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 7000 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 to use it as a proxy for the fluctuations of the abundance of river-borne clastic fraction versus authigenic carbonates in sediment. As the Rhône River is the only one 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 hydrographical activity of the Rhône river as it is known through geomorphological studies of well-dated archaeological sites (Bravard et al., 1992; Bravard, 1996). Over the last 7200 years, the record is consistent with the regional evolution of lake water-level fluctuations (Magny, 2004). Hence, while the intensity of the MS signal seems to 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 NW Alps.

Keywords

River discharge, climate, human impact, magnetic susceptibility, major elements

Introduction

Although it appeared to be a climatically-stable period when compared to older glacial times, recent studies showed 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; Blauuw et al. in press), volcano emissions (Zielinski, 1995; Lamoureux et al., 2001) and/or ocean/atmosphere interactions (Bianchi & 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 highlighted the phase opposition between Scandinavian and Alpine glaciers 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 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 Europe precipitations vary in opposition to the Mid-Europe ones. North Western Alps paleo-hydrology appears to be one of the key features in understanding the 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 climatic records spanning the Holocene have yet been established in the Alps (Leeman & Niessen, 1994; Arizteguy et al., 1996; Lanci et al., 1999; 2001).

This paper presents preliminary results from an ongoing multi-proxy 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 River. In normal regime, Lake Le Bourget is a tributary of the Rhône river 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 river-borne sediment input to the lake. In this paper, we present a 7000 years 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 Subalpine and Jurassian 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 (Fig. 1). For about 10,000 years, only major floods from the Rhône river enter the northern part of the lake through the lake outlet: the Savières Canal (Chapron, 1999; Fig. 1). This sporadic input brings a suspended load with a specific mineralogical signature, delivered mainly by the two main Rhône river tributaries upstream of Lake Le Bourget: the Arve and Fier rivers (Revel et al., submitted; Fig. 1), typifying the hydrographical 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 sub-basin of Lake Le Bourget at 129 m water-depth (Fig. 1). The sedimentary environment is under the influence of the Rhône river interflows and, while the site is 15 meters above the deep-lake floor, it was reached by catastrophic underflow deposits from the Rhône river during the Little Ice Age (cf. core B10 description in Chapron et al., 2002). The present-day alumino-silicate fraction represents about 40 percent of the total sediment, the remaining 60 percent being composed of carbonate (Chapron, 1999).

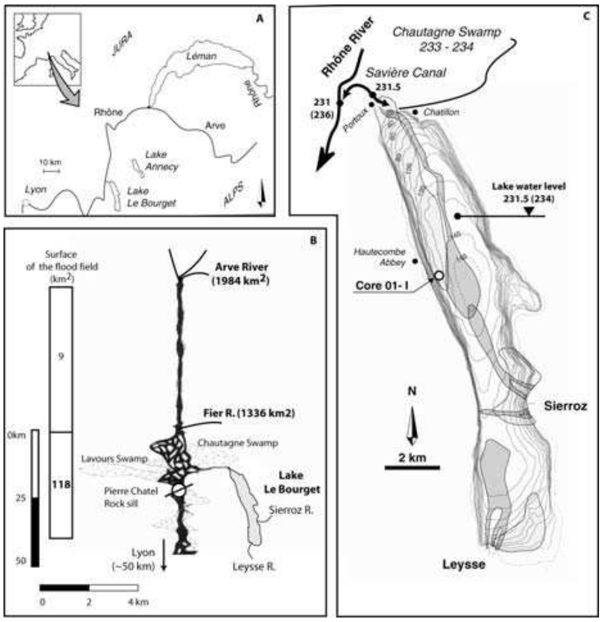

Figure 1: Location map of Lake Le Bourget and its relation with Rhône river through the "*Canal de Savières*". A) Location of Lake Le Bourget in front of NW Alps. Also reported is the location of Lake Annecy, referred in the text. B) The flooding zone of Rhône River in the vicinity of Lake Le Bourget in 1882, prior to major river management (modified after Bravard, 1987): the Arve and Fier rivers are the main tributaries of the Rhône river upstream the Chautagne and Lavours swamp which constitute together the first great flooding area of the Upper Rhône river. This flooding area is limited downstream by the Pierre-Chatel rock sill, inducing a Holocene-long sediment accumulation responsible of the Lake Le Bourget water-level continuous rise (Bravard, 1987; cf. explanation in text) C) Bathymetric map of Lake Le Bourget, together with the location of main places referred in the text. Numbers refer to the altitudes in meters, numbers into brackets refer to water-levels in the Savières Canal and the lake itself during the 1905 AD Rhône river flood. Also reported are the extension of the Little Ice Age flood deposits from the main tributaries: the Leysse, Sierroz and Rhône rivers (undeflow in dark grey and interflow in light grey), modified after Chapron (1999). The Core 01-I was taken on the north western flank of Lake Le Bourget where sedimentation is dominated by Rhône river interflow deposits.

Analytical proceedings

Two twin-cores (LDB 0101 and LDB 0102) were taken using the Uwitec® coring device on site I (N 45°44,848'; E 5°50,891') of the *ECCHYMOSE 2001* coring survey, corresponding to the B10 short-core (~ 1m) 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 two meters in sediment-depth and about five meters 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 Bartington® MS2E1 surface scanning sensor following a continuous sampling step of 5 millimetres. One centimetre thick samples were taken every 10cm 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 & Goslar, 2001). All ^{14}C ages were calibrated using Calib 4.3 (Stuiver & Reimer, 1993; dataset 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 (Fig. 2), namely the *Eutrophicated Unit (EU)*, *Unit 1 (U1)* and *Unit 2 (U2)* (Fig. 2). The EU (0 – 18 cm depth) is made of strongy laminated dark silty sediment. It is enriched in organic matter and has been related by Chapron (1999) to the eutrophication of the lake ca. AD 1940. The U1 (18 – 440cm) is made of dark grey clayey-silt with some interbedded dark underflow deposits. The U2 (440 – 886cm) differs from the U1 by a gradual lightening and fining of the

sediment. Below 470cm, 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 63cm 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 extensively described in Chapron (1999) and Chapron et al. (1999).

Laboratory code	Depth (cm)	^{14}C age (+/- 2 σ)	Median Calibrated age BP (+/- 2 σ)
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

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

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 of 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

Age-depth relationship of the first meter was established using the chronostratigraphic marks highlighted by Chapron et al. (1999), namely the lake eutrophication (AD 1940), the AD 1822 earthquake-triggered deposit and the oldest known historical flood deposit of the Rhône river (AD 1732). The deepest eight meters were dated using six ^{14}C AMS measurements (Tab. 1).

Following the method previously used by Chapron et al. (1999) and Arnaud et al. (2002), the age-depth model (Fig. 2) takes into account the identified instantaneous deposit (namely, the 1822 AD slump deposit). No continuous age-depth model (polynomial and cubic-spline models with up to 7 parameters were tested) was able to reproduce the ^{14}C ages distribution, so we used a discontinuous model assuming constant sedimentation rates in 3 domains determined by the available chronological marks: 1) from the top of the core to the top of the 1822 AD slump, 2) from the bottom of the slump to the 407cm ^{14}C age, and 3) from the 407cm ^{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 (Fig. 2). The good fit of the 407cm ^{14}C date with both regression curves argues for the onset of a brutal change in sedimentation rate. This breakpoint was determined as the cross-point of the regression curves and located at 397 cm depth corresponding to an age of 1680 cal. BP.

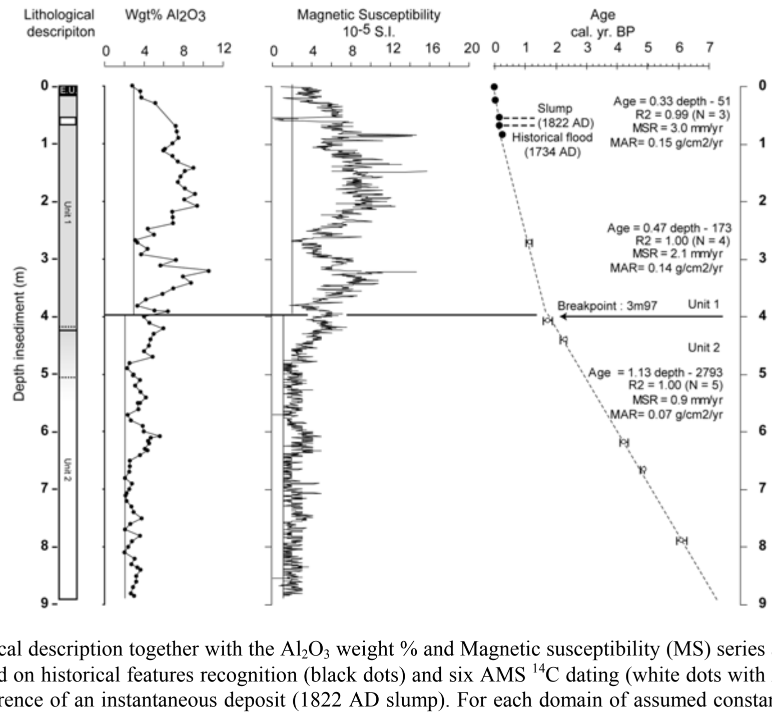

Figure 2: Synthetic lithological description together with the Al_2O_3 weight % and Magnetic susceptibility (MS) series and the age-depth relationship. The depth-age model is based on historical features recognition (black dots) and six AMS ^{14}C dating (white dots with 2σ error bars, see also Tab. 1). It takes account of the occurrence of an instantaneous deposit (1822 AD slump). For each domain of assumed constant sedimentation rates, are also reported 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 infers an abrupt change in sedimentation rates located at 3.97 m, corresponding to an age of ~1700 cal. BP (250 AD).

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 ferri-magnetic (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., submitted). The question of the origin of the end-members has to be addressed.
Based on river sediment geochemical measurements, Revel-Rolland et al. (submitted) showed that only two Lake Le Bourget emissaries bring a significant load of silicate minerals: the Rhône and at 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 1 (Fig. 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 river. 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 (Fig. 3) support the hypothesis that the MS signal reflects directly the relative importance of the detrital Rhône river-borne silicate fraction vs. the autochthonous carbonate one. Thus, the MS signal may be considered as an indicator of the Rhône river solid discharge to Lake Le Bourget.

Discussion

A 3000 years Lake Le Bourget and Upper Rhône coupled history

In this section we compare the MS record with the Rhône river 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).

Lake Le Bourget is the relict of a former post-glacial great lake partly due to the retreat of the Wurmian Rhodanian Glacier from which the present-day Rhône river derives (Nicoud et al., 1987; Van Rensbergen et al., 1999). During the Early Holocene, the post-glacial rise of the Rhône river bed increased the sedimentation in the Lavours and Chautagne swamps, isolating the lake from direct input of Rhône river since the Boreal period (Bravard, 1987). Consequently, the Rhône river has become an emissary of the lake, through its natural outlet: the Savières Canal (Fig. 1). During major Rhône floods, the current in the outlet is inverted and the river bypasses into the lake. At the beginning of the XXth century, this phenomenon was occurring on average 30 days per year (Bravard, 1987) and is supposed to have occurred 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 river experienced a global rise of its water-bed due to the infilling of the glacial depression upstream the Pierre-Châtel bedrock sill (Fig. 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).

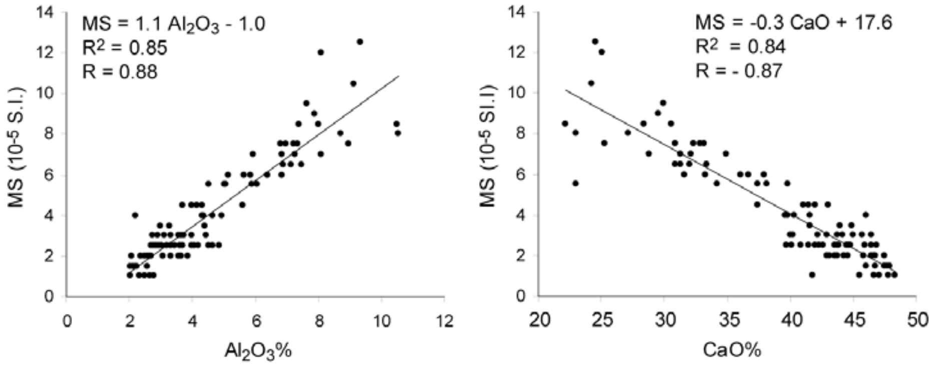

Figure 3: Magnetic Susceptibility (MS) plotted vs. aluminium and vs. calcium contents in sediment.

Using shallow-water sediment cores Magny & Richard (1985) reconstructed Lake Le Bourget water-levels over the last 4500 years. They documented the general rising trend but also highlighted oscillations within. Figure 3 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-river bed 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. nearby our coring site (Fig. 1).

To check the significance of the MS signal as a proxy of the Rhône river activity we reported on figure 3 the results of a synthesis of the Rhodanian 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 Fig. 1) (Bravard et al., 1992; Bravard, 1996). To facilitate the comparison we establish 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 1st Iron Age culture is accompanied by a climatic deterioration ca. 2700 cal. BP which, possibly coupled with changes in land-use, resulted in the accumulation of a huge amount of sediment in the river-bed which was thus drastically raised (Bravard et al., 1992). According to Magny and Richard (1985) this hydrological crisis resulted in a > 1.5m rise of the Lake Le Bourget water-level. This event is not well-marked in the MS signal but, after an abrupt peak centred ca. 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 Rhone: 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 Rhone river-bed, inducing >2 m rise in Lake Le Bourget water-level (Magny and Richard, 1985). The so-called Medieval Warm Period (MWP) is marked by very low MS values between 1200 and 1000 cal. BP corresponding to dry conditions in the Rhone 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 890 AD. This might be correlated with the fossilization of the Northwestern Chautagne peat by Rhone sediments, dated 1170 +/- 40 BP (Evin et al., 1983) corresponding to 880 +/- 200 cal. AD 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) *s.s.*, beginning around 1350 AD, but matches well the historical record of the first known post-MWP village destruction by Rhone river floods as early as 1095 AD (Bravard, 1987). Moreover, historical chronicles evidence the oldest known period of Rhône river freezing close to its delta, in Arles, at the end of the XIth century (Jorda and Roditis, 1994). In the Alps the first LIA glacial crisis is reported in France between 1150 and 1300 AD (Leroy-Ladurie, 1983) whereas Holzauser (1992) note 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., submitted) related to the hugest sedimentation crisis recorded in the Upper Rhône over the Holocene (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	"Quiet 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"

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

Extending the Rhône paleohydrological 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 Rhone extending from 5500 to 2700 cal. BP. Nevertheless fluctuations in MS signal exist and their significance is supported by the covariation of the concentrations in silicate-borne elements (Fig 2).

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

The most outstanding feature in the Lower Rhône records is a very long crisis of erosion between 4900 and 3700 cal. BP (Arnaud-Fasseta, 2000; Jorda & Provansal, 1996).

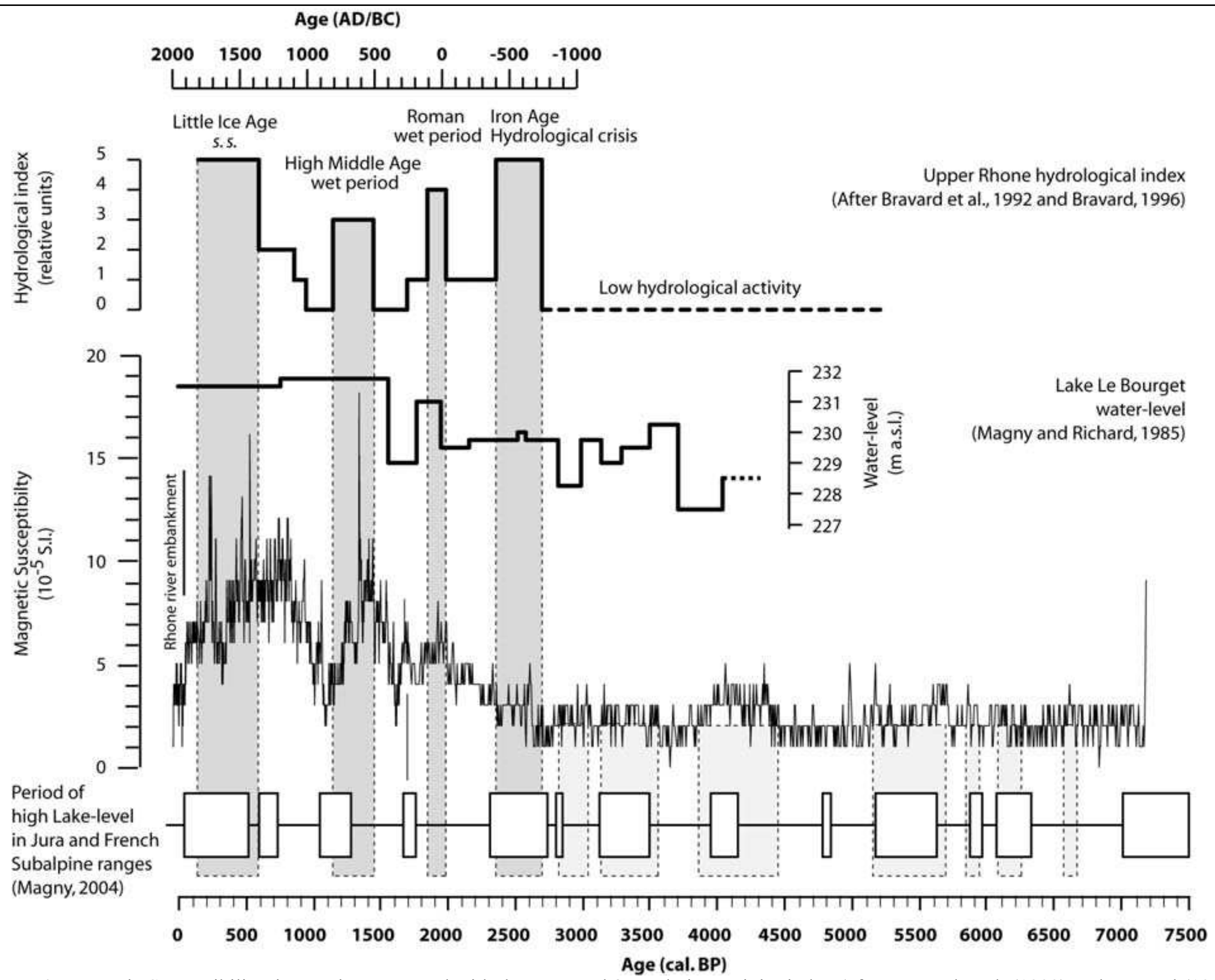

Figure 4: Magnetic Susceptibility time-series compared with the Upper Rhône relative activity index (after Bravard et al. (1992) and Bravard (1996); cf. Table 2 and explanation in text), Lake Le Bourget water-level fluctuations (Magny and Richard, 1985), and the periods of higher lake-level in Jura and 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.

While this crisis was reported only in the lower Rhone sub-catchments: Provence and Southern Alps (Jorda & 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 sub-catchments (Jorda & 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 may 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 know hydrological activity in the Upper Rhône river (Fig. 4) might be paced exclusively by human activity only if it had a strong effect on water fluxes. Now, 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-years 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 250 AD. By that time archeologists report a period when trees (absolute dendrochronological ages of cut down: 148 to 168 AD) were cut down to construct large shallow-water structures related to fishing and/or navigation nearby the village of Portoux (Marguet, 2000) in the vicinity of the Savières Canal (Fig. 1). Moreover the existence of a military port has been suggested to explain the presence of Roman time underwater structures (dated 250 AD) nearby the village of Chatillon (Marguet, pers. com.). 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 it is shown by the presence of Mediterranean pottery in the Roman site of Portoux (Marguet, pers. com.). This should have facilitated the overflowing of the Rhône river to the lake, increasing thus the sensitivity of the lake to the Rhone flooding activity. It is also possible that the growing agricultural activity associated with the Roman colonisation led people to clear the vegetation between the Rhone and the Chautagne Swamp, thus facilitating the input of Rhône material (J.-P. Bravard, pers. com.).

Such a forest clearance is also supposed to have occurred around the IXth 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 (~ 890 AD) 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 XIth 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 account of a +/-100 years 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 levels 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-Fassetta et al., 2002) and was characterised by a ~ 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 the relevance of the other two periods of high MS values.

Conclusion & perspectives

The strong correlation of 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., submitted), 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 widely affected by the colonisation of the alpine massif by human settlements. Nevertheless the timing of the evidenced oscillations in detrital sediment delivery is mainly related to climate as it 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 regional-wide lake level transgressions (Magny, 1993; Magny, *2004*). Ongoing studies, including remnant magnetisation parameters, organic matter and stable isotopes 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 the human impact on soil stability.

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