont Blanc massif during the LIA (Dorte-Monachon 1988; Holzhauser & Zumbhl 1999; Vincent *et al.* 2004; Deline 2005). Successive similar Rhone River flood deposits contributed to reflection A in Lake Le Bourget during the early 15th, 16th and mid-18th centuries (Chapron *et al.* 2002) and are attributed to the enhanced fluvio-glacial regime of the Arve River (Ballandras & Jaillet 1996) and the intense deposition of coarse sediments associated with the downstream propagation of a braided pattern along the Rhone valley documented by Bravard (1989) and Salvador *et al.* (2004).

Back in time, the development of reflection B is contemporaneous with a regional lake transgression (Magny 2004) and to the burial of the Chautagne peat by Rhone River silty sediments as far as *c.* 2 km from the river bed (Fig. 2) dated to 1170 ± 40 yr BP (880 ± 200 cal.yr BP; Evin *et al.* 1983; Bravard 1989). These Rhone River flood deposits in the Chautagne swamp are associated with the deposition of gravel beds in the alluvial plain between AD 650 and 1250 (Salvador *et al.* 2004) downstream from the Pierrechtel gorge (Fig. 2), highlighting a significant change in the Rhone River water discharge. This is in agreement with extreme precipitation and a small lake level rise documented by Borel *et al.* (1994) between AD 940 and 970 at the Colletiere archaeological site in Lake Paladru (Fig. 1). However, the strong impact of land use on hill slopes and alluvial plains (discussed below) probably enhanced the consequences of climate fluctuations in the study area, since only solifluction is described in the Arve catchment area near the Tour glacier (Ballandras & Jaillet 1996) and in the Swiss Alps (Maisch *et al.* 2000), but no clear alpine glacier fluctuations were reported in the western Swiss and French Alps by Holzhauser & Zumbhl (1999).

The outstanding reflection C in Lake Le Bourget matches a distinct advance of (i) the Aletsch glacier between AD 350 and 650 in the Vallais (Maisch *et al.* 2000; Holzhauser *et al.* 2005), and (ii) the Argentiere glacier around AD 470 (1480 ± 40 cal.yr BP) in the Mont Blanc massif at the origin of the Arve River (Bless 1984). According to Salvador *et al.* (2004), downstream from Lake Le Bourget the Rhone River alluvial plain is characterized by a period of high energy, including gravel-bed deposition and meander cut-offs between 1440 and 1880 cal.yr BP. This evidence for an enhanced glaciofluvial regime in the Arve and Rhone rivers at the time of the development of reflection C is associated with a 3 m rise in lake level in Lake Le Bourget (Magny & Richard 1985; Fig. 8).

Reflector D formed at the transition from a period when the Aletsch glacier was much smaller than today (~ 3250 – 3080 cal.yr BP) to significant glacier expansion between 2800 and 2550 cal.yr BP (Holzhauser 2004; Holzhauser *et al.* 2005). The latter glacier advance is also recognized in the Mont Blanc massif at the Argentiere glacier (2419 ± 223 cal.yr BP) by Bless (1984) and at the Miage glacier between 2700 and 2300 cal.yr BP by Deline & Orombelli (2005). The onset of the first Iron Age culture and a climatic deterioration *c.* 2700 cal.yr BP triggered the development of a braided pattern and the aggradation of the Upper Rhone River bed (Bravard *et al.* 1992), which resulted in a >1.5 m transgression in Lake Le Bourget (Magny & Richard 1985). This environmental change is not well marked in the MS signal at LDB01-1 or in the seismic profiles from the deep basin, but seems to have initiated a clear increase of Rhone River

discharge into Lake Le Bourget (Arnaud *et al.* 2005; Chapron *et al.* in press).

The older reflector E in Unit 5 formed when the Miage glacier advance started to dam the Combal Lake in the Mont Blanc massif *c.* 5000–480 cal. yr BP (Deline & Orombelli 2005). It also follows a glacier expansion in the Swiss Alps (Maisch *et al.* 2000), a general tree-limit decline in the Alps and an abrupt transgression in Lake Constance at the time when the Neolithic 'Alpine Iceman' was quickly buried below snow and ice cover in the Tyrolean Alps around 5300 cal. yr BP (Magny & Hass 2004). Near the NW Alps this reflector can be correlated to a regional lake transgressive phase (Fig. 8), especially well documented in Lake Chalain (French Jura) by Magny (2004) and presently under investigation in Lake Le Bourget.

Finally, the estimated age of reflection F coincides with the reactivation of a sandur in front of the Tour glacier at 7315 ± 90 cal. yr BP in the Arve drainage basin (Ballandras & Jaillet 1996; Ballandras & Deline 2002) and a regional lake transgression well documented in Lake Cerin (Magny 2004) located only 20 km to the west of Lake Le Bourget at the southern limit of the Jura mountains.

Land use and Rhone River floods

First evidence of human impact on the closed forest environment in the study area comes from pollen analysis in lakes Bourget and Cerin during the recent Atlantic period, but starts to be more strongly felt from the beginning of the Subatlantic period during the first Iron Age *c.* 2700 cal. yr BP (Magny & Richard 1985; Bossuet *et al.* 1996). This is in agreement with recent investigations showing that the well-developed and well-advanced Late Bronze Age agrarian economy around Lake Le Bourget was essentially limited to the landscape surrounding the villages (Boudy & Billaud 2001). Later on, during the Subatlantic period, the forest was no longer completely closed in the Rhone River alluvial plain downstream from Lake Le Bourget (Salvador *et al.* 2004), and anthropogenic pollen indicators point to a continuous agro-pastoral activity of variable intensity until the Antiquity and the Middle Age. According to Noël *et al.* (2001), forest clearing and intensification of agriculture since the Roman invasion released soil components from deeper than the forest floor and significantly enhanced sedimentation rates in Lake Annecy (Fig. 1). Similar ongoing studies on the organic geochemistry of the sediments in LDB01-1 suggest higher rates of soil erosion in SU 1 than in SU 2, and may thus confirm an anthropogenic contribution to the increase in Rhone River flood deposits and in sedimentation rate during the Subatlantic period in Lake Le Bourget. Since no clear glacier fluctuations can be correlated with the formation of reflection B between AD 966 and 1093, this

period of enhanced Rhone River flooding events may have been significantly favoured by intense land use in the Upper Rhone valley. However, the effect of human activity on water fluxes is known to be limited (Dearing & Jones 2003), and since Lake Le Bourget is only sensitive to major Rhone River flooding events, the formation of reflections C, B and A can still be used as a regional record of enhanced precipitation regimes in the NW Alps. The reflections D, E and F may, in addition to palaeohydrology, document non-anthropogenic fluctuating erosion rates in the Rhone catchment area and corresponding fluctuations in the Rhone River suspended load.

Rhone River palaeohydrology and climate forcing

The climatic signal in MS curves over the past 7000 years in the Alps is further discussed in Arnaud *et al.* (2005). However, based on the seismic stratigraphy calibrated by sediment cores, and the detailed correlations with fluctuating environments in the catchment area described above, it is possible to recognize (i) the influence of a long-term climate forcing, and (ii) the occurrence of superimposed millennial-scale fluctuations.

In the long term, the increase in the frequency and intensity of Rhone River flooding activity in Lake Le Bourget after the Holocene climatic optimum (Fig. 8) may be attributed to onset of the Neoglacial around 5600 cal. yr BP (Steig 1999). The transition from the Hypsithermal to the Neoglacial in our study area probably enhanced the influence of a glaciofluvial regime in the alpine rivers during the time when reflector E formed. This climatic transition favoured the progressive downstream propagation of a braided pattern in the Arve and Rhone valleys resulting in the transgressive trend of Lake Le Bourget water level since the Neolithic (Fig. 8).

The Holocene fluctuations of Mont Blanc glaciers and of associated proglacial sedimentary environments documented at the time when reflectors A, C, D, E and F formed in Lake Le Bourget suggest the persistence of cold and wet conditions at 45°N. Following Magny *et al.* (2003), and taking into account dating uncertainties, these periods of cold and wet conditions are contemporaneous with high lake level phases in mid-Europe (Fig. 8) probably resulting from higher precipitation regimes associated with a displacement of the westerlies to lower latitudes. This is supported by the good correlation of strong amplitude reflectors in Unit 5 with cold and dry periods reconstructed from proglacial lacustrine sediments in western Norway (Nesje *et al.* 2001). As glacier mass-balance variations in western Norway and in the western Alps are out of phase and strongly related to the North Atlantic Oscillation (NAO) index (Nesje *et al.* 2001; Six *et al.* 2001), the winter precipitation curve in western Norway shown in Fig. 8 may reflect large-scale Holocene

variations in atmospheric circulation during winter in the North Atlantic region. NAO-like periodicities detected in inter- and underflow deposits near LDB01-1 and LDB01-2 coring sites during the LIA (Chapron *et al.* 2002) also reflect the sensitivity of the Rhone River water discharge to large-scale ocean–atmosphere interactions across the North Atlantic sector. As a working hypothesis, the periods of enhanced Rhone River flood deposits in Lake Le Bourget presented in this study may therefore reflect the persistence of a ‘NAO negative mode’ during Holocene cold periods due to the displacement of the westerlies to lower latitudes.

Conclusion and perspectives

Periods characterized by enhanced Rhone River flood deposits in the deep basin of Lake Le Bourget inferred from sub-bottom seismic profiling and sediment cores can be correlated with documented Holocene fluctuations in Rhone River water discharge or environmental changes in the NW Alps back to *c.* 8000 cal. yr BP. These environmental changes were reflected by fluctuations of Mont Blanc glaciers and probably enhanced a glaciofluvial regime in the Rhone River during LIA-like cold and wet periods at *c.* 7200, 5200, 2800, 1600 and 200 cal. yr BP. Increasing land use starting *c.* 2700 cal. yr BP may have enhanced the impact of Rhone River floods at least since the Roman time, and be responsible for major flood deposits in Lake Le Bourget between AD 966 and 1093. Nevertheless, Rhone River flooding activity in Lake Le Bourget remains a good proxy for Holocene palaeohydrology in the NW Alps and can be correlated to several high lake level phases in mid-Europe.

In order to confirm the climate patterns involving enhanced precipitation regimes during cooling periods and human impact on environment changes, ongoing studies in Lake Le Bourget involve analysis of long cores in more proximal Rhone River flood deposits. These proximal sediments will be used to: (i) further constrain the chronology of strong amplitude reflections in Unit 5, (ii) extend back in time our understanding of the evolution of the vegetation cover, and (iii) document the timing of MWD and their potential relation with lake level changes.

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References

- Arnaud, F., Revel, M., Chapron, E., Desmet, M. & Tribovillard N. 2005: 7200 years of Rhone River flooding activity in Lake Le Bourget: a high-resolution sediment record of the NW Alps hydrology. *The Holocene*.
- Ballandras, S. & Jaillet, S. 1996: Chronologie holocène des dépôts de mise en place catastrophique dans une haute vallée alpine: Le cas du comblement de l’ombilic du Tour (Alpes françaises du Nord). *Quaternaire* 7, 85–96.
- Ballandras, S. & Deline, P. 2002: Paléohydrologie dans le massif du Mont Blanc depuis le Tardiglaciaire: un état des lieux. In Bravard, J.-P. & Magny, M. (eds.): *Histoire des rivières et des lacs de Lascaux à nos jours*, 185–194. Errance, Paris.
- Billaud, Y. & Marguet, A. 1997: L’archéologie subaquatique dans les lacs alpins français. In Bravard, J.-P. & Prestreau, M. (eds.): *Dynamique du paysage. Entretiens de Géoarchéologie, DARA* 15, 219–264.
- Bless, R. 1984: Beiträge zur spät- und post-glazialen Geschichte der Gletscher im Nordöstlichen Mont Blanc Gebiet. *Geographisches Institut der Universität Zürich, Physikalische Geographie* 15, 116 pp.
- Borel, J.-L., Brochier, J.-L. & Druart, J.-C. 1994: Microlaminations lacustres: variations bathymétriques et climatiques avant l’an Mil sur le site de Colletière, Lac de Paladru, France. *Quaternaire* 5, 105–111.
- Bossuet, G., Ruffaldi, P., Magny, M., Richard, H. & Mouthon, J. 1996: Dynamique et approche quantitative des remplissages fini- et postwürmiens du bassin lacustre de Cerin (Jura, France). *Bulletin de la Société Géologique de France* 167, 483–494.
- Boudy, L. & Billaud, Y. 2001: Economie agraire à la fin de l’âge du Bronze sur les bords du lac du Bourget (Savoie, France). *Comptes Rendus de l’Académie des Sciences de Paris*, 333, 749–756.
- Bravard, J.-P. 1981: La Chautagne, dynamique de l’environnement d’un pays savoyard. *Institut des Etudes Rhodaniennes des Universités de Lyon, Mémoires et Documents* 18, 175 pp.
- Bravard, J.-P. 1989: La métamorphose des rivières des Alpes françaises à la fin du Moyen-Age et à l’époque moderne. In Petit, F., Laurant, A. & Pissart, A. (eds.): *Rivières: formes, processus, milieu de vie. Bulletin de la Société de Géographie de Liège* 25, 145–157.
- Bravard, J. P., Verot-Bourrely, A. & Salvador, P. G. 1992: Le climat d’après les informations fournies par les enregistrements sédimentaires étudiés sur des sites archéologiques. In Le climat à la fin de l’Age du Fer et dans l’Antiquité (500 BC–500 AD). Méthodes d’approches et résultats. *Les Nouvelles de l’Archéologie* 50, 7–13.
- Chapron, E. 1999: Contrôles climatique et sismo-tectonique de la sédimentation lacustre dans l’avant-pays alpin (Lac du Bourget, Léman) durant le Quaternaire récent. *Géologie Alpine, mémoire hors série* 30, 261 pp.
- Chapron, E., Arnaud, F., Marguet, A., Billaud, Y., Perdereau, L. & Magny, M. In press. Evolution des paléoenvironnements alpins durant l’Age du Bronze: apports des archives sédimentaires littorales et profondes du Lac du Bourget (Savoie, France). Proceedings of the 129th congress of the CTHS, Besançon, 19 to 24 April 2004, France.
- Chapron, E., Beck, C., Pourchet, M. & Deconinck, J. F. 1999: 1822 earthquake-triggered homogenite in Lake Le Bourget (NW Alps). *Terra Nova* 11, 86–92.
- Chapron, E., Desmet, M., De Putter, T., Loutre, M.-F., Beck, C. & Deconinck, J.-F. 2002: Climatic variability in the northwestern Alps, France, as evidenced by 600 years of terrigenous sedimentation in Lake Le Bourget. *The Holocene* 12, 177–185.
- Chapron, E., Van Rensbergen, P., Beck, C., De Batist, M. & Paillet, A. 1996: Lacustrine sedimentary record of brutal events in Lake

- Le Bourget (Northwestern Alps-Southern Jura). *Quaternaire* 7, 155–168.
- Chapron, E., Van Rensbergen, P., De Batist, M., Beck, C. & Henriot, J.-P. 2004: Fluid-escape features as a precursor of a large sub-lacustrine sediment slide in Lake Le Bourget, NW Alps, France. *Terra Nova* 16, 305–311.
- Dearing, J. A. & Jones, R. T. 2003: Coupling temporal and spatial dimensions of global sediment flux through lake and marine sediment records. *Global and Planetary Change* 39, 147–168.
- Deline, P. 2005: Change in surface debris cover on Mont Blanc massif glaciers after the 'Little Ice Age' termination. *The Holocene* 15, 302–309.
- Deline, P. & Orombelli, G. 2005: Glacier fluctuations in the western Alps during the Neoglacial as indicated by the Miage morainic amphitheatre (Mont Blanc massif, Italy). *Boreas* 34, 456–467.
- Dorthe-Monachon, C. 1988: Les variations glaciaires dans la vallée de l'Arve (Haute-Savoie), après le dernier maximum Würmien et jusqu'à l'Holocène. *Quaternaire* 2, 97–101.
- Evin, J., Maréchal, J. & Marien, G. 1983: Lyon natural radiocarbon measurements IX. *Radiocarbon* 25, 59–128.
- Finckh, P., Kelts, K. & Lambert, A. 1984: Seismic stratigraphy and bedrock forms in perialpine lakes. *Bulletin of the Geological Society of America* 95, 1118–1128.
- Girardclos, S., Fiore, J., Rachoud-Schneider, A.-M., Baster, I. & Wildi, W. 2005: Petit-Lac (western Lake Geneva) environment and climatic history from deglaciation to the present: a synthesis. *Boreas* 34, 417–433.
- Holzhauser, H. 2004: Holocene glacier fluctuations in the Swiss Alps. 129e Congrès national des Sociétés historiques et scientifiques «Le Temps», Besançon 19–24. Avril 2004, abstract book, p. 120.
- Holzhauser, H., Magny, M. & Zumbühl, H. Z. 2005: Glacier and lake-level variations in west-central Europe over the last 3300 years. *The Holocene* 15, 789–801.
- Holzhauser, H. & Zumbühl, H. J. 1999: Glacier fluctuations in the western Swiss and French Alps in the 16th century. *Climatic Change* 43, 223–237.
- Lafargue, E., Marquis, F. & Pillot, D. 1998: Rock-Eval 6: applications in hydrocarbon exploration, production and soil contamination studies. *Revue de l'Institut Français du Pétrole* 53, 26 pp.
- Magny, M. 2004: Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric settlements. *Quaternary International* 113, 65–79.
- Magny, M., Bégeot, C., Guiot, J. & Peyron, O. 2003: Contrasting patterns of hydrological changes in Europe in response to Holocene climate cooling phases. *Quaternary Science Reviews* 22, 1589–1596.
- Magny, M. & Hass, J.-N. 2004: A major widespread climatic change around 5300 cal. yr BP at the time of the Alpine Iceman. *Journal of Quaternary Science* 19, 1–8.
- Magny, M. & Richard, H. 1985: Contribution à l'histoire Holocène du lac du Bourget: recherches sédimentologiques et palynologiques sur le site de Conjux-la-Chatière (Savoie, France). *Revue de Paléobiologie* 4, 253–277.
- Maisch, M., Wipf, A., Denneler, B., Battaglia, J. & Benz C. 2000: Die Gletscher der Schweizer Alpen, Gletscherhochstand 1850, Aktuelle Vergleichen, Gletscherschwund-szenarien. *Schlussbericht, NFP 31, V/D/F*, Zürich, 373 pp.
- Manalt, F., Beck, C., Disnar, J.-R., Deconinck, J.-F. & Recourt, P. 2001: Evolution of clay mineral assemblages and organic matter in the Late Glacial–Holocene sedimentary infill of Lake Annecy (northwestern Alps): paleoenvironmental implications. *Journal of Paleolimnology* 25, 179–192.
- Marguet, A. 2002: Savoie, lac du Bourget. Elaboration de la carte archéologique des gisements du lac du Bourget. In: *Bilan Scientifique 2000 du DRASSM*, 26. DRASSM-Eaux intérieures. Travaux et recherches archéologiques de terrain, Rhône-Alpes. Paris: Ministère de la Culture et de la Communication, Direction de l'Architecture et du Patrimoine, Sous-Direction de l'Archéologie, 117–137.
- Moscariello, A., Pugin, A., Wildi, W., Beck, C., Chapron, E., De Batist, M., Girardclos, S., Ochs, S. I., Racoud-Schneider, A. M., Signer, C. & Van Clauwenberghe, T. 1998: Déglaciation würmienne dans des conditions lacustres à la terminaison occidentale du bassin molassique (Suisse occidentale et France). *Eclogae Geologicae Helveticae* 91, 185–201.
- Nesje, A., Matthews, J. A., Dahl, S. O., Berrisford, M. S. & Andersson, C. 2001: Holocene glacier fluctuations of Flatebreen and winter-precipitation changes in the Jostedalbreen region, western Norway, based on glaciolacustrine sediment records. *The Holocene* 11, 267–280.
- Nicoud, G., Monjuvent, G. & Maillat-Guy, G. 1987: Contrôle du comblement quaternaire des vallées alpines du Nord par la dynamique lacustre. *Géologie Alpine, mémoire hors série* 13, 457–468.
- Noël, H., Garbolino, E., Brauer, A., Lallier-Vergès, E., de Beaulieu, J.-L. & Disnar, J.-R. 2001: Human impact and soil erosion during the last 5000 yrs as recorded in lacustrine sedimentary organic matter at Lac d'Annecy, the French Alps. *Journal of Paleolimnology* 25, 229–244.
- Revel, M., Arnaud, F., Chapron, E., Desmet, M. & Givélet, N. In press. Sr and Nd isotopes as tracers of sources of clastic material in the Bourget lake sediment (NW Alps, France) during the Little Ice Age: paleohydrology implications. *Chemical Geology*.
- Salvador, P.-G., Berger, J. F., Gauthier, E. & Vannière, B. 2004: Holocene fluctuations of the Rhone River in the alluvial plain of the Basses Terres (Isère, Ain, France). *Quaternaire* 15, 177–186.
- Six, D., Reynaud, L. & Letréguilly, A. 2001: Bilans de masse des glaciers alpins et scandinaves, leurs relations avec l'oscillation du climat et de l'Atlantique Nord. *Comptes Rendu de l'Académie des Sciences de Paris* 333, 693–698.
- Stuiver, M. & Reiner, P. J. 1993: Extended C data base and revised CALIB 3.0 C age calibration program. *Radiocarbon* 35, 215–230.
- Van Rensbergen, P., De Batist, M., Beck, C. & Chapron, E. 1999: High-resolution seismic stratigraphy of glacial to interglacial fill of a deep glacial lake: Lake Le Bourget, Northwestern Alps, France. *Sedimentary Geology* 128, 99–129.
- Van Rensbergen, P., De Batist, M., Beck, C. & Manalt, F. 1998: High-resolution seismic stratigraphy of Late Quaternary fill of Lake Annecy (northwestern Alps): evolution from glacial to inter-glacial sedimentary processes. *Sedimentary Geology* 117, 71–96.
- Vincent, C., Kappenberger, G., Valla, F., Bauder, A., Funk, M. & Le Meur, E. 2004: Ice ablation as evidence of climate change in the Alps over the 20th century. *Journal of Geophysical Research* 109, D10104.