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Fluid-escape features as a precursor of a large sublacustrine sediment slide in Lake Le Bourget, NW Alps, France

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ABSTRACT

The north-western corner of Lake Le Bourget is situated along an active fault zone and accommodated a large sediment supply from the Rhone River until the end of the Late Glacial period. On the delta slope, the Holocene sheet drape that covers the largest buried mass wasting deposit (the HDU) shows undulations, small fractures and discontinuities that are attributed to downslope creep. Evidence for episodes of vigorous fluid expulsion is found in association with these discontinuities. All these features are rooted at the top of the HDU and occur along two specific isobaths. These observations indicate a close link between fractures and focused fluid flow. We suggest that focused fluid flow triggered by earthquakes facilitates the formation of small-scale faults that accommodate part of the downslope movement and eventually link up to form a head-scarp of a large slide (*c.* 10^7 m^3).

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Introduction

Glacial lakes are prone to large-scale sediment slides and slumps owing to their high sediment supply, steep slopes and common situation in active tectonic settings. In these lacustrine basins, large slides are often associated with catastrophic waves (seiche effect), especially when they occur in combination with earthquakes (Siegenthaler *et al.*, 1987; Schilts and Clague, 1992; Chapron *et al.*, 1999; Schnellmann *et al.*, 2002). The possible consequences of such large landslides and waves along populated lake shores, and the effects on the trophic state of the lake (i.e. destabilization and re-suspension of polluted sediments or sediments rich in organic matter), makes a better understanding of the stability of the lacustrine sedimentary fill and of the processes that may trigger such subaqueous sediment slides a priority.

Although sediment slides in lakes can be produced by lake-level fluctuations (Ringrose, 1989) or even by human impacts along deltas (Kelts and Hsü, 1980), large sublacustrine slides are most often triggered by sediment liquefaction during strong local earthquakes (Schilts and Clague, 1992). Earthquake-induced sediment liquefaction refers to the process of temporary suspension of sediment grains in the pore fluid due to cyclic loading (Lowe, 1975; Ringrose, 1989; Sims and Garvin, 1995; Lignier *et al.*, 1998; Moretti *et al.*, 1999) and results in complete loss of sediment strength (Maltman and Bolton, 2003). Earthquake-triggered liquefaction is facilitated by pore fluid pressure increase caused by ineffective dewatering of low-permeability sediments and by biogenic gas production from the decay of organic matter (Nisbet and Piper, 1998). When the low-permeability seal of liquefied sand or silt is breached, focused fluid flow and sediment fluidization occur. Hence, earthquake-induced liquefaction is often associated with fluid escape features at the sediment surface such as sand boils, spring pits or collapse craters (Allen, 1982).

In this paper we describe sublacustrine fluid escape features in a delta slope environment associated with discontinuous small-scale faults and fractures, and we discuss how they may interact to form a large sediment slide. Side-scan sonar mapping and high-resolution seismic profiling supported by sediment cores allows predictions of the volume of unstable sediment that is expected to slide. This study is focused on the north-western corner of Lake Le Bourget, NW Alps (France).

Lake Le Bourget (18 km long, 2–3 km wide and 146 m deep) is a narrow over-deepened basin of glacial origin situated along an active fault zone and characterized by large sediment supply until the Late Glacial and by numerous stacked mass wasting deposits. Historical seismicity around Lake Le Bourget is essentially associated with strike-slip transfer faults (Culoz and Col du Chat faults, Fig. 1). The strongest historical earthquake in the French NW Alps (the *Chautagne event*, 18/02/1822, MSK intensity VII–VIII) was localized close to the Culoz fault (Fig. 1) and reached an equivalent magnitude of 5.5–6 (Thouvenot *et al.*, 1990). This earthquake produced large site effects within the palaeolake area and triggered a large subaqueous sediment slide ($\sim$840 000 m^3) in Lake Le Bourget together with significant seiche waves (Chapron *et al.*, 1999).

Methodology and data

This study is based on geophysical data and sediment cores acquired during several surveys. Bathymetry and side-scan sonar mosaics date from a survey in 1992 in collaboration with IFREMER-GENAVIR (Chapron *et al.*, 1996). High-resolution seismic data (sparker profiles) were obtained from surveys in 1991 and 1993 (Van Rensbergen *et al.*, 1999). In 2000, a detailed survey of gravity instabilities was performed in the northern part of the lake, using a SEISTEC boomer at a mean frequency of 3.5 kHz together with a short single-channel S.I.G. streamer from a mini-research vessel (RCMG's

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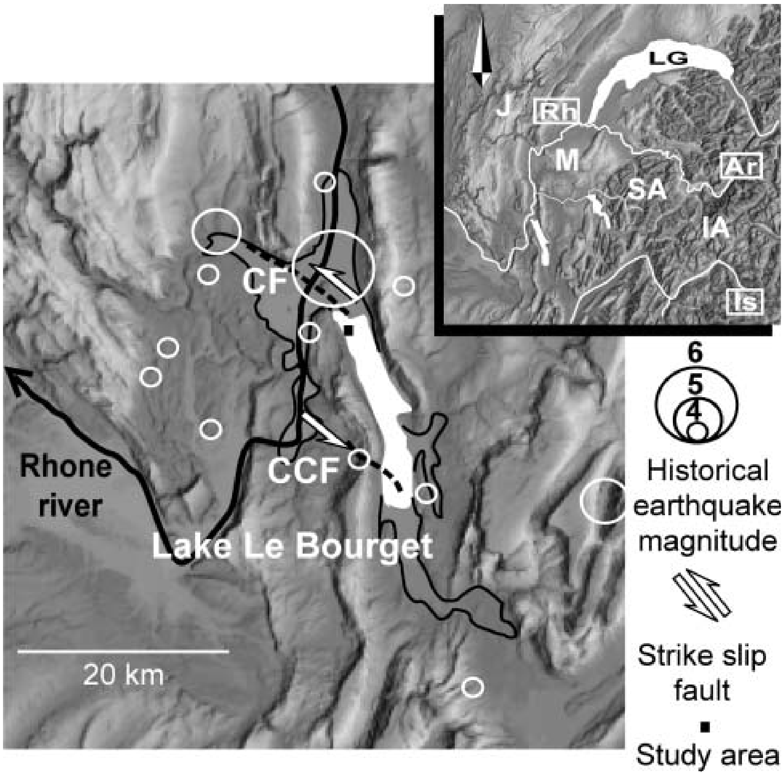

Fig. 1 General location of the study area (black square) in Lake Le Bourget, French NW Alps (J: Jura mountains; M: Molasse basin; SA: Subalpine massifs; IA: Inner Alps; Rh: Rhone river; Ar: Arve river; Is: Isère river; LG: Lake Geneva). Also indicated is the extension of the postglacial palaeolake (black line) compared with the present one (white area). The northern part of the palaeolake was filled up by Rhone river sediment during the Late Glacial, and since the Preboreal the Rhone River has bypassed the lake toward the west. Only large Rhone river floods presently overflow into the lake. The historical seismicity of the area (open circles; size proportional to the magnitude at the epicentre) is closely related to the two main strike slip faults affecting the Lake Le Bourget basin (CF: Culoz Fault; CCF: Col du Chat Fault). The onshore and offshore locations of the active faults are indicated by dashed lines. The strongest historical event in AD 1822 reached an estimated magnitude of 5.5–6 just north of the study area.

Opus-3D system). GPS positioning and the highly manoeuvrable research vessel provided a very dense grid of profiles with line spacing ranging from 200 m to 15 m (Fig. 2). A 3-m-long piston core was retrieved in 80 m water depth (Fig. 2) using an UWITEC coring system in order to provide a correlation of acoustic and sedimentary facies of the upper 3 m.

Data description and interpretation

In the north-western part of the basin three main types of deposit can be distinguished on the basis of seismic records (Fig. 3): (a) Late Glacial clastic sediments from the Rhone River, (b) a mainly authigenic Holocene sheet drape and (c) intercalated mass wasting deposits. This sedimentary infill is locally affected by faulting and fluid escape phenomena.

Lacustrine sediments

Rhone River sediments accumulate in the lake basin by means of interflows or underflows. Interflow deposits accumulate along the western margin of the basin and are characterized by a parallel-stratified seismic facies with continuous reflections of varying amplitude that drape the morphology of the basin (Figs 3 and 4). Underflow deposits accumulate along the steepest slope gradient of the basin in a channel–levee system with high-amplitude channel fill facies and continuous divergent reflections of variable amplitude (overbank levees). The channel levee system was then abandoned at the end of the Late Glacial and less-frequent underflows deposited coarse-grained deposits in depressions (seen as highly reflective lenses on the seismic profile).

At the beginning of the Holocene, the course of the Rhone River changed, and as the river largely bypassed Lake Le Bourget, a wide swamp developed since the Preboreal between the lake and the river (Bravard, 1987). Only sporadic major floods of the Rhone River entered the lake, and Holocene sediments occur as a sheet drape, about 10–15 m thick with continuous, parallel reflections over the entire lake (including the steep slopes, Fig. 3). Discrete high-amplitude reflections are interpreted to be caused by periods of enhanced clastic input (Figs 3 and 4). Periodic enhanced clastic input is described in distal Rhone River interflow deposits (Chapron *et al.*, 2002; Arnaud *et al.*, in press) and is also documented by the lithology of the more proximal interflow deposits retrieved in the piston core (Fig. 5) close to the seismic line in Fig. 4. This core is mainly composed of silty clay size, faintly laminated marls with a mean grain size of 4–6 μm. Periods of enhanced clastic input are highlighted by dark coloured silt layers (mean grain size of 13 μm), up to 1 cm thick and rich in illite (Chapron, 1999; Thevenin, 2001). Such layers occur at 60–90 cm and at 250 cm from the base of the core and correspond on seismic data with high-amplitude horizons (indicated A and B on Fig. 4).

Former mass wasting deposits

Numerous mass wasting deposits affected the sedimentary record since the Late Glacial. Up to four generations of mass movements or mass flows can be recognized: (1) above the well-developed levees during the Late Glacial; (2) into the interflow deposits at the end of the Late Glacial (a part of the larger Hautecombe Disturbed Unit, HDU); (3) within the Holocene drape; and (4) at the lake floor (Figs 2 and 3). Mass movements near the delta front are characterized by lens-shaped bodies with

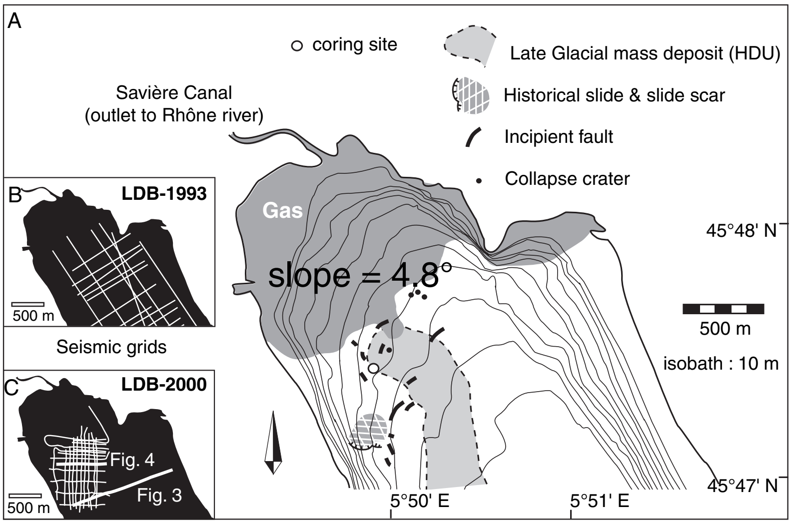

Fig. 2 Bathymetric map of northern Lake Le Bourget (A), showing the extent of gas-rich sediments near the Savière canal, and the specific locations of incipient faults, collapse craters and an historical slide and its slide scar. Gas accumulation, which extends down to about 80 m water depth, has a complex geometry and is attributed to the decay of biogenic organic matter (clastic and authigenic origin). The extension of a large Late Glacial slide (the Hautecombe Disuturbed Unit, HDU) discussed in the text is also shown. Seismic grids (B and C) and the coring site used in this study are indicated (LDB-1993: Sparker survey; LDB-2000: Boomer survey) as well as locations of seismic lines presented in Figs 3 and 4.

high-amplitude chaotic internal reflections (Fig. 4), ranging in a basinward direction into more remoulded deposits with more transparent acoustic facies (Fig. 3). The HDU in this area occurs on the delta slope and is thickest at the slope breaks (decrease in slope, Fig. 4). Parallel undulations of the Holocene drape near the gas-rich sediments (Fig. 2) and at the delta front are interpreted to be the result of downslope sediment creep (Fig. 4).

Synsedimentary faults and fluid-escape features

Different generations and styles of synsedimentary faults can be recognized in the sedimentary record of the study area: (1) some listric faults on sparker profiles affecting the complex migration of channel levee systems of the Rhone River palaeofan (Chapron *et al.*, 1996; Van Rensbergen *et al.*, 1999); (2) some smaller faults offsetting Late Glacial to early Holocene deposits (i.e. along the western levee in Fig. 3); and (3) several disruptions occurring within the Holocene sheet drape and affecting the lake floor. The disruptions extend laterally over 50–100 m and occur along the 90-m and 75-m isobaths. They are rooted in the upper part of the HDU mass deposit (Figs 2 and 4). On the high-resolution seismic data, it seems that these small faults are not single faults but consist of a network of small disruptions, with very little displacement (i.e. 'incipient' faults). Some faults are marked by diffraction hyperbolae along almost their entire length. The fractures occur at slope breaks, where the HDU is thickest (Fig. 4).

Associated with this network of disruptions, fluid-escape features occur on seismic and on side-scan sonar data. Small collapse structures occur within the upper 5 m of the Holocene drape (Fig. 4). At the lake floor it forms a 20-m-wide and ~1-m-deep circular crater. Up to four craters were mapped on side-scan sonar mosaics and boomer profiles (Fig. 2). They are interpreted as fluid expulsion craters (pockmarks) related to one or several

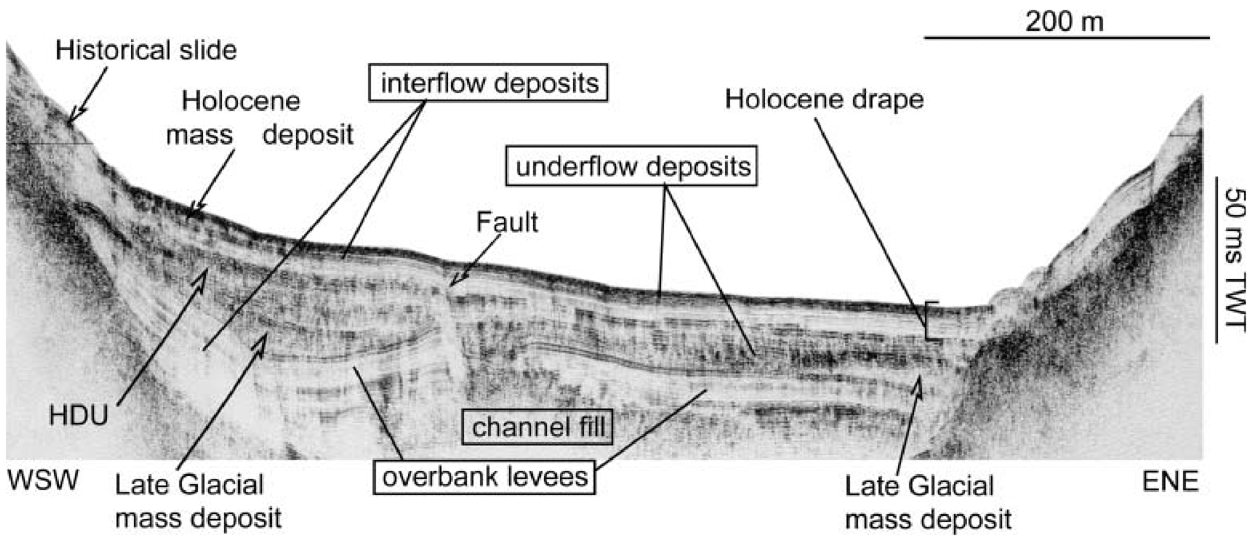

Fig. 3 Seismic section across the northern basin of Lake Le Bourget, showing the typical acoustic facies of interflow and underflow deposits during the Late Glacial and the Holocene. The sedimentary infill is locally affected by faulting and by four generations of mass movement or mass flows (including the HDU).

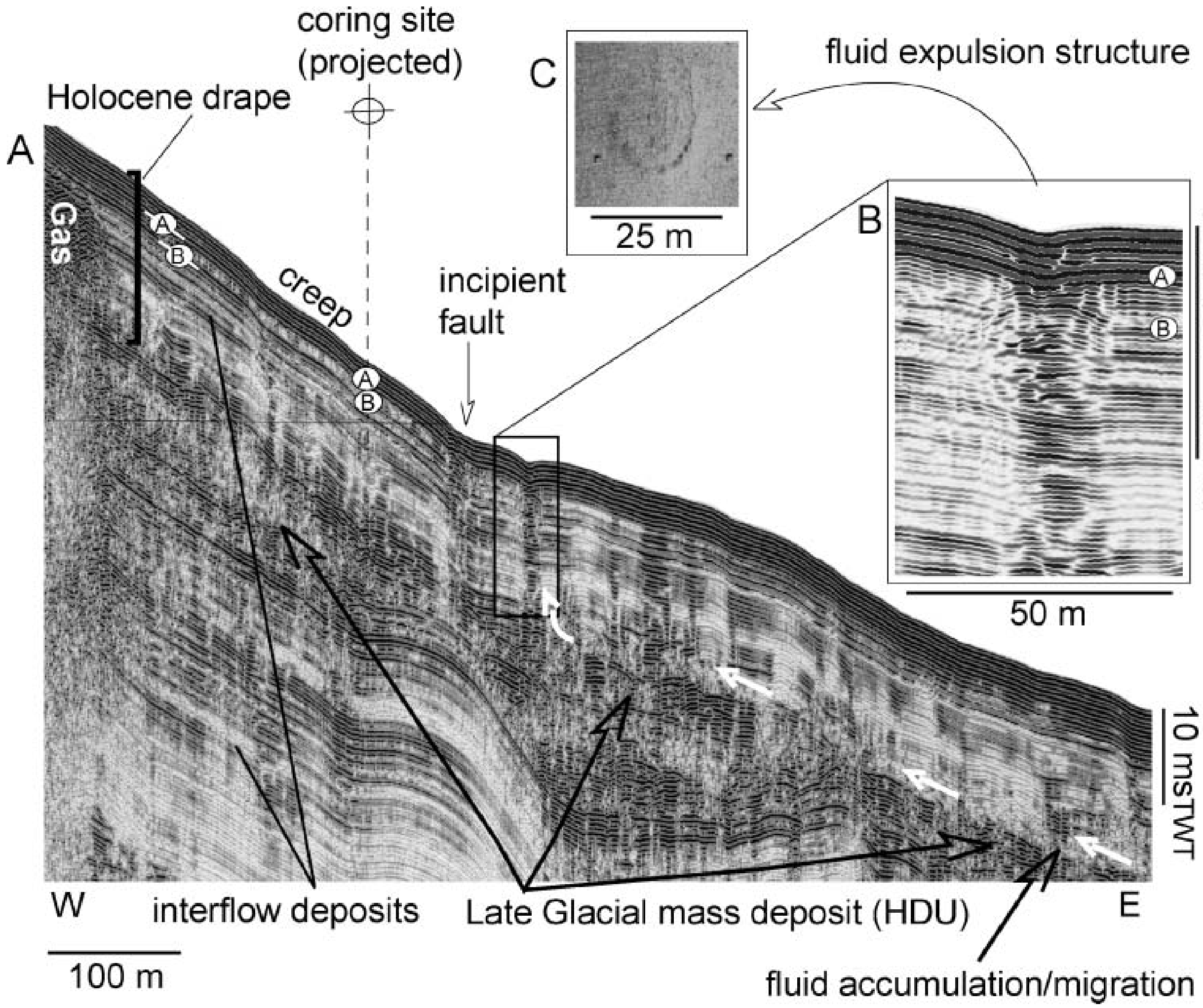

Fig. 4 Seismic section along the slope of the study area (A), illustrating the acoustic signatures of Late Glacial to Holocene interflow deposits and of the HDU in this proximal environment. The Holocene drape is creeping along the slope near gas-rich sediments and is locally affected by an incipient fault, and by a focused fluid expulsion structure that are both rooted at the top of the HDU deposits. At the base of the Holocene drape and above thick HDU deposits, fluid accumulation and migration is indicated by white arrows and produce locally some acoustic blanking. Low-amplitude patches within the Holocene drape are also visible and discussed in the text. Detailed and unprocessed seismic section across the focused fluid escape feature (B) and side-scan sonar image of a collapse crater identified at the lake floor (C) on top of this feature. The nearby coring site is also shown, as well as two reflections of enhanced amplitudes (A and B) related to periods of enhanced interflow deposits.

events of focused fluid flow along an incipient fault.

A second type of fluid-escape feature is recognized at the top of the HDU, where vertical wipe-out or low-amplitude patches occur at the base of the Holocene drape (Fig. 4). Almost all patches terminate at the discrete high-amplitude reflections within the lacustrine drape. These patches are interpreted as traces of fluid migration caused by irregular compaction and water expulsion from a very heterogeneous water-rich mass deposit. A piston core retrieved across such a low-amplitude acoustic feature shows many cracks (Fig. 5) probably related to the presence of fluids in the sediments.

Discussion

The above observations indicate a close link between vertical fractures and focused fluid flow. In this paper, we suggest that focused fluid flow facilitates the formation of small-scale faults that may accommodate part of the downslope movement and eventually link up to form a continuous fault or a head wall escarpment of a large slide (i.e. a slide scar).

The fractures and fluid migration features occur within the Holocene drape, mainly above the large HDU deposit. In addition, the Holocene sediment drape is affected by downslope creep over proximal interflow and mass wasting deposits at the delta front. The acoustic facies of the HDU deposit in the area (Fig. 4) is characteristic of coarse- and fine-grained remoulded sediments and probably rather permeable deposits with high water content (cf. Baltzer *et al.*, 1998).

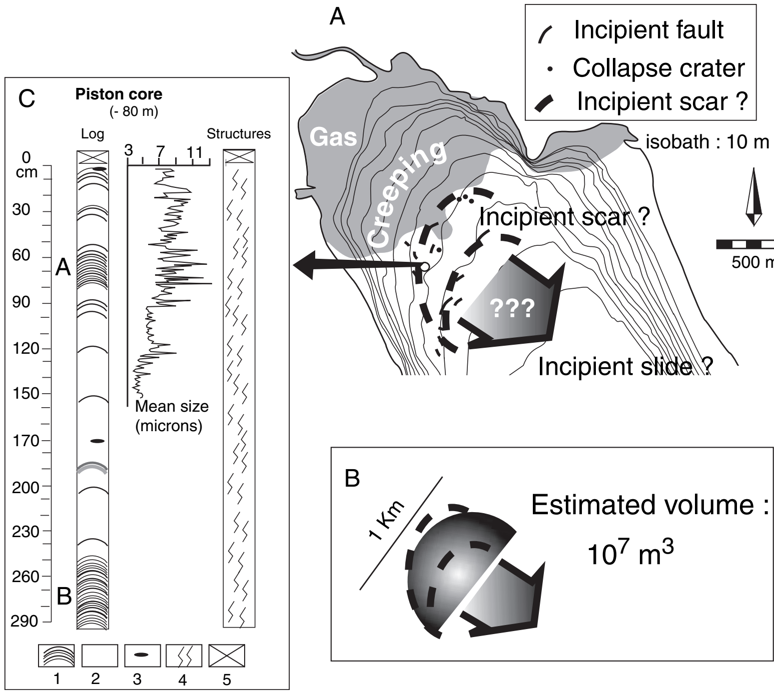

Fig. 5 Synthetic lithological description of the sediment core and tentative location of two incipient slide scars affecting the full thickness (10 m) of the Holocene drape in the study area (A). The estimated volume of the incipient slide that could result if failure occurs along these incipient scars is also indicated (B). (C) Graphic log of the piston core and grain size signature of interflow deposits. 1: interflow deposits; 2: faintly laminated marls; 3: wood debris; 4: gas decompression cracks; 5: missing uppermost sediments (estimated to be ~ 20 cm; Thevenin, 2001), based on correlations of historical horizons with nearby short gravity cores described in Chapron (1999). Periods of enhanced Rhone River flooding activity (A and B) have coarser mean grain size than the host mud and are correlated with strong amplitude reflections in the lacustrine drape (see Fig. 4).

The HDU deposit can therefore be the source of the observed fluid expulsion and migration features. In addition, the Late Glacial fill is probably still connected in the subsurface to the huge alluvial pile north of the lake and a large hydraulic head may cause groundwater flow towards the delta slope. Such widespread fluid influx from undercompacted mass wasting and Late Glacial deposits into the Holocene drape would cause pore fluid overpressure within sealed silty flood deposits. Overpressured flood deposits may form detachment surfaces for gravitational gliding during a strong local earthquake (Perissoratis and Papadopoulos, 1999).

The study area is located at the prolongation of the active Culoz fault zone where a strong historical earthquake occurred in AD 1822. According to the description of the earthquake event, it was associated with violent fluctuations of the water table (Rothé, 1941). Such water table fluctuations, cyclic loading due to seismic wave propagations during an earthquake, and cyclic and residual stress of waves during a seiche effect (McManus and Duck, 1988) can trigger sediment fluidization and fluid expulsion. It is possible that the small historical mass deposit mapped in the study area (Figs 2 and 3) has been triggered by such processes during the AD 1822 event. Eye-witness accounts during the AD 1822 earthquake, reported by Archbishop Billet (in Rothé, 1941), describe that in addition to the seiche effect, large bubbles were observed at the lake surface during the earthquake. Such bubbles can result from sudden gas escape at the lake floor, and might be related to the development of craters in the study area. These fluid expulsion craters bear similarities with pockmarks resulting from gas seepages at the sea floor (i.e. Field *et al.*, 1982; Piper *et al.*, 1992). Pockmarks formed by continuous gas venting can be periodically interrupted by short-duration violent events of enhanced gas seepage triggered by earthquakes. These events will leave a distinctive signature within the seismic reflection record (Pickrill, 1993; Hasiotis *et al.*, 1996). Similar fluid escape features were recently reproduced by experimental models including high pore-fluid pressure in the triggering of submarine mass movements (Vendeville and Gaullier, 2003). Therefore, the craters and related fluid escapes observed in Lake Le Bourget at the sediment surface and in the shallow subsurface are interpreted as due to episodic gas/fluid migration and escape during the Holocene, possibly related to former earthquakes.

A decollement surface is developing at the base of the downslope creeping Holocene sequence, probably aided by the accumulation and migration of fluids (water, gas or both) at the top of the large slide deposits (Fig. 4). The fractures and fluid expulsion features occur at slope breaks (decreasing slope gradient) and are partly lined along two isobaths (75-m and 90-m isobaths, Fig. 5) but they do not join. Vertical fluid expulsion related to earthquake-triggered fluidization may help to create and maintain fractures and faults. As the displacement on the faults increases, the fault length may increase, and the individual faults tips may join and develop ~1-km-wide incipient scars (Fig. 5). These two incipient scars may roughly follow the bathymetry and disrupt the total thickness of the Holocene drape (10 m). The development of a glide plane at the top of the HDU deposits would then result in the generation of a large sublacustrine slide with a volume of ~ 10^7 m^3, assuming a simple geometrical shape (Fig. 5) and not taking into account the development of regressive slides within upslope Holocene sediments.

Conclusions

The observations presented above support the prediction that a large (~10^7 m^3) incipient sediment slide is forming in the north of Lake Le

Bourget. Localized fluid escape features along specific zones of weaknesses in the sedimentary series appear to be a precursor for large-scale sediment instability. In order to be more precise about the possible relation of this incipient slope failure with the active seismo-tectonic setting of the study area, further studies near the incipient slide scar should involve a geotechnical characterization of the Holocene sediments and of the remoulded Late Glacial deposits (HDU). In particular, the horizontal acceleration needed to trigger Holocene sediment instability can be calculated from slope stability analysis, where the safety factor gives the slope's state of equilibrium. Such a study could confirm the potential need for earthquake-induced sediment liquefactions and fluid escape phenomena to trigger this incipient slide.

The incipient slide is estimated to be ten times larger than a historical earthquake-induced slide that produced large seiche waves at the lake shores. Hence, large seiche effects can be expected following the predicted slide. Modelling sediment displacement should allow an estimation of the potential development of a seiche effect and the generation of large waves along the populated lake shores.

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