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7200 years of Rhône river flooding activity in Lake Le Bourget, France: a high-resolution sediment record of NW Alps hydrology

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Abstract: Magnetic susceptibility (MS) was measured with high resolution (5 mm) on a 9 m long, ^{14}C dated core from Lake Le Bourget (Savoie, France), spanning the last 7200 years. The strong correlation ($R = 0.85$) of the MS with the silicate-borne suite of elements (Si, Al, Fe, Mg, K) and anti-correlation with the carbonate content ($R = -0.87$) allows it to be used as a proxy for the fluctuations of the abundance of riverborne clastic fraction versus authigenic carbonates in sediment. As the Rhône is the only river bringing a significant amount of silicate minerals to the coring site, the MS downstream is interpreted as a proxy of the Rhône suspended load discharge in Lake Le Bourget. This is confirmed over the last 3000 years by the good match with the evolution of hydrological activity of the Rhône as it is known through geomorphological studies of well-dated archaeological sites. Over the last 7200 years, the record is consistent with the regional record of lake water-level fluctuations. While the intensity of the MS signal might be widely affected by the human impact on soil stability, the timing of the period of enhanced hydrological activity appears to be mostly climate-related, and should thus constitute a first step toward a high-resolution (< 8 yrs) continuous history of hydrological conditions in the NW Alps.

Key words: River discharge, floods, palaeohydrology, climate, human impact, magnetic susceptibility, silicate minerals, major elements, Rhône, Alps, France, Holocene.

Introduction

Although it appeared to be a climatically stable period compared to older glacial times, recent studies have shown that the Holocene experienced many climatic oscillations (Meese *et al*., 1994; O'Brien *et al*., 1995; Stuiver *et al*., 1995). According to different authors, these oscillations should have been paced by solar activity (Magny, 1993; Bond *et al*., 2001; Blaauw *et al*. 2004), volcano emissions (Zielinski, 1995; Lamoureux *et al*., 2001) and/or ocean/atmosphere interactions (Bianchi and McCave, 1999; Broecker, 2001). In order to understand these natural oscillations and then to compare them to modern human-induced 'global warming', it is of prime importance to establish their spatial influence and possible phasing in different areas.

Recent publications have highlighted the phase opposition between Scandinavian and Alpine glacier growth as a response to the North Atlantic Oscillation (NAO) over the last few decades (Six *et al*., 2001). Over the Holocene, Nesje *et al*. (2000; 2001) showed the phasing of Scandinavian glacier retreats and ice-rafted debris (IRD) events in the North

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Atlantic Ocean (Bond *et al*., 1997; 2001) and Magny (1999) proposed a relation between French subalpine lake-level fluctuations and Bond's IRD events (Bond *et al*., 1997). Recently, Magny *et al*. (2003) proposed to integrate all these records in a common scheme of west European climatic oscillations where northern and southern European precipitation levels vary in opposition to the mid-European ones. Northwestern Alps palaeohydrology appears to be one of the key features in understanding present and past climate dynamics over western Europe (Magny *et al*., 2003). However, unlike the Scandinavian and North Atlantic regions, only a few continuous, high-resolution climate records spanning the Holocene have yet been established in the Alps (Leeman and Niessen, 1994; Ariztegui *et al*., 1996; Lanci *et al*., 1999; 2001).

This paper presents preliminary results from an ongoing multiproxy study performed on sediment cores from Lake Le Bourget (NW Alps, France) aimed at reconstructing the Holocene NW Alps hydrological history through the hydrological activity of the largest river draining the NW Alps: the Rhône. Under a normal regime, Lake Le Bourget is a tributary of the Rhône through its natural outlet the Savières Canal. However, during major Rhône floods the current in the outlet is inverted and the river bypasses into the lake. Chapron *et al*. (2002) showed that in the northern part of the lake the balance between allochthonous and autochthonous sediments can be used as a direct proxy of episodic Rhône riverborne sediment input to the lake. In this paper, we present a 7200-year-long, high-resolution (<8 years) continuous record of this balance reconstructed from magnetic susceptibility measurements. Mid-resolution (~ 100 years) measurements of major elements are also used in order to check the significance of the MS signal. Finally, the significance of the MS signal as a climate proxy is discussed in the framework of the increasing human impact on soil erosion during the Holocene.

Study site

Lake Le Bourget is a fjord-type foreland lake located in front of the French NW Alps, within the Molasse Basin between the Subalpine and Jura ranges. It is connected to the Lavours and Chautagne swamps which represent the first important flood plain reached by the Upper Rhône downstream of its alpine torrential part (Figure 1). For about 10 000 years, only major floods from the Rhône enter the northern part of the lake through the lake outlet: the Savières Canal (Chapron, 1999; Figure 1). This sporadic input brings a suspended load with a specific mineralogical signature, delivered mainly by the two main Rhône tributaries upstream of Lake Le Bourget: the Arve and Fier rivers (Revel-Rolland *et al*., 2005; Figure 1), typifying the hydrographic activity of the Rhône river (Chapron *et al*., 2002). The core presented here (LDB 01-I) was taken on the western flank of the northern deep subbasin of Lake Le Bourget at 129 m water depth (Figure 1). The sedimentary environment is under the influence of the Rhône river interflows and, while the site is 15 m above the deep-lake floor, it was reached by catastrophic underflow deposits from the Rhône during the 'Little Ice Age' (cf. core B10 description in Chapron *et al*., 2002). The present-day alumino-silicate fraction represents about 40% of the total sediment, the remaining 60% being composed of carbonate (Chapron, 1999).

Analytical methods

Two twin-cores (LDB 0101 and LDB 0102) were taken using an Uwitec® coring device on site I (45°44.848′N; 5°50.891′E) of the *ECCHYMOSE 2001* coring survey, corresponding to the B10 short-core (~ 1 m) site of the *CORMORAN 1997* survey (Chapron *et al*., 2002). Each synthetic core is composed of a succession of three cores. The second core succession was shifted by 2 m in sediment depth and about 5 m in position, in order to ensure the continuity of the record. Cores were cut into <2 m sections, split, described and stored at 4°C. During core description, terrestrial vegetal remains were sampled for ^{14}C dating. Cores were then video-captured and measured for magnetic susceptibility (MS) using a Bartington® MS2E1 surface scanning sensor following a continuous sampling step of 5 mm. Samples 1 cm thick were taken every 10 cm for geochemical analyses. Major elements were analysed using X-ray fluorescence at the University Claude Bernard of Lyon (1.4% accuracy).

Radiocarbon dating was performed on individual terrestrial vegetal remains in the Poznan Radiocarbon Laboratory (Czernik and Goslar, 2001). All ^{14}C ages were calibrated using Calib 4.3 (Stuiver and Reimer, 1993; data set from Stuiver *et al*., 1998).

Results

Lithological description

Based on lithological description the core LDB 01-I has been divided into three distinct lithological units (Figure 2), namely the Eutrophicated Unit (EU), Unit 1 (U1) and Unit 2 (U2) (Figure 2). The EU (0–18 cm depth) is made of strongly laminated dark silty sediment. It is enriched in organic matter and has been related by Chapron (1999) to the eutrophication of the lake *c.* AD 1940. The U1 (18–440 cm) is made of dark grey clayey-silt with some interbedded dark underflow deposits. The U2 (440–886 cm) differs from the U1 by a gradual lightening and fining of the sediment. Below 470 cm, the sediment is a light grey clay in which no interbedded dark level has been described. The U2/U1 transition (400–470 cm) is gradual and many sandy levels are interbedded within the clayey sediment.

A slump deposit has been described between 57 and 63 cm depth. It consists of shallow-water carbonate muds interbedded with the darker sediments of U1. This slump is assumed to be related to the AD 1822 earthquake whose effects on the Lake Le Bourget sediments is detailed in Chapron (1999) and Chapron *et al*. (1999).

Magnetic susceptibility and Al_2O_3 contents

Figure 2 presents a synthetic stratigraphic log of core LDB 01-I, magnetic susceptibility (MS) and aluminium content as a function of depth. The unit 2/unit 1 transition is marked by an increase of MS and Al_2O_3 concentrations. Superimposed on this general trend, the MS and Al_2O_3 contents display fluctuating high and low values. Even within unit 2, where they are of weaker amplitude, the significance of MS fluctuations is supported by both the correlation of the twin-cores signals ($r > 0.80$) and the correlation between MS and the aluminium content ($r = 0.92$ in unit 2).

Age-depth relationship

The age-depth relationship of the first metre was established using the chronostratigraphic markers highlighted by Chapron *et al*. (1999), namely the lake eutrophication (AD 1940), the

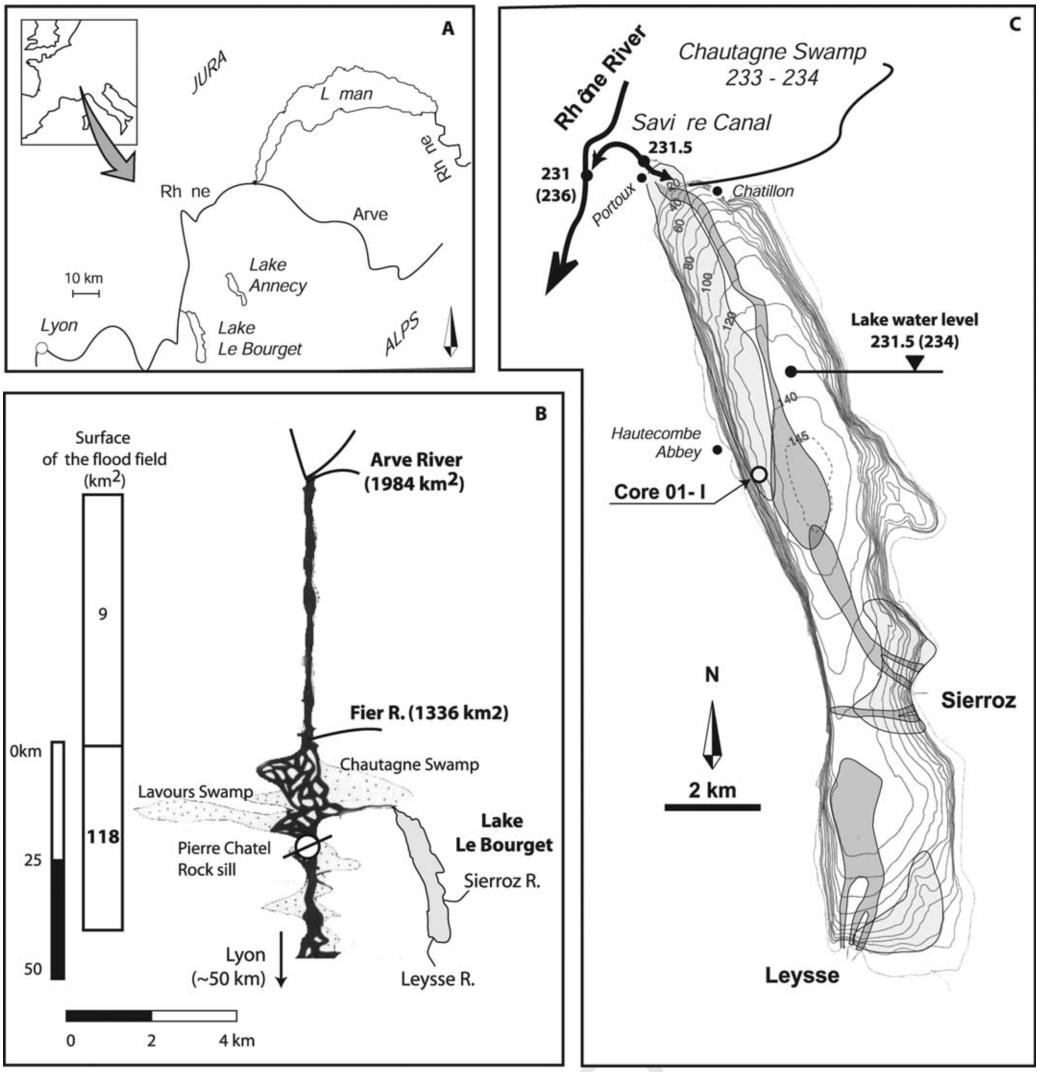

Figure 1 Location map of Lake Le Bourget and its relation with the Rhône through the Canal de Savières. (A) Location of Lake Le Bourget in front of the NW Alps. Also shown is the location of Lake Annecy, referred to in the text. (B) The flooding zone of the Rhône in the vicinity of Lake Le Bourget in 1882, prior to major river management (modified after Bravard, 1987): the Arve and Fier rivers are the main tributaries of the Rhône upstream of the Chautagne and Lavours swamp which constitute together the first great flooding area of the Upper Rhône. (C) Bathymetric map of Lake Le Bourget, together with the location of main places referred to in the text. Numbers refer to the altitudes in metres, and numbers in brackets refer to waterlevels in the Savières Canal and the lake itself during the AD 1905 Rhône flood. Also reported are the extension of the 'Little Ice Age' flood deposits from the main tributaries: the Leysse, Sierroz and Rhône rivers (underflow in dark grey and interflow in light grey), modified after Chapron (1999).

AD 1822 earthquake-triggered deposit and the oldest-known historical flood deposit of the Rhône (AD 1732). The deepest 8 m were dated using six ^{14}C AMS measurements (Table 1).

Following the method previously used by Chapron *et al*. (1999) and Arnaud *et al*. (2002), the age-depth model (Figure 2) takes into account the identified instantaneous deposit (namely, the AD 1822 slump deposit). No continuous age-depth model (polynomial and cubic-spline models with up to seven parameters were tested) was able to reproduce the ^{14}C age distribution, so we used a discontinuous model assuming constant sedimentation rates in three domains determined by the available chronological markers: (1) from the top of the core to the top of the AD 1822 slump; (2) from the bottom of the slump to the 407 cm ^{14}C age; and (3) from the 407 cm ^{14}C age to the bottom of the core. The age-depth model was established by fitting three linear regression curves between the chronological tie-points (Figure 2). The good fit of the 407 cm ^{14}C date with both regression curves argues for the onset of a sharp change in sedimentation rate. This breakpoint was determined as the crosspoint of the regression curves and located at 397 cm depth corresponding to an age of 1680 cal. BP.

Interpretation

Magnetic susceptibility (MS) is carried together by diamagnetic (e.g., calcite and quartz; MS negative), paramagnetic (mostly clay minerals; MS weak and positive) and ferro- and ferrimagnetic (magnetite, titanomagnetite; MS high and positive) minerals. In order to check the relation between the sediment composition and the MS signal, we use the aluminium content as a marker of the detrital fraction. This is proved by its excellent correlation with silicon ($r = 0.94$), but moreover with the other silicate-borne cations, namely iron ($r = 0.99$), magnesium ($r = 0.98$) potassium ($r = 0.97$) and sodium ($r = 0.85$). All these elements are strongly anti-correlated with the calcium content ($r < -0.90$) arguing for a two end-members system composed of a mixture of silicates and carbonates as it was previously shown over the last 600 years (Revel-Rolland *et al*., 2005). The question of the origin of the end-members has to be addressed.

Based on river sediment geochemical measurements, Revel-Rolland *et al*. (2005) showed that only two Lake Le Bourget

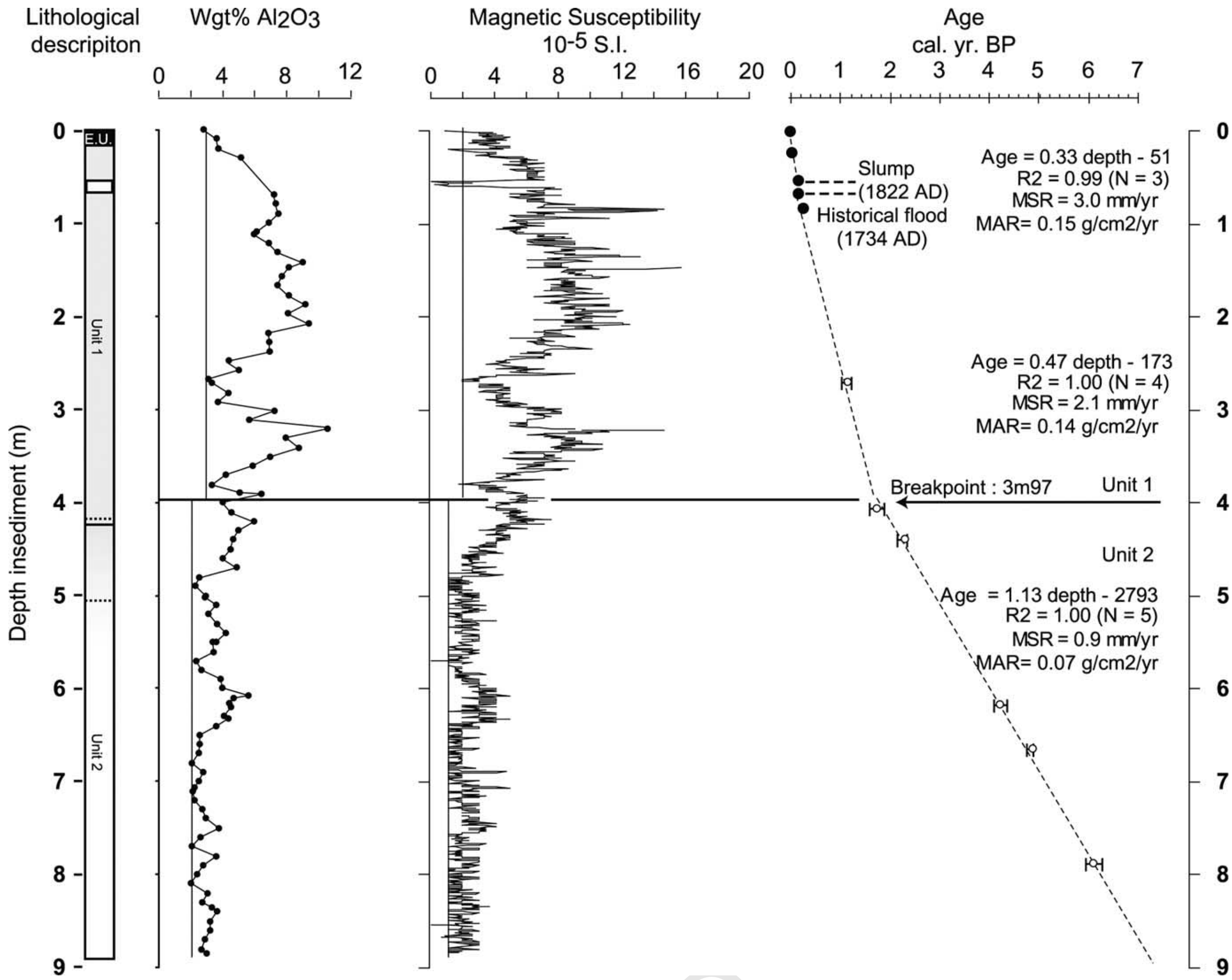

Figure 2 Synthetic lithological description together with the Al_2O_3 weight% and magnetic susceptibility (MS) series and the age-depth relationship. For each domain of assumed constant sedimentation rates, also given are the age (cal. years BP) = f(depth) (mm) function, the determination coefficient of the regression curve (number of points used for the regression are into brackets), the mean sedimentation (MSR) and mass accumulation (MAR) rates. The age-depth model implies an abrupt change in sedimentation rates located at 3.97 m, corresponding to an age of ~1700 cal. BP (AD 250).

tributaries bring a significant load of silicate minerals: the Rhône and to a lesser degree the Sierroz. The extensive short core and seismic survey led in 1997 (Chapron, 1999) showed that even during the 'Little Ice Age', which is the historically known period of higher hydrological activity, only Rhône interflow deposits reached the coring site (Figure 1) whereas the Sierroz deposits are restricted to the eastern shore (interflows) and the deeper basin (underflows). Hence, one may consider that the silicate input recorded at site 1 comes exclusively from the Rhône. Some information about the origin of the carbonate fraction is brought by the very strong anti-correlation (r = −0.95) between calcium and magnesium, excluding a major detrital carbonate fraction which should bring some magnesium. We thus suppose that the carbonates are mainly composed of bio-induced calcite which is the most common sediment source in the lakes located in temperate climate zones and carbonaceous geological settings.

Both the correlation between MS and the aluminosilicate suite of elements and the anti-correlation between MS and calcium content (Figure 3) support the hypothesis that the MS signal reflects directly the relative importance of the detrital Rhône riverborne silicate fraction versus the autochthonous carbonate one. Thus, the MS signal may be considered as an indicator of the Rhône sediment discharge to Lake Le Bourget.

Table 1 Accelerator mass spectrometry ^{14}C dates and calibrated ages (Stuiver and Reimer, 1993) for core LDB 01-I

Laboratory code	Depth (cm)	^{14}C age ($\pm 2\sigma$)	Median calibrated age BP ($\pm 2\sigma$)
POZ 710	271	1200±30	1010–1130–1230
POZ 718	407	1800±45	1570–1710–1860
POZ 716	440.5	2250±30	2150–2260–2340
POZ 717	619	3820±30	4090–4200–4350
POZ 715	667.5	4280±40	4740–4840–4870
POZ 721	791	5310±40	5950–6080–6270

Discussion

A 3000-year Lake Le Bourget and Upper Rhône coupled history

In this section we compare the MS record with the Rhône hydrological activity as it has been reconstructed from the geomorphological and sedimentological study of well-dated archeological sites, over the last 3000 years (Bravard *et al.*, 1992; Bravard, 1996).

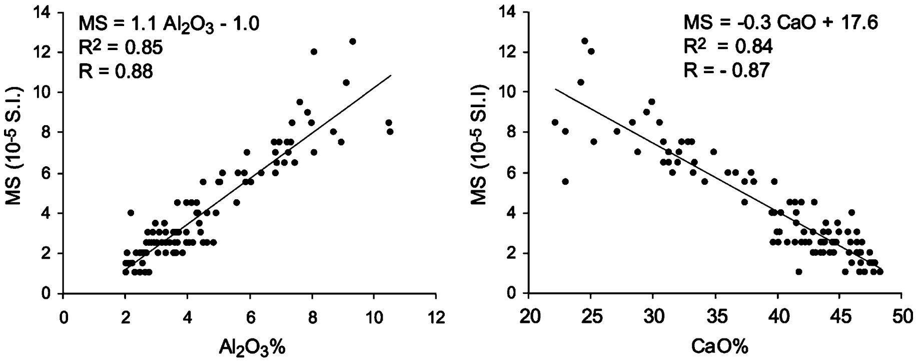

Figure 3 Magnetic susceptibility (MS) plotted versus aluminium and versus calcium contents in sediment.

Lake Le Bourget is the relict of a former postglacial great lake partly due to the retreat of the Wurmian Rhodanian Glacier from which the present-day Rhône derives (Nicoud *et al*., 1987; van Rensbergen *et al*., 1999). During the early Holocene, the postglacial rise of the Rhône riverbed increased the sedimentation in the Lavours and Chautagne swamps, isolating the lake from the direct input of the Rhône since the Boreal period (Bravard, 1987). Consequently, the Rhône has become an emissary of the lake, through its natural outlet the Savières Canal (Figure 1). During major Rhône floods, the current in the outlet is inverted and the river bypasses into the lake. At the beginning of the twentieth century, this phenomenon was occurring, on average, on 30 days per year (Bravard, 1987) and is supposed to have occurred on around 60 days per year prior to any management of the river (Magny and Richard, 1985).

According to Bravard (1987) the Rhône bed elevation controls the Lake Le Bourget water level. During the Holocene, the Rhône experienced a general rise of its riverbed due to the infilling of the glacial depression upstream of the Pierre-Châtel bedrock sill (Figure 1). In Lake Le Bourget, this Holocene-long rising trend is reflected in the succession of underwater archaeological remains which are deeper the older they are (Bravard, 1987; Marguet, 2000).

Using shallow-water sediment cores, Magny and Richard (1985) reconstructed Lake Le Bourget water levels over the last 4500 years. They documented the general rising trend but also highlighted oscillations within it. Figure 4 displays the MS signal compared with the Magny and Richard (1985) Lake Le Bourget water level data. Both curves are in general agreement suggesting a control of Rhône riverbed elevation, not only on the water budget but also on the sediment flux from the Rhône to the lake. This relationship is in accordance with historical chronicles, with one witness reporting in 1832 that, during the Rhône river overflow to the lake, the water was turbid 'until the vicinity of the Hautecombe Abbey' (Ruffieu, 1832, cited in Bravard, 1987), i.e., near to our coring site (Figure 1).

To check the significance of the MS signal as a proxy of the Rhône river activity we show in Figure 4 the results of a synthesis of the Rhône activity over the last 3000 years as evidenced by the study of fluvial deposits in archaeological sites in the vicinity of Lyon (cf. location on Figure 1) (Bravard *et al*., 1992; Bravard, 1996). To facilitate the comparison we established a relative hydrological index based on the data from Bravard *et al*. (1992) and Bravard (1996). The relation between the original literal description and our semi-quantitative index is reported in Table 2.

The onset of the first Iron Age culture is accompanied by a climatic deterioration *c*. 2700 cal. BP which, possibly coupled with changes in land use, resulted in the accumulation of a huge amount of sediment in the riverbed which was thus drastically raised (Bravard *et al*., 1992). According to Magny and Richard (1985) this hydrological crisis resulted in a >1.5 m rise of the Lake Le Bourget water level. This event is not well marked in the MS signal but, after an abrupt peak centred *c*. 2650 cal. BP, it seems to have initiated a rising trend of the river discharge until the next hydrological crisis. Afterward, the MS matches closely the evolution of the hydrological activity of the Upper Rhône: the Roman (2000–1850 cal. BP) and High Middle Age (1450–1150 cal. BP) periods of high hydrological activity are well marked in the signal. The High Middle Age was an important period of sediment delivery to the Rhône riverbed, inducing >2 m rise in Lake Le Bourget water level (Magny and Richard, 1985). The so-called 'Mediaeval Warm Period' (MWP) is marked by very low MS values between 1200 and 1000 cal. BP corresponding to dry conditions in the Rhône valley which Bravard (1996) documents as a period of 'deficient hydrology' between 1150 and 950 cal. BP. One exception is an intra-MWP peak in MS dated AD 890. This might be correlated with the fossilization of the northwestern Chautagne peat by Rhône sediments, dated 1170 ± 40 BP (Evin *et al*., 1983) corresponding to cal. AD 865 ± 65 and might thus track a local change in geomorphology or human land use (Bravard, 1987).

The following increase in MS values appears to slightly precede the 'Little Ice Age' (LIA), beginning around AD 1350, but matches well the historical record of the first-known post-MWP village destruction by Rhône floods as early as AD 1095 (Bravard, 1987). Moreover, historical chronicles evidence the oldest-known period of Rhône freezing close to its delta, in Arles, at the end of the eleventh century (Jorda and Roditis, 1994). In the Alps the first LIA glacial crisis is reported in France between AD 1150 and 1300 (Leroy-Ladurie, 1983) while Holzauser (1992) notes a period of glacier flooding in Switzerland. The LIA is well marked in the MS record by a long-lasting period of high values and by peaks in MS tracing the occurrence of historically known major floods deposits (Chapron *et al*., 2002). Thus we confirm that the LIA was a period of enhanced sediment flux to Lake Le Bourget (Chapron *et al*., 2002; Revel-Rolland *et al*., 2005) related to the largest sedimentation crisis recorded in the Upper Rhône over the Holocene (Bravard, 1996).

Extending the Rhône palaeohydrological record to the last 7200 years

Low MS values in unit 2 are in agreement with the observations of Bravard *et al*. (1992) of a period of low hydrological activity in the Upper Rhône extending from 5500 to 2700 cal. BP. Nevertheless fluctuations in the MS signal exist and their significance is supported by the covariation of the concentrations in silicate-borne elements (Figure 2).

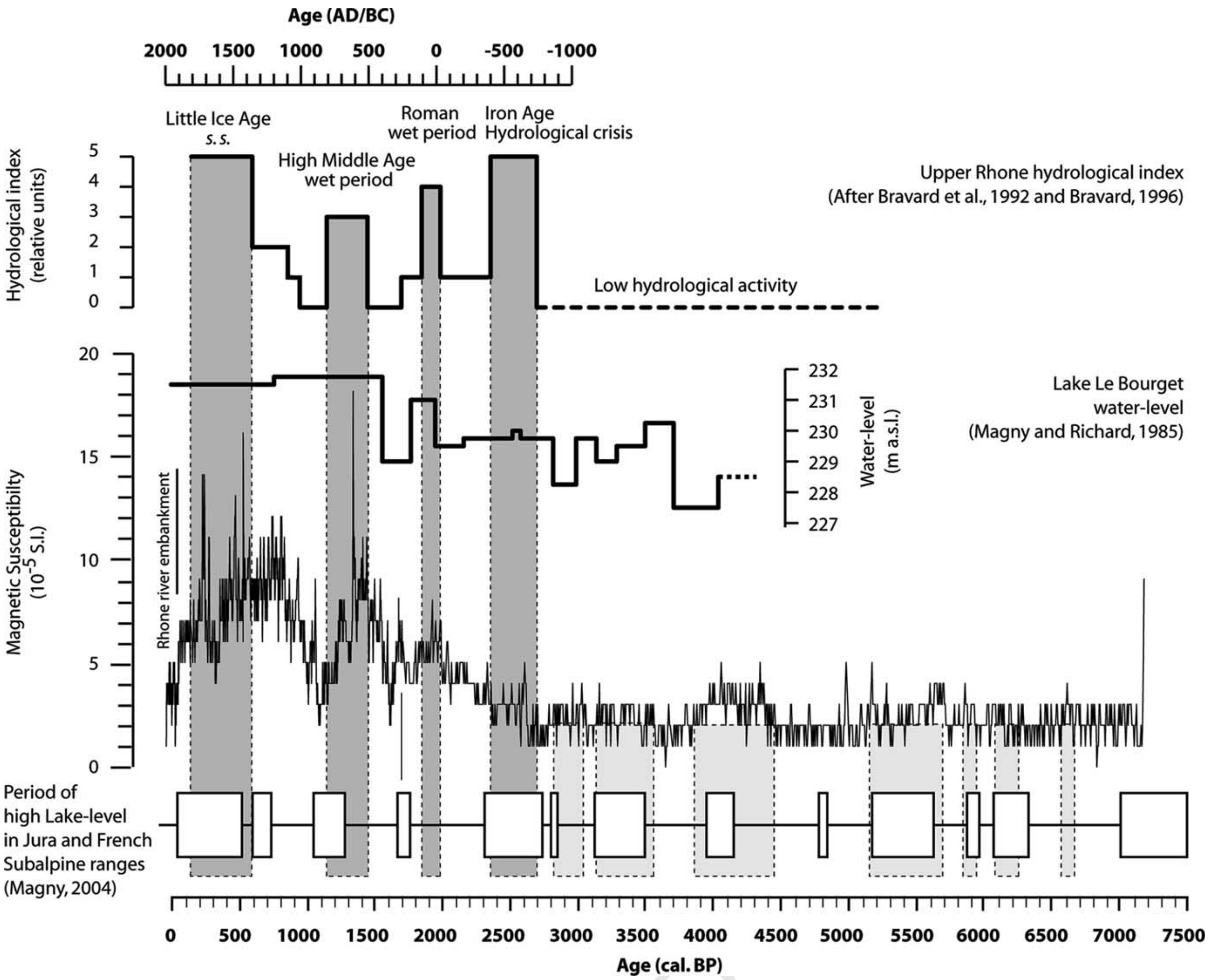

Figure 4 Magnetic susceptibility timeseries compared with the Upper Rhône relative activity index (after Bravard *et al*., 1992, and Bravard 1996; cf. Table 2 and explanation in text), Lake Le Bourget water-level fluctuations (Magny and Richard, 1985) and the periods of higher lakelevel in Jura and French subalpine ranges (Magny, 2004; white boxes). Darker grey boxes outline the periods of higher Rhône activity as observed by Bravard *et al*. (1992) and Bravard (1996); the lighter ones mark the MS-inferred periods of higher Upper Rhône activity prior to 2800 cal. BP.

There are only few sparse data concerning the Rhône hydrographic activity patterns before 2800 cal. BP (Arnaud-Fasseta, 2000) and they concern essentially the Lower Rhône subcatchments. Long-distance correlations along the course of a river as complex as the Rhône, with subcatchment areas spanning radically different climate regions, from the NW Alps to the Mediterranean area, must be made very carefully. Nevertheless data from the delta might provide a general framework as they integrate all phenomena occurring in the river subcatchments (Arnaud-Fasseta, 2000).

The most outstanding feature in the Lower Rhône records is a very long period of erosion between 4900 and 3700 cal. BP (Arnaud-Fasseta, 2000; Jorda and Provansal, 1996). While this phase was reported only in the lower Rhône subcatchments of Provence and the southern Alps (Jorda and Provansal, 1996), it is tempting to relate the most outstanding period of relatively high MS values (4500–3850 cal. BP) to this crisis. Moreover, around Lake Le Bourget (Marguet, 2000), as around most of the subalpine lakes (Magny, 2004), this period corresponds to the desertion of the littoral habitats by Neolithic populations, possibly in response to a major lake-level rise.

The following quiet period in the Rhône delta (3700–3500 cal. BP) should be compared to the period of depleted MS in Lake Le Bourget between 3800 and 3500 cal. BP. Afterwards, data are particularly sparse in the delta between 3500 and 2500 cal. BP. It seems the sedimentation was reactivated around 3500 cal. BP (Arnaud-Fasseta, 2000) and experienced a drastic rise both in southern subcatchments (Jorda and Provansal, 1996) and in the delta itself (Arnaud-Fasseta, 2000) during the Iron Age hydrological crisis as described above in the Upper Rhône. The corresponding MS signal shows also a transition to slightly higher detrital input around 3500 cal. BP and exhibits many oscillations until the 2650 cal. BP rising trend.

Human impact or climatic oscillations?

The complex interaction of climate and human impact on sediment delivery to lake basins is frequently discussed (e.g., Stockhausen and Zolitschka, 1999; Noël *et al*., 2001; Berglund, 2003; Dearing and Jones, 2003). However, the fact that only major floods can enter the lake and bring the detrital fraction should have buffered the Lake Le Bourget sedimentary system relative to human impact, as it requires not only sediment availability but also an important water flux. Hence, the excellent match with known hydrological activity in the Upper Rhône river (Figure 4) might be paced exclusively by

Table 2 Establishment of a relative Upper Rhône hydrological index based on the literal descriptions in Bravard *et al*. (1992) and Bravard (1996)

Cal.BP	Hydrological index	Literal description (Bravard *et al*., 1992; Bravard, 1996)
5450–2750	0	'Low hydrological activity'
2700–2400	5	'High hydrological activity'
2400–2050	1	'Quick hydrology'
2050–1850	4	'Repeated heavy rain episodes'
1850–1700	1	'Rare flood events'
1700–1450	0	'Relatively dry'
1450–1150	3	'Moderate torrential activity'
1150–950	0	'Deficient hydrology'
950–850	1	'Rare erosive events'
900–700	2	'Flood events'
600–150	5	'Major torrential crisis'

human activity only if it had a strong effect on water fluxes. Even in the case of very strong human-triggered deforestation, this effect is far less important than the one affecting the geomorphologic behaviour of the rivers. For instance, Brooks and Brierley (1997) showed that the deforestation of 100% of the lower Bega River catchment within a few decades led to drastic changes in river geomorphology, mainly due to increasing flood competence, but only a moderate increase of 20% of effective runoff, and had virtually no impact on major flood frequency and intensity.

Nevertheless, the human impact must not be neglected as an enhancing factor of sediment yield since at least the Iron Age, when the MS signal experiences a 700-year-long rising trend apparently unrelated with the regional record of lake-level changes (Magny, 2004). This rising was indeed initiated by a major crisis of sedimentation affecting the Upper Rhône (Bravard *et al*., 1992) which was triggered by the climatic deterioration around 800 BC (van Geel *et al*., 1998) and probably enhanced by a change in land use following the onset of the Iron Age culture (Bravard *et al*., 1992).

The next evidence for human impact on flooding should be the drastic change in sedimentation rate around AD 250. By that time archaeologists report a period when trees (absolute dendrochronological ages of cutting AD 148 to 168) were cut down to construct large shallow-water structures related to fishing and/or navigation nearto the village of Portoux (Marguet, 2000) in the vicinity of the Savières Canal (Figure 1). Moreover the existence of a military port has been suggested to explain the presence of Roman underwater structures (dated AD 250) nearto the village of Chatillon (A. Marguet, personal communication). It is then possible that the Romans deepened the Savières Canal in order to facilitate an increasing navigation between Lake Le Bourget and the Rhône, as shown by the presence of Mediterranean pottery in the Roman site of Portoux (A. Marguet, personal communication). This should have facilitated the overflowing of the Rhône to the lake, thus increasing the sensitivity of the lake to the Rhône flooding activity. It is also possible that growing agricultural activity associated with Roman colonization led people to clear the vegetation between the Rhône and the Chautagne Swamp, thus facilitating the input of Rhône material (J.-P. Bravard, personal communication).

Such a forest clearance is also supposed to have occurred around the ninth century AD and led to the fossilization of the NW Chautagne peat bog by Rhône sediments (Bravard, 1987). In the MS signal this is marked by a peak (AD $\sim$890) within the MWP low-MS period, but as it corresponds to a regional wide period of lake-level rise (Magny, 2004), the human cause of this peak is difficult to confirm.

Finally, the high values in MS since the very beginning of the LIA are probably due to a great amount of sediment made available to erosion by the forest clearances that occurred in the whole Alpine area during the MWP and reworked by the increasing fluvial activity of the later eleventh century. All through the LIA, the decreasing trend in MS should reflect the gradual decrease of this sediment stock of easily transportable material. A similar scheme occurred in the neighbouring Lake Annecy, marked by increasing magnetic minerals (Dearing *et al*., 2001) and terrestrial organic matter (Noël *et al*., 2001) fluxes related to the destabilization of surrounding soils in response to intensive deforestation.

In order to check the regional climatic meaning of the MS record, we report in Figure 4 the periods of high water level in French Jura and subalpine lakes evidenced by Magny (2004). Taking into account the age uncertainty due to the age-depth model approximations, the oscillations in MS lie in general agreement with periods of higher lake level. This suggests that the Lake Le Bourget record of Rhône river activity should be used as a regional record of hydrological conditions. The main differences concern three periods of enhanced hydrology evidenced in the MS record and not in the regional lake-level data: the Roman wet period, the beginning of the 4500–3800 cal. BP peak and a short and small oscillation around 6600 cal. BP. At least one of them, the Roman wet period (2000–1850 cal. BP) is attested to have been a period of enhanced hydrological fluxes in the whole Rhône valley (Bravard, 1996; Bruneton *et al*., 2001; Arnaud-Fasseta, 2002) and was characterized by a $\sim$1.5 m water-level rise in Lake Le Bourget (Magny and Richard, 1985) so that the accuracy of the MS record is validated for this event. Further studies will allow testing of the relevance of the other two periods of high MS values.

Conclusion

The strong correlation of the high-resolution MS signal with geochemical tracers of silicate input argues for its accuracy as a proxy of detrital input to Lake Le Bourget. This is mostly due to the recording system which may be simplified as a two end-member mixing model. Because it has been shown that the detrital material settling at coring site 1 comes essentially from the Rhône (Chapron, 1999; Chapron *et al*., 2002; Revel-Rolland *et al*., 2005), we may provide the first continuous high-resolution record mirroring the Rhône river activity throughout the last 7 ka. Over the last 3000 years, the intensity of the MS signal is probably enhanced by the colonization of the alpine massif by human settlements. Nevertheless, the timing of the evidenced oscillations in detrital sediment delivery is mainly related to climate, as is shown by the good match with archaeological evidences of flood frequency enhancement in the Upper Rhône (Bravard *et al*., 1992; Bravard, 1996) and with region-wide lake-level transgressions (Magny, 1993; 2004). Ongoing studies, including remnant magnetization parameters, organic matter and stable isotope analysis, should allow more detailed interpretation of this unique record as a climate proxy through a better understanding of the complex behaviour of the climate–erosion–sedimentation system and in particular how is it affected by human impact on soil stability.

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