Reconstructing historical seismicity from lake sediments (Lake Laffrey, Western Alps, France)

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Abstract

Sediment archives from a mountain lake are used as indicators of seismotectonic activity in the Grenoble area (French western Alps, 45°N). Sedimentological analysis (texture and grain-size characteristics) exhibits several layers resulting from instantaneous deposits in Lake Laffrey: six debris flow events up to 8 cm thick can be attributed to slope failure along the western flank of the basin. Dating with 210Pb and 137Cs gamma counting techniques and the reconnaissance of historical events, provide a constrained age-depth model. Over the last 250 years, five of such debris flow deposits could be related to historical earthquakes of MSK intensities greater than VI over an area of <60 km. One debris flow deposit triggered at the beginning of the last century can be related to an historical landslide possibly triggered by the artificial regulation of the lake level.

Introduction

Since a few decades lacustrine sedimentary records are used to infer palaeoseismic activities in areas where large events occurred (Sims, 1975; Ben-Menahem, 1976; Doig, 1986; Marco and Agnon, 1995; Inouchi et al., 1996). First studies dating palaeoseismological events using radiocaesium (137Cs and 210Pb) and AMS 14C techniques in lake sediments were done in Quebec (Doig, 1986, 1990, 1998). Recently, in several French alpine lakes of contrasted size and setting these techniques highlighted that some lake sediments could be good recorders of earthquakes, even in moderate seismicity areas (Chapron et al., 1999; Lignier, 2001; Arnaud et al., 2002). Those studies have shown that sedimentary structures triggered by earthquakes (i.e. slope failure and seiche deposits) can be easily detected and characterized with high-resolution laser grain size measurements.

Lebrun et al. (2001), demonstrated that a significant site effect exist in the vicinity of a historical earthquake. This is the case for Lake Artense (45°N) in France where the thickness of the deposit varies from 15 cm to 50 cm, depending on the distance from the site of the epicentre. Moreover, they showed that there is a significant difference in the thickness of the deposit between the study of the sedimentary structures triggered by earthquakes and the deposit related to the artificial regulation of the lake level. This is the case for Lake Artense where the thickness of the deposit is 20 cm for the artificial regulation and 70 cm for the earthquake. Therefore, it is important to take into account the site effect when interpreting the sedimentary structures triggered by earthquakes.

Fig. 1 Location of Lake Laffrey in the French Alps. Main historical earthquakes discussed in the text are indicated by circles, with corresponding MSK intensities at epicentres and local Richter magnitude (ML). Lakes Le Bourget and Anterne, as well as the extension of the Grésivaudan and the Trièves palaeolakes (Monjuvent, 1978; Nicoud et al., 1987) are also located.
Grenoble urban area (French western Alps) and that the amplification of ground motion in this large alpine valley can cause large risk in some part of the city. Lake Laffrey located 20 km south of Grenoble (Figs 1 and 2), was selected among other surrounding lakes for coring and multidisciplinary sedimentological studies in order to test the seismic database of the area that extends over the last 500 years (Lambert et al., 1996, 1997; BRGM, IPSN, EDF, 2002). The sedimentary infill of this lake is the most suitable because of its location close to well-known significant historical earthquake epicentres (Fig. 2). This study describes the characteristics as well as the chronology of the first metre of sediments accumulated in the deep basin of Lake Laffrey, and discusses the sensitivity of this site to record the regional seismicity.

**Geological setting**

Large tectonic features such as basement thrusts and strike-slip faults characterize the western Alps south of Grenoble. This tectonically active region (Fig. 2A) is affected by moderate magnitude earthquakes (Lambert et al., 1997; Thouvenot et al., 2003). Historic earthquakes mainly cluster around estimated magnitudes 4–5 and stronger events (such as the Corrençon event in 1962) were above but below Mw 6. The city of Grenoble in the Isère glacial valley is built on a thick quaternary infill (Monjuvent, 1978; Nicoud et al., 1987) and a major risk exists in the centre of the basin for an Mw 5.5 earthquake located at <20 km (Cotton et al., 1999; Lebrun et al., 2001). Evidences for strong palaeoearthquakes were described in glaciolacustrine to lacustrine clayey formations associated with the Grésivaudan and the Trièves palaeo-lakes (Fig. 1) of post-Riss and Würmian.
Lakes Laffrey, Petitch, Pierre-Chatel and Mort are small glacial lakes dammed by successive frontal moraine belts. These lakes were formed during the Wurm glaciation by the retreat on the Matheysin plateau of a small branch of the large Romanche glacier (Monjuvent, 1978). Lake Laffrey (2.7 km long, 0.6 km wide and 39 m deep) is the largest lake of the Matheysin plateau. It has a nivo-pluvial catchment area of 17.4 km² culminating at 2135 m a.s.l. and the main tributary of the catchment drains first into the nearby Lake Petitch (Fig. 2B). Lake Laffrey is oligothrophic, dimictic and it has a limited clastic supply (Delaquaize, 1979). Its water level is mainly resulting from a ground water flow in the glacial deposits and since its artificial regulation at the beginning of the twentieth century; the lake level has a mean annual variation of 2 m. The bathymetric map of Lake Laffrey performed by Delebecque (1898) shows no significant delta development, but highlights steep western slopes and a littoral platform with steep platform slopes surrounding the central basin (Fig. 2B). At 20 m depth in the northern part of the basin, Pourchet et al. (1989) suggested the occurrence of some mixing in the recent sediments, based on 137Cs measurements.

### Methods

The core LAF0103 corresponds to the first metre of sediment sampled at 45°00′53″N and 5°46′40″E by 38 m water depth (Fig. 2B). This core was retrieved in 2001 using UWITEC...
devices and represents the upper section of a 14 m long coring site (Desmet et al., 2003).

Sedimentological investigations on LAF0103 involved detailed lithological descriptions, high-resolution video captures, smear slides analyses, grain size and carbonate content measurements (Fig. 3). Laser grain size measurements were realized every 5 mm using Malvern Mastersizer S. Carbonate contents were also measured with the same instrument, using the comparison of obscuration on total sediment samples and on decarbonated samples, as described by Trentesaux et al. (2001).

The chronology of the core is based on $^{210}\text{Pb}$ and $^{137}\text{Cs}$ dating techniques. $^{210}\text{Pb}$, $^{241}\text{Am}$, $^{137}\text{Cs}$ and $^{226}\text{Ra}$ were measured in dried sediment by direct gamma assay in a large, low background, well-type germanium detector located in the underground laboratory of Modane (LSM) in the French Alps (M.I.M 96). Methods are described in Reyss et al. (1995). Supported $^{210}\text{Pb}$ in each sample was assumed to be in equilibrium with the in situ $^{226}\text{Ra}$. Unsupported $^{210}\text{Pb}$ was calculated by subtracting $^{226}\text{Ra}$ activity from total $^{210}\text{Pb}$.

Data presentation and interpretation

Sedimentology

Core description and lithology

Core LAF0103 is subdivided into two distinct facies (Fig. 3A): a fine-grained faintly laminated pattern (facies 1) interbedded with thick coarser-grained layers (facies 2). Throughout the core, facies 1 consists of dark and white millimetric laminae made of clastic particles (quartz, feldspar, calcite) and biogenic ones (diatoms, authigenic calcite, fragment of Arthropods). Facies 2 is a matrix-supported graded bed, with a sharp base and a gradational upper limit characterized by a dark blue colour. Smear slide microscopic observations revealed that these layers have nearly the same composition than facies 1, although their base have higher carbonate content (up to 37%) essentially made of cauliflower-like forms of carbonate concretions. Six layers of facies 2, up to 8 cm thick, are visible on the core and labelled from 1 to 6 in Fig. 2.

Grain-size measurements

Facies 1 is relatively homogenous, characterized by clayey-silt deposits...
with a mean grain size of 23 \textmu{}m, a sorting of 2.1 with both low standard deviations (Fig. 3B). Facies 2 is significantly less sorted than facies 1 and ranges from sandy-silt to clayey-silt deposits from the bottom to the top, respectively. In detail, these layers are matrix-supported deposits characterized by a coarsening upward sequence at the base to a fining upward sequence at the top.

### Sedimentary processes

The grain-size characteristics of facies 1 (Q99 and mean grain size, Fig. 3A) are typical from uniform suspension deposits formed by a rain of particles not sorted by bottom currents (Passenga and Byramjee, 1969). This facies is thus interpreted as the result of a continuous lacustrine sedimentation pattern essentially resulting from the settling of clastic and biogenic sediments in the water column. On the contrary, facies 2 highlights grain-size characteristics that are typical from uniform suspension deposits from the bottom to the top, respectively. In detail, these layers are matrix-supported deposits characterized by a coarsening upward sequence at the base to a fining upward sequence at the top.

### Age-depth model

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Following the nomenclature of Mulder and Cochonat (1996), the occurrence of inverse-grading in these mass flow deposits is interpreted as due to the development of debris flows. In the coarse fraction of facies 2, the occurrence of carbonate concretions that are typical from the littoral platform bench according to Magny (1992), suggests a source area for the debris flows located in the steep western slopes of the lake surrounding our coring site (Fig. 2B). Because dominating N-S winds are only developing significant fetch at the extremities of the lake basin, these debris flows cannot be related to storms events (i.e. tempestites).

### Chronology

#### Radionuclide measurements

The $^{210}$Pb unsupported activity curve (Fig. 4A) is non-linear in a semi-log graph and the activity in the debris flow deposits is less important than in facies 1. Values of $^{137}$Cs radioactivity vs. thickness (Fig. 4A) highlight a progressive increase starting at 25 cm, and a significant increase till 10 cm followed by a plateau and finally a clear peak above 300 Bq kg$^{-1}$ at 1.8 cm, whereas young sediments have about 200 Bq kg$^{-1}$. The progressive rise in $^{137}$Cs up to 60 Bq kg$^{-1}$ and the formation of a plateau from 5 to 10 cm indicate a significant mixing of sediments contaminated by the atmospheric nuclear weapon tests that culminated in 1963.

#### Modern age-depth model

Following Arnaud et al. (2002), we propose to exclude the $^{210}$Pb and $^{137}$Cs values associated with debris flow deposits and to establish a model of sediment thickness involving only facies 1 deposits. Removing the facies 2 events makes the unsupported $^{210}$Pb profile more linear (Fig. 4B) and allows us to calculate a mean accumulation rate (AR) of 2.2 mm yr$^{-1}$ or 0.078 g cm$^{-2}$ yr$^{-1}$ ($R^2 = 0.9$) since AD 1850 using a simple $^{210}$Pb decay model (CFCS) as described by Goldberg (1963) and Appleby and Oldfield (1978). Removing the debris flow deposits (DF 1 and 2) makes the $^{137}$Cs profile clearer (Fig. 4C): the progressive increase from 13 to

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10 cm (model thicknesses) and plateau from 10 to 5 cm are related to the occurrence of first nuclear tests starting in 1954 and to the mixing of contaminated sediments after 1963. This interpretation is comforted by the first occurrence of $^{241}$Am in the sediments at 12 cm (Appleby et al., 1991) (see Fig. 4 for details).

**Discussion**

**Age-depth model accuracy**

According to Pourchet et al. (1989), $^{137}$Cs mixing in the sediments of Lake Laffrey before the accident of Chernobyl is due to a rapid diffusion process (i.e. bioturbation). The changes in modern AR deduced from our radionuclide measurements together with the sporadic occurrence of $^{137}$Cs mixing may therefore be the result of changes in the trophic state of the lake system due to changes in land use, as already documented by Delaquaize (1979) and presently monitored by fishing state agencies (R. Soupiset, personal communication). In such a setting, the reconnaissance of recent historical data in sediment cores is useful to further constrain (i) the AR deduced from radionuclide measurements and (ii) their extrapolation down-core. In Lake Laffrey, the two stacked debris flow deposits DF 1 and DF 2 at 12.5 cm (model thickness) occurred after 1954 based on the values of $^{137}$Cs. Assuming a mean AR of 2.8 mm yr$^{-1}$ since 1954, these two events were triggered around 1957. DF 1 and DF 2 can thus reasonably be correlated with the strongest regional historical earthquakes during the last century located close to Lake Laffrey (1962 and 1963 events; Figs 1 and 4). The mean AR of 2 mm yr$^{-1}$ till 1850 deduced from our $^{210}$Pb data and its extrapolation down-core within facies 1 deposits is similarly strongly supported by the correlation of DF 4, 5 and 6 with strong historical earthquakes (Fig. 5).

**Earthquake-triggered debris flows**

Palaeoseismology studies using lake sediments are based on the detailed characterization of sedimentary events and on the establishment of a precise chronology. Because mass wasting deposits such as DF could also be produced by other processes (such as lake level changes or overloading), the best argument to assess a seismic triggering is to correlate such sedimentary event with a well-documented historical earthquake (Doig, 1986; Siegenthaler et al., 1987; Chapron et al., 1999; Arnaud et al., 2002; Schnellmann et al., 2002). In this study, two stacked debris flow deposits (DF 1 and 2) dated to have occurred in 1957 are correlated with the Corrençon-en-Vercors earthquake in 1962 and the Monteynard earthquake in 1963, which both shook the Grenoble urban area and damaged buildings (Lambert et al., 1996, 1997; BRGM, IPSN, EDF., 2002). Near Lake Laffrey, these two earthquakes had local intensities VI (MSK). The grain size and textural characteristics of the related stacked sedimentary events are clearly different from the background sedimentation and their characteristics are similar to the ones of DF 4, 5 and 6. Based on our age-depth model (Fig. 5), and on the local intensity required in 1962 and 1963 to trigger DF 1 and 2, DF 4 can be related to the well-documented historical earthquake of 1881 (local MSK intensity V–VI) rather than the one of 1866 (local MSK intensity IV–V). Following the same procedure, DF 5 matches the earthquake of 1782 (local MSK intensity V) and DF 6 the one of 1754 of unknown intensity. The

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**Fig. 6** Distance from epicentre vs. MSK intensity showing the sensibility of the Lake Laffrey sedimentary record to regional seismicity: only events with MSK intensities =VI, located at <60 km are recorded. Largest regional historical earthquakes of the NW Alps area (1822 and 1905) recorded in other lakes and other earthquakes discussed in the text (1866, 1901, 1904) are also indicated in this graph.
calculated age of DF 3 not only matches two earthquakes with local MSK intensities < IV near Lake Laffrey (Fig. 5), but also a large landslide affecting the western flank of the catchment (Fig. 2B) dating around 1900–1910 (M. Martin, personal communication). Because earthquakes in 1901 and 1904 had relatively low intensity near lake Laffrey, DF 3 is interpreted as resulting from the historical landslide (Figs 2B and 5).

Sensibility of the Lake Laffrey sedimentary record to regional seismicity

When the intensity of the regional historical earthquakes is plotted against their distance from Lake Laffrey (Fig. 6) it appears that only seismic events with MSK intensities = VI and distances below 60 km are recognized in this study. The most intense historic earthquake reported in the NW Alps area (18/02/1822, Fig. 1) of MSK intensity VII–VIII and an estimated equivalent magnitude of 5.5–6 (Thouvenot et al., 1990), was well recorded in Lake Le Bourget (Chapron et al., 1999), but apparently located to far from Lake Laffrey (Fig. 1). Similarly the 1905 event of Emosson (MSK intensity VII–VIII) well documented in Lake Anterne (Arnaud et al., 2002), has not been recognized in this study.

Conclusions

Age-depth model combining $^{137}$Cs and $^{210}$Pb dating techniques with detailed sedimentological studies in core LAF0103, allows to recognize and to successfully correlate five debris flow deposits with strong regional historical earthquakes over the last 250 years. The grain-size characteristics of the debris flow deposits alone are not sufficient to disentangle the triggering factor (earthquake or landslide). Lake Laffrey sedimentary infill has the potential to precise and to extend the regional earthquake catalogue for seismic events with MSK intensities = VI, located at < 60 km from the lake. Variable ARs highlighted in this study suggest that Lake Laffrey is also highly sensitive to modifications in its catchment area. Further multidisciplinary characterization of the sedimentary processes is thus required to extend palaeoenvironmental and palaeoseismic reconstructions back in time.

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