Multibeam Bathymetry Investigations of Mass Movements in Lake Le Bourget (NW Alps, France) Using a Portable Platform

G. Ledoux, P. Lajeunesse, E. Chapron, and G. St-Onge

Abstract Here we report on a recent survey undertaken on Lake Le Bourget (NW Alps, France) using a multibeam echosounder mounted on a portable and shallow-draft platform. The 3.6 × 2.8 m survey platform can be transported from one lake to another and deployed within a few hours. Its shallow draft allows surveying in areas as shallow as 3 m, while the multibeam echosounder allows maximum sounding depths of 500 m. The collected data have allowed identifying two main areas of the lake affected by mass movements. In the northwest sector of the lake, a large mass wasting deposit of 1.8 km^2 is found at the base of a very steep slope. This large deposit may be correlated with a major late-glacial mass-wasting event that triggered a seiche in Lake Le Bourget. To the north of this deposit a mass-wasting deposit is interpreted to have been caused by the AD 1822 earthquake. In the southeast sector of the lake, many lobes and a large mass wasting deposit are reported for the first time. The presence of gas-rich sediments in this area has prevented acoustic penetration and thus their identification during previous seismic surveys. The occurrence of mass movements is correlated with interflow deposition zones. In addition to the mass movements, a series of collapse craters are identified in the northern sector of the lake. These collapse craters are located near the head scars of an incipient slide. Considering that earthquakes are common in the region and can cause liquefaction within the lake sediments, there is a possibility that this incipient slide may further develop and eventually generate a massive (>107 m^3) slide.

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1 Introduction

Glacial lakes are environments that are prone to the occurrence of sublacustrine mass movements due to their high sediment supply during deglaciation, steep slopes and, in many cases, location in tectonically active regions (Chapron et al. 2004). In the Western Alps, disturbed lake sediment layers have been attributed to major postglacial seismic events (Beck et al. 1996; Chapron et al. 1996, 1999; Guyard et al. 2007). Previous studies conducted in Lake Le Bourget (NW Alps) using seismic and sidescan sonar data revealed the presence of sublacustrine mass-movement features that include slumps, slides, debris flows and homogenites (i.e., seiche deposits) that were attributed to the Holocene seismic activity (Chapron et al. 1996, 1999, 2004; Chapron 1999). The location of this lake in an active seismo-tectonic region and the presence of thick layers of deglacial and postglacial sediments on its steep slopes are conditions that are favorable for the occurrence of sublacustrine mass movements. In this paper, we present new multibeam echosounder data collected in 2008 in Lake Le Bourget. The data image in great detail the mass movements that were reported in previous studies and bring new information on the occurrence of mass movements in areas of the lake that were not well documented.

1.1 Regional Setting

Lake Le Bourget (45° 45′ N, 52° 5′ E) is a narrow over-deepened basin of glacial origin oriented North–South (Fig. 1). This warm monomictic and mesotrophic lake is 18 km long, 2–3 km wide and has a maximum depth of 146 m. The water level is currently at an altitude of 231.5 m. The pluvionival watershed of Lake Le Bourget is about 629 km^2. The two main tributaries of the lake are the Leysse and the Sierroz rivers (Chapron 1999). The lake is located in a syncline underlain by Tertiary molasse deposits. This molassic basin is bordered on the South-East by the Subalpine chains and on the North-West by the inner Jura mountains. Lake Le Bourget is surrounded by the first ranges of the south end of the Jura Mountains that mainly consist of Jurassic and Cretaceous limestone. It is located in an area of strike-slip transfer faults and is bounded in the North by the Culoz Fault and in the South by the Col du Chat Fault (Fig. 1). Earthquakes generated by recent tectonic movements in the region reached maximum magnitudes of 6 on the Richter scale (Thouvenot et al. 1990).

Lake Le Bourget is a relic of a large postglacial lake that filled the glacial valley eroded by the Rhone and Isere glaciers (Bravard 1987). During deglaciation, the main tributary of this lake was the Rhone River. The progradation of the Rhone fan delta has gradually filled the northern sector of the lake, which is now occupied by

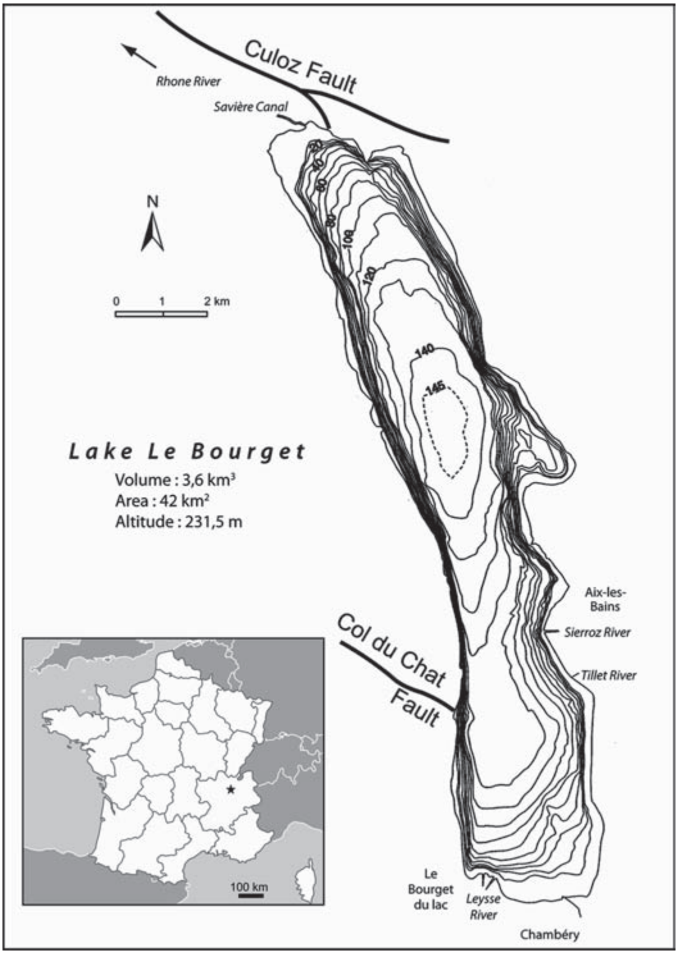

Fig. 1 Location and bathymetry (Chapron, 1999) of Lake Le Bourget (NW French Alps)

the Chautagne and Lavour swamps. This filling led to the isolation of the lake, which then induced a drastic reduction in the sedimentary inputs from the Rhone. Following this event, only major floods of the Rhone entered the lake through its natural outlet, the Saviere canal, and/or the Chautagne swamp (Chapron 1999).

1.2 Previous Work

In 1991 and 1993, two seismic surveys (sparker source and a single-channel streamer) were conducted by the Renard Center of Marine Geology (RCMG) of

Ghent University and the Laboratoire de Géodynamique des Chaînes Alpines (LGCA) of University of Savoie (van Rensbergen et al. 1999; Chapron 1999). Those campaigns used a sparker source and allowed the identification of five main seismic units within the sedimentary infill of Lake Le Bourget, which reaches a total thickness of 250 m. The sedimentary sequence is composed -from base to top- of glacial outwash deposits (unit 1), glacio-lacustrine sediments (unit 2), proglacial lacustrine fans (unit 3), alluvial fan deltas (unit 4) and a Holocene lacustrine drape of mainly authigenic sediments (unit 5) (van Rensbergen et al. 1999). In 2000, the RCMG conducted another seismic survey in the northern sector of the lake using a SEISTEC boomer at a mean frequency of 3.5 kHz (Chapron et al. 2004). In 2002, the Institut des Sciences de la Terre d'Orléans (ISTO) of Orléans University, performed a very high-resolution seismic survey in the main basin (Chapron et al. 2005) with a chirp source (modulating frequency centered at 12 kHz). The 8–15.5 m thick authigenic lacustrine drape (unit 5) is characterized by a parallel-stratified seismic facies of varying amplitude that conformably drapes the morphology of the basin (Chapron et al. 2004, 2005). Chapron et al. (2002, 2005) and Arnaud et al. (2005) have shown that the seismic reflectors within this Holocene lacustrine drape correspond to an alternation of inter- and underflow deposits identified on short gravity and long piston cores. These flood deposits highlighted a significant increase of clastic sedimentation since 2800 years BP.

In the entire northern basin, the Holocene sediment drape is underlain by the Hautecombe Disturbed Unit (HDU), a late-Glacial deposit associated with a major mass-movement event, which affected the northwestern slope of the lake basin (Chapron et al. 1996). The HDU is a 24 m thick chaotic unit with an irregular base that extends across the entire northern part of the lake, north of the Sierroz delta (Chapron et al. 1996). In the central sector of the northern basin, the HDU is partly covered with a 4 m thick reflection-free layer interpreted as a seiche deposit (van Rensbergen et al. 1999).

Numerous mass movements have been identified by the seismic surveys and sedimentological analysis (Chapron et al. 1996, 1999, 2002, 2004, 2005; van Rensbergen et al. 1999). They include slumps, slides, debris flows, seiche deposits, as well as creeping and slide-induced compression features. Most of coeval sublacustrine mass movements identified in the sedimentary infill of lake basins in the western, central and south central Alps in France, Switzerland and Italy have been attributed to earthquakes (Siegenthaler et al. 1987; Beck et al. 1996; Schnellmann et al. 2002; Fanetti et al. 2008). In Lake Bramant (French western Alps), Guyard et al. (2007) identified a slump caused by the AD 1881 Allemond earthquake and attributed a turbidite to the AD 1822 Chautagne earthquake. The epicenter of the 1822 earthquake was located near the Culoz fault. This earthquake resulted in the formation of a large subaqueous slide (ca. 840,000 m^3) in Lake Le Bourget. This slide and the earthquake wave propagation triggered a violent seiche effect during the event and resulted in a 19 cm thick seiche deposit occurring today at 20 cm below the sediment surface in the deepest part of the lake (Chapron et al. 1999).

2 Data and Methods

The multibeam echosounder survey was conducted on a 3.6 m × 2.8 m UWITEC® portable coring platform (Figs. 2a–c). This sectionalized platform is easily transportable from one lake to another and can be deployed within a few hours. Its shallow draft (<1 m) allows surveys in areas as shallow as 3 m. The high-resolution bathymetric data of Lake Le Bourget was obtained using a Reson Seabat 8101 (240 kHz) multibeam echosounder installed through the coring hole of the platform (Fig. 2c). More than 80 h and about 220 km of multibeam recordings allowed us to cover the entire surface of the lake floor below depth of 5 m with a grid size of 5 m at a vertical accuracy of <1 m. The movements of the platform were measured by an IXSEA Octans III motion sensor while the multibeam processor applied compensations for the attitudes. Sound velocity profiles were collected using a SeaBird SBE-19 CTD profiler and the corrections were applied to the multibeam data. An SXBlue II (Geneq Inc.) GPS receiver with a horizontal accuracy of <2.5 m was used to georeference the data. The collected multibeam data was processed using the Hypack 8.0® software on a Panasonic Toughbook® portable and waterproof computer. Visualization of the bathymetry and the lake floor geomorphology was achieved with the Fledermaus® software and mapping was realized with ArcGIS 9.2®.

3 Results

3.1 *Bathymetry*

The bathymetry of Lake Le Bourget is characterized by a North–South oriented basin (Fig. 3). This basin reaches a maximum depth of 146 m in the north central portion of the lake. The western basin slopes of the lake are very steep and range between 10° and 50°; the eastern basin slopes are generally smoother and range between 10° and 20° but can reach maximum values of 30°. Well-documented molasse sequences outcropping on land also occur along the NW slopes of the lake and locally form plateaus allowing sediments deposition (Fig. 4). The northern and the southern part of the lake are characterized by lower slopes of 2° to 4°.

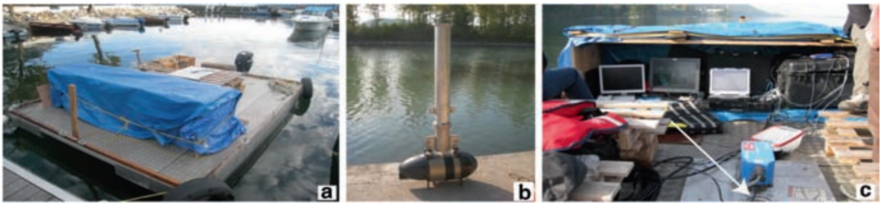

Fig. 2 (**a**) Multibeam survey platform, (**b**) Reson Seabat 8101 mount and (**c**) installation through the coring hole (shown by *arrow*)

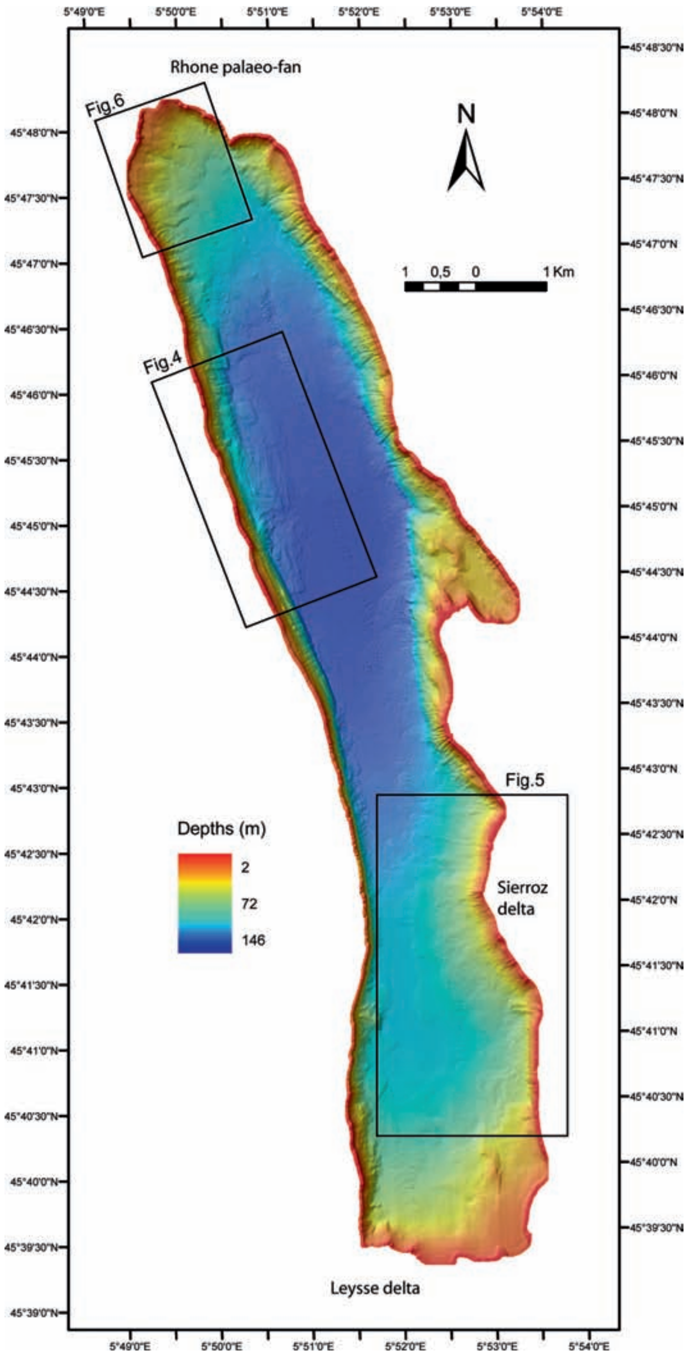

Fig. 3 Multibeam bathymetry of Lake Le Bourget showing the Sierroz, the Leysse and the Rhone palaeo-fan and the localization of the figures

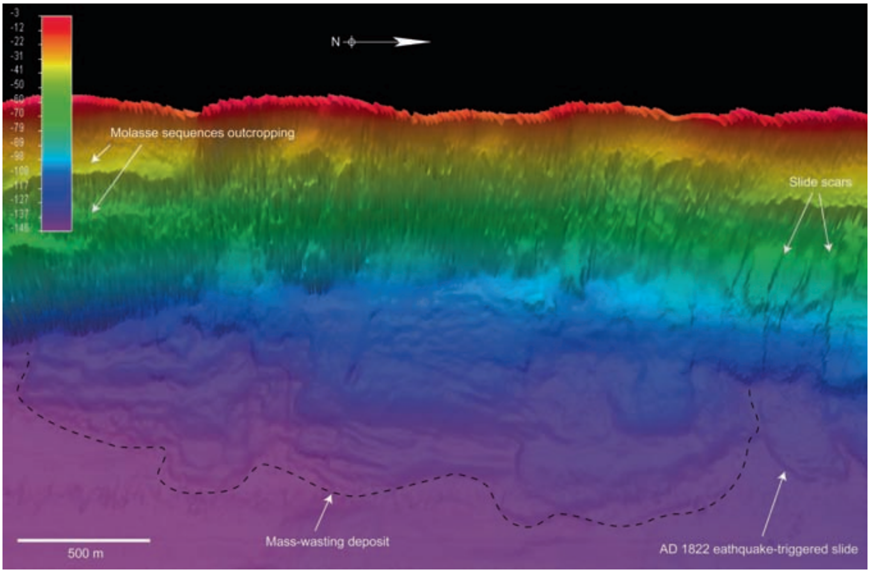

Fig. 4 Multibeam bathymetry of the northwestern slope of basin of Lake Le Bourget showing a large mass-wasting and the 1822 earthquake-triggered sublacustrine slide identified by Chapron et al. (1999)

3.2 Lacustrine Sediment Disturbances

3.2.1 Mass-Wasting Deposits

Mounds of sediment with hummocky upper surface located at the base of steep slopes are interpreted as mass-wasting deposits (MWDs). Large MWDs can be identified along the northwestern slope of the basin (Fig. 4) and at the South of the Sierroz delta (Fig. 5). Side scars are clearly noticeable on both sides of the MWD situated south of the Sierroz delta (Fig. 5). Smaller MWDs are scattered all around the lake basin and can be observed beside the Col du Chat fault, in the southwestern part of the lake, and along the eastern slope of the basin. Beside the large MWD of the northwestern slope, a well preserved lobe-shape MWD of 300 × 325 m associated with slide scars on its upper slope suggests the occurrence of a recent slide (Fig. 4). The size of the MWDs observed in Lake Le Bourget ranges between a few thousands to several tens of thousands m^2. These MWDs can extend more than 600 m from the base of the slopes.

3.2.2 Debris Flow Deposits

Large lobe-like features are located along the Sierroz delta slope (Fig. 5). These lobes are interpreted as debris flow deposits and could represent the evolution of slides or slumps into debris flows (e.g., Mulder and Cochonat 1996). These debris

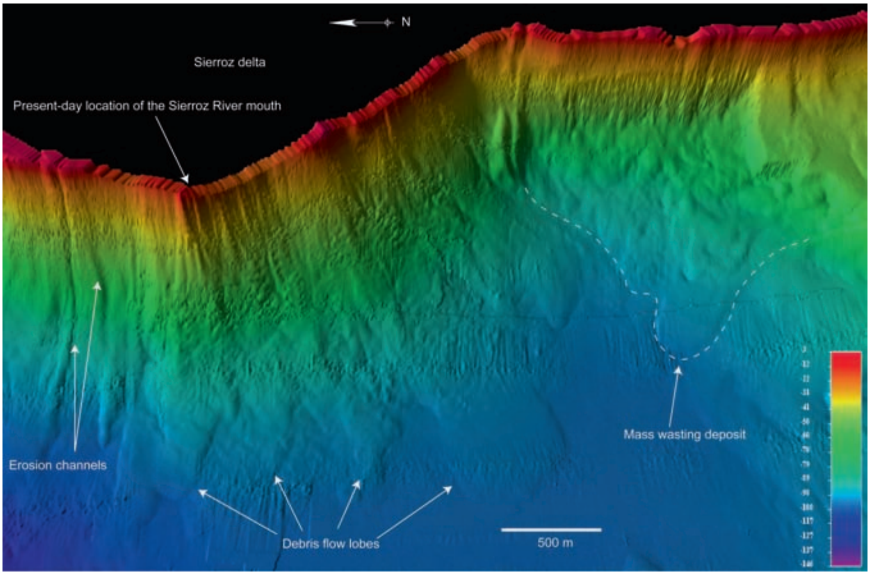

Fig. 5 Multibeam bathymetry of the Sierroz delta slope showing debris flow lobes, channels eroded by debris flows and a mass-wasting deposit

flow lobes can extend nearly 800 m on the lake floor from the base of the slopes and reach few hundred thousands of m^2. Most of the lobes observed along the Sierroz delta are coalescent while others are isolated.

3.2.3 Erosion Channels and Canyons

Erosion channels are located on the Sierroz delta slope (Fig. 5) and in the northern sector of the lake (Fig. 6). The erosion channels observed on the Sierroz delta slope occur in the north of the present-day location of the mouth of the Sierroz River (Fig. 5). It is about 500 m long by 40 m wide. These erosion channels could represent the palaeo-Sierroz channel formed by frequent underflows during flash floods events formerly entering the lake at this location (Chapron 1999). The erosion channel observed in the northern sector is about 750 m long by 65 m wide (Fig. 6) and is not related to any inlet. This feature suggests the occurrence of recent gravity reworking processes affecting the shallow water littoral platform. Numerous canyons are also observed along the steep slopes of the lake basin. These canyons are probably active, as shown by the occurrence of slope aprons downslope.

3.2.4 Collapse Craters

Small circular depressions are revealed by the multibeam data in the northern sector of the lake (Fig. 6). These depressions are interpreted as collapse craters, as identified by Chapron et al. (1996, 2004) on side scan sonar and seismic data. They are 10–20 m

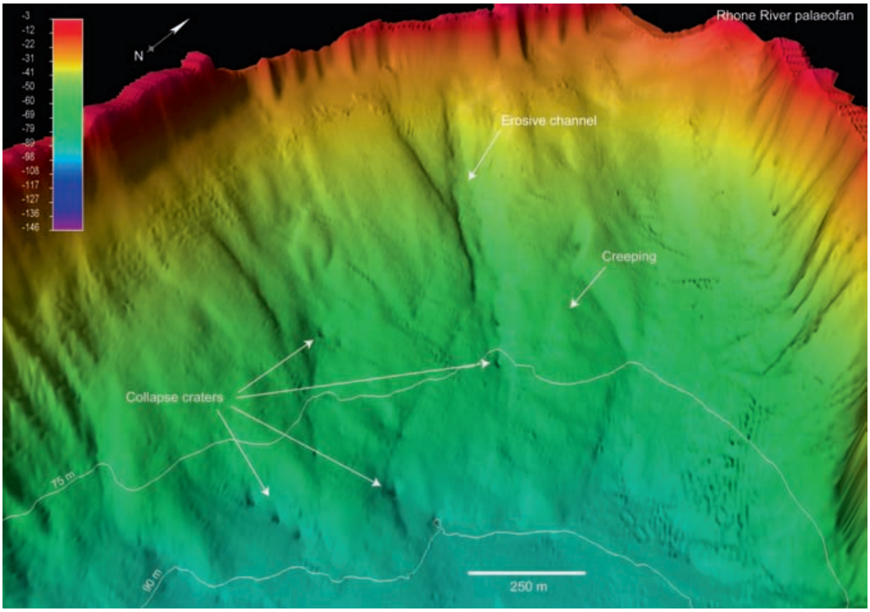

Fig. 6 Multibeam bathymetry of the northern sector of Lake Le Bourget showing collapse craters, erosion channel and the 75 and 90 m isobaths were occur the incipient scar of the ongoing sediment slide identified by Chapron et al. (2004) on sub-bottom profiles

in diameter and their central depression can be 0.5–2 m deep. The collapse craters identified on the Rhone palaeo-fan are located between 70 and 90 m deep. These collapse craters are interpreted as resulting from the expulsion of water and/or gas migration due to faults in the sediment (Chapron et al. 2004), and to sediment liquefaction induced by earthquakes or by the increasing pore-pressure due to sediment loading, a common process in this environment (Allen 1982). Chapron et al. (2004) have shown that the funnels associated with these collapse craters affect the entire Holocene sediment drape, which is about 10 m thick in this area. These authors have demonstrated lateral water and/or gas accumulation and migration between the HDU and the Holocene sediment drape. Rippled surface situated beside the erosion channel of the Rhone palaeo-fan highlight the occurrence of creeping in gas rich sediments (Fig. 6), which suggest that a large area of the Rhone palaeo-fan is affected by ongoing gravity reworking processes.

4 Discussion

The new multibeam data presented in this paper reveal that the northwestern and the southeastern sectors of Lake Le Bourget are strongly affected by mass movements. These mass movements are located where the Holocene sediment cover is the thickest, reaching 24 m locally (van Rensbergen et al. 1999). The multibeam data shows for the first time that mass movements also affected the southeastern portion of the lake near the Sierroz delta slope (Fig. 5), where gas-rich sediments are preventing sub-bottom seismic profiling. Sedimentary inputs from the Sierroz and the Leysse rivers in this part of the lake and the subsequent sedimentation on the steep delta slope (6° to 10°) are conditions that are favorable for the occurrence of mass movements in that sector. Interflows from the Leysse River are in particular derived to the east by the Coriolis force and contribute to increase sediment thickness along the southeastern portion of the lake (Chapron 1999, 2002). These sedimentary inputs and the degradation of organic matter into gas contribute to decrease the shear strength by increasing sediment drape thickness and thus, higher downslope moving forces (Allen 1982).

There is presently no river that flows into the lake along the northwestern sector of Lake Le Bourget. Therefore, mass movements identified in this area do not occur on the slope of a delta. However, the large and rapid sediment inputs from the Rhone River interflows during deglaciation (van Rensbergen et al. 1999) and the Holocene have been deflecting to the west by the Coriolis force, which favored sediment deposition in this sector (Chapron et al. 2002, 2005). This enhanced fined-grained sediments to accumulate along the western slope of the basin and thus, the possibility of mass movement triggering. The rippled topography of the large MWD identified in this sector occurs where Chapron et al. (1996) identified a large sublacustrine slide that can be linked to the formation of the HDU. The size of the identified deposit as well as its morphology suggests that this feature could be associated with the slide-induced HDU that is now buried and draped by 10 m of Holocene sediments. Beside this large MWD, the lobe-shape MWD with slide scar in the upper slope (Fig. 4) occurs where Chapron et al. (1999) identified a slide triggered by the AD 1822 earthquake. The well preserved slide scar and slide-induced compressions on the upper surface of the lobe-shape deposit suggest that it corresponds to the AD 1822 earthquake-triggered slide.

Some of the collapse craters reported here within the Rhone palaeo-fan occur in gas-rich sediments. Due to the absence of signal penetration in such sedimentary conditions, most of these collapse craters have not been observed in previous studies using sub-bottom profilers. Our multibeam data show that collapse craters occur in an area characterized by a network of small disruptions associated with the incipient scars of an ongoing large sublacustrine sediment slide of ~10^7 m^3 (Chapron et al. 2004). According to Chapron et al. (2004), these scars are located along the 75 m and the 90 m isobaths. These incipient scars and the small disruptions have probably contributed to the expulsion of fluid and/or gas trough the impermeable Holocene sediments that formed collapse craters at these depths. Our results are consistent with the work of Chapron et al. (2004) and demonstrate that this sector of the Rhone palaeo-fan shows signs of slope instability. In addition to the presence of gas in the sediment that increases pore pressure and thus reducing sediment strength (Nisbet and Piper 1998), the presence of these collapse craters could be related to gas destabilization. According to Rothwell et al. (1998), most of the large slides result from gas destabilization. A small earthquake or even a new sediment supply delivered by a flooding river could lead to a slide (Nisbet and Piper 1998). Earthquakes are common in the region and major Rhone River floods can enter into the lake by the Saviere Canal. Such conditions are favorable for a large slide triggering in the northern sector of Lake Le Bourget. This slide is susceptible to generate a seiche that could have significant consequences along the inhabited shores of the lake.

5 Conclusion

In this paper, we report on a multibeam echosounder survey conducted in Lake Le Bourget (NW Alps) using a shallow-draft and portable platform. The new multibeam data allowed us to identify features that have not been reported in previous studies due to the limited signal penetration of acoustic sediment profilers in gas-rich sediment zones. This study allowed the identification of two major areas of the lake that are affected by mass movements. In the northwest of the basin, a large deposit of ~1.8 km^2 can be identified at the base of the steep slope. This large deposit could be associated with a major late-glacial mass movement that led to the formation of a thick disturbed unit (HDU) covered by a seiche deposit. The subaqueous slide caused by the AD 1822 earthquake can also be observed in detail for the first time in the northwestern sector of the lake. Many mass movement features, such as debris flow lobes and a large mass-wasting deposit are also reported here for the first time along the southeastern slope of the lake. In the northern portion of the lake, collapse craters are situated in an area of a network of small disruptions associated with the incipient scars of an ongoing large sublacustrine sediment slide. The relationship between the seismo-tectonic setting of the region and the sublacustrine mass movements has been demonstrated in previous studies on several alpine lakes. In order to improve the understanding of the causes of mass movement triggering in Lake Le Bourget, further studies involving sub-bottom profiling and coring data should date Holocene MWDs and take into account the possible link between Holocene lake level fluctuations and anthropogenic factors along this populated lake shore, especially along the Sierroz delta (Aix-les-Bains urban area).

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References

Allen JRL (1982) Sedimentary Structures: Their Character and Physical Basis. Elsevier, Amsterdam.

Arnaud F, Revel M, Chapron E et al (2005) 7200 years of Rhone river flooding activity in Lake Le Bourget, France: a high-resolution sediment record of NW Alps hydrology. Holocene 15:420–428.

Beck C, Manalt F, Chapron E et al (1996) Enchanced seismicity in the early post-glacial period: evidence from the post-Würm sediments of Lake Annecy, northwestern Alps. J Geodyn 22:155–171.

Bravard JP (1987) Le Rhone: Du Léman à Lyon. La Manufacture, Lyon.

Chapron E (1999) Contrôle climatique et sismo-tectonique de la sédimentation lacustre dans l'Avant-Pays Alpin (Lac du Bourget) durant le Quaternaire récent. Géologie Alpine, Mémoire H.S. 30.

Chapron E, Van Rensbergen P, Beck C et al (1996) Lacustrine sedimentary record of brutal events in Lake Le Bourget (Northwestern Alps-Southern Jura). Quaternaire 7:155–168.

Chapron E, Beck C, Pourchet P et al (1999) 1822 earthquake-triggered homogenite in Lake Le Bourget. Terra Nova 11:86–92.

Chapron E, Desmet M, De Putter T et al (2002) Climatic variability in the northwestern Alps, France, as evidenced by 600 years of terrigenous sedimentation in Lake Le Bourget. Holocene 12:177–185.

Chapron E, Van Rensbergen P, De Batist M et al (2004) Fluid-escape features as a precursor of a large sublacustrine sediment slide in Lake Le Bourget, NW Alps, France. Terra Nova 16:305–311.

Chapron E, Arnaud F, Noël H et al (2005) Rhone river flood deposits in Lake Le Bourget: a proxy for Holocene environmental changes in the NW Alps, France. Boreas 34:404–416.

Fanetti D, Anselmetti FS, Chapron E et al (2008) Megaturbidite deposits in the Holocene basin fill of Lake Como (Southern Alps, Italy). Palaeogeogr Palaeoclimatol Palaeoecol 259: 323–340.

Guyard H, Chapron E, St-Onge G et al (2007) High-altitude varve records of abrupt environmental changes and mining activity over the last 4000 years in the Western French Alps (Lake Bramant, Grandes Rousses Massif). Quat Sci Rev 26:2644–2660.

Mulder T, Cochonat P (1996) Classification of offshore mass movements. J Sediment Geol 66:43–57.

Nisbet EG, Piper DJW (1998) Giant submarine landslides. Nat 392:329–330.

Rothwell RG, Thomson J, Kähler G (1998) Low-sea-level emplacement of a very large Late Pleistocene 'megaturbidite' in the western Mediterranean Sea. Nat 392:377–380.

Schnellman M, Anselmetti FS, Giardini D et al (2002) Prehistoric earthquake history revealed by lacustrine slump deposits. Geol 30:1131–1134.

Siegenthaler C, Finger W, Kelts K et al (1987) Earthquake and seiche deposits in Lake Lucerne, Switzerland. Eclogae Geologica Helvetiae 80:241–260.

Thouvenot F, Frechet J, Guyoton F et al (1990) SISMALP: an automatic phone-interrogated seismic network for the western Alps. Cahiers du Centre Européen de Géodynamique et de Séismologie 1:1–10.

van Rensbergen P, De Batist M, Beck C et al (1999) High-resolution seismic stratigraphy of glacial to interglacial fill of a deep glacigenic lake: Lake Le Bourget, Northwestern Alps, France. Sediment Geol 128:99–129.