New Evidence of Holocene Mass Wasting Events in Recent Volcanic Lakes from the French Massif Central (Lakes Pavin, Montcineyre and Chauvet) and Implications for Natural Hazards

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Chapter 23

New Evidence of Holocene Mass Wasting Events in Recent Volcanic Lakes from the French Massif Central (Lakes Pavin, Montcineyre and Chauvet) and Implications for Natural Hazards

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Abstract High-resolution seismic profiling (12 kHz) surveys combined with sediment cores, radiocarbon dating, tephrochronology and multibeam bathymetry (when available) allow documentation of a range of Holocene mass wasting events in nearby contrasting lakes of volcanic origin in the French Massif Central (45°N, 2°E): two deep maar lakes (Pavin and Chauvet) and a shallow lake (Montcineyre) dammed by the growth of a volcano. In these lacustrine environments dominated by authigenic sedimentation, recent slide scars, acoustically transparent to chaotic lens-shaped bodies, slump deposits or reworked regional tephra layers suggest that subaqueous mass wasting processes may have been favoured by gas content in the sediments and lake level changes. While these events may have had a limited impact in both lakes Chauvet and Montcineyre, they apparently favoured the development of lacustrine meromicticity in maar Lake Pavin along with possible subaerial debris flows resulting from crater outburst events.

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23.1 Introduction

On August 15, 1984 in Lake Monoun and August 21, 1986 in Lake Nyos, two catastrophic limnic eruptions with sudden outgassing of CO_2 from meromictic crater lake deep waters, occurred in Cameroun and killed 37 and 1,700 people, respectively (Sigurdsson et al. 1987). These two events demonstrated that meromictic maar lakes are prone to specific geological hazards. The possible triggering factors and the evolution of processes during limnic eruptions are still controversial, but their association with violent waves and subaquatic landslides suggest that these rare events can be recorded in the deep basin infills of maar lakes (Chapron et al. 2010a). Lake Pavin is the only meromictic maar lake in France and is surrounded by several contrasting small lakes of volcanic origin (Fig. 23.1). The investigation of the basin infill of these three lakes may thus help reconstructing environmental changes and evaluating specific natural hazards associated with meromictic maar lakes.

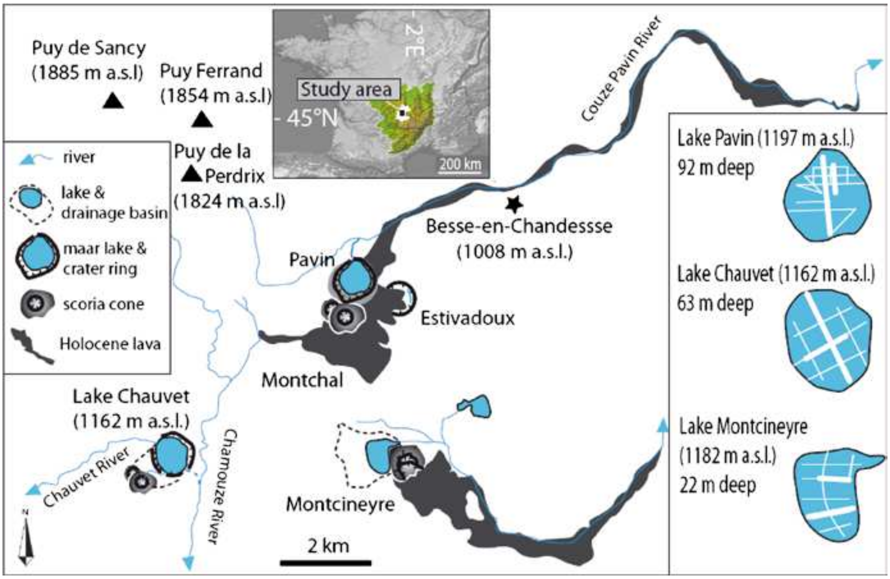

Fig. 23.1 Geomorphologic setting and location of investigated volcanic lakes in the French Massif Central, also showing the seismic grids surveyed in each lake and illustrated seismic sections (*thick lines*). Ice extent (*white area in small upper panel*) during the last glacial period in the Puy de Sancy area is also indicated (After Etlicher and Göer de Herve 1988)

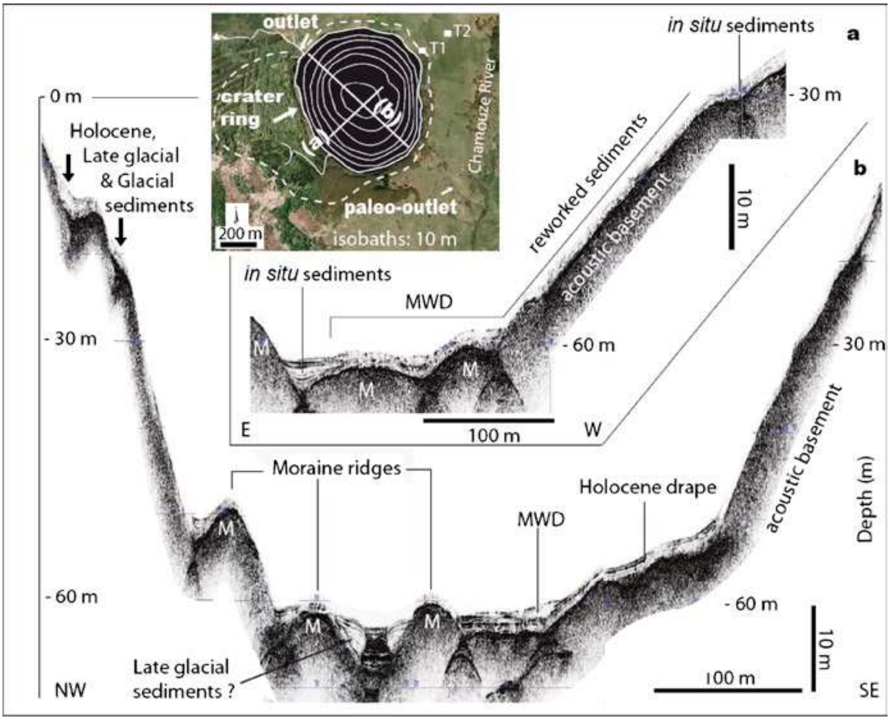

Fig. 23.2 Lake Chauvet geomorphology (*upper panel*) and seismic sections illustrating the occurrence of Glacial Moraines(*M*), Late Glacial and Holocene deposits. Holocene mass wasting deposits (*MWD*) are visible on two sections in the deep basin and described by Juvigné (1992) from piston cores in shallower environments (*black arrows*)

23.1.1 Geological Setting

The southern flanks of the Sancy stratovolcano constructed between 1 and 0.25 Ma (Boivin et al. 2009) today culminate at 1,885 m above sea level (asl) and were shaped by mountain glaciers extending down to ca. 650 m asl during the last glacial period (Etlicher and Göer de Herve 1988). Moraines locally outcrop near the Lake Chauvet outlet and were also documented by Juvigné (1992) in trenches T1 and T2 around this circular lake (Fig. 23.2). In the early Holocene, four small nearby volcanoes (Fig. 23.1) successively developed within a short period, as documented by previous tephrostratigraphic studies on outcrops and on tephra layers in peat deposits (Gewelt and Juvigné 1988; Bourdier 1980): first Montcineyre (ca. 6027 ± 660 year BP, i.e. 6812 ± 680 cal BP); then Estivadoux (ca. 6760 ± 130 year BP; 7635 ± 115 cal BP); Montchal (ca. 6670 ± 160 year BP; 7555 ± 130 cal BP) and finally Pavin (ca. 6000 ± 110 year BP; 6864 ± 140 cal BP). Lava flows associated with Montcineyre and Montchal scoria cones were essentially developed in fluvial valleys of glacial origin, while Estivadoux and Pavin phreatomagmatic eruptions formed deep craters (Fig. 23.1). The regional seismicity of the study area is presently moderate (Boivin et al. 2009).

Lakes Chauvet, Montcineyre and Pavin have very small drainage basins compared to their areas (Fig. 23.1) and are thus dominated by organic rich authigenic Holocene sedimentation. The first bathymetric maps acquired by Delebecque (1898) revealed that these lakes have different maximum depths, but are all characterized by steep slopes and conical shapes. Juvigné (1992) and Chapron et al. (2010a) documented mass wasting deposits (MWDs) within Holocene fine-grained sediments in maar lakes Chauvet and Pavin, respectively.

23.1.2 Methods

The lakes were mapped in 2009 using a 12 kHz Knudsen subbottom profiler and conventional GPS positioning from an inflatable boat. In lakes Chauvet and Montcineyre, these grids allowed generating bathymetric and isopach maps using the ArcGIS and Surfer V9 software. In Lake Pavin, a detailed bathymetric map was previously established with a multibeam echosounder (Chapron et al. 2010a) and this dataset has been merged together with a detailed (5 m resolution) digital elevation model of the Pavin crater ring using ENVI and MA Publisher software.

New gravity cores were retrieved in Lake Pavin at 20 m (PAV09C5) and 92 m (PAV09B1) water depths in 2009 and at 17.5 m (PAV10E) in 2010 using a UWITEC hammer action corer. Gravity cores were also retrieved in Lake Montcineyre at 9 m (MO 10 G) and 18.5 m (MO 10B) water depths in 2010. Sediment cores were split in two halves and analysed in detail: sediment magnetic susceptibility (MS) and diffuse spectral reflectance were measured using a Bartington MS2E1 point sensor and a Minolta 2600D hand-held spectrophotometer, respectively. The lithology of each core was established through detailed visual descriptions and digital radiographs using a Siemens Axiom Iconos R200. Two new AMS radiocarbon ages obtained from plant macro remains sampled in cores PAV09C5 and PAV09B1 were dated at the Poznan Radiocarbon Laboratory, Poland. Data from Lake Pavin is correlated with previously available sediment data and 14 radiocarbon ages from piston core PAV08 (Chapron et al. 2010a; Chapron et al. 2010b) and used for the present study.

23.2 Results

23.2.1 High Resolution Seismic Reflection Mapping

In Lake Chauvet, seismic profiling revealed an irregular acoustic basement morphology, with local ridges of variable sizes and diffractions in the deep basin and along the northern slopes (Fig. 23.2). In between these ridges and in the deep basin,

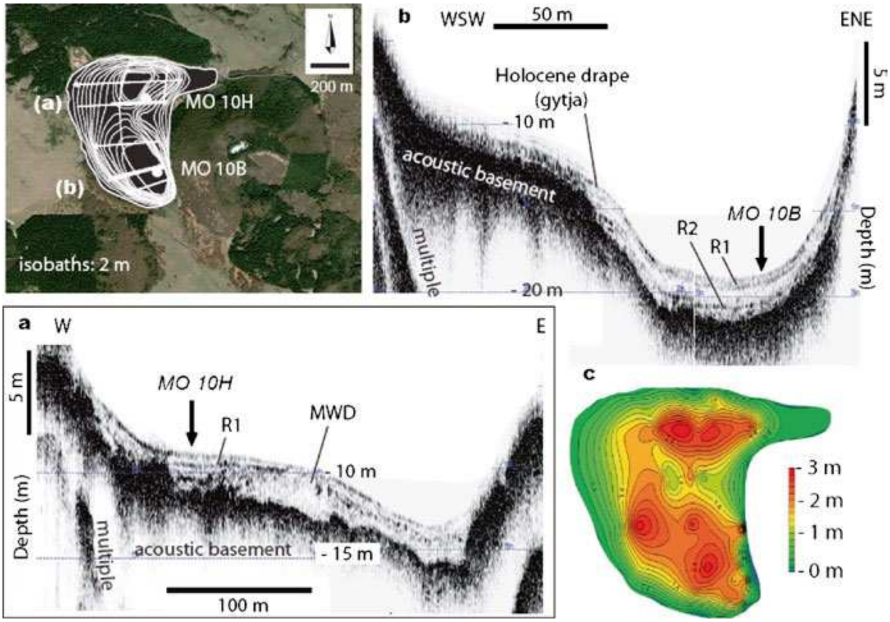

Fig. 23.3 Lake Montcineyre geomorphology map (*left upper panel*), seismic sections (**a** and **b**) illustrating the basin fill geometry in each sub-basin together with gravity core locations. A sediment isopach map (**c**) is also shown

up to 5 m of fine-grained sediments are identified. Locally, a chaotic to transparent lens-shaped body is also identified near the lake floor.

In Lake Montcineyre, the acoustic basement is characterized by two sub-basins (maximum depth: 22 m) and its morphology becomes more irregular above 15 m water depths (Fig. 23.3). Up to 3 m of fine-grained sediments are identified in the deepest parts of the sub-basins. The basin infill is made of a transparent acoustic facies developing a draping geometry that thins out laterally above 10 m water depths (Fig. 23.3d). Above 10 m water depth, acoustic penetration is low, probably due to local gas pockets. Two basin-wide higher amplitude and continuous reflections are identified: one at ca. 0.5 m below the water-sediment interface (R1) and the other (R2) just above the acoustic basement. R2 is only observed in the deepest part of the sub-basins and may reflect regional tephra layers. Locally, an up to 2.5 m thick and 100 m wide transparent to chaotic lens-shaped body caped by R1 is identified in the northern sub-basin.

In Lake Pavin, the acoustic basement shows a subaquatic plateau with a hummocky morphology along the northern part of the basin (Fig. 23.4). In the deep flat basin, the penetration of the acoustic signal is very limited due to the presence of gas in the sediments (Chapron et al. 2010a). Up to 5 m of fine-grained sediments are visible above the plateau, but the steep basin slopes are almost free of sediment cover. Three main acoustic facies are identified on the plateau with the 12 kHz subbottom profiler: (i) a littoral facies (between 26 m water depths and the shore line) that thins quickly upslope and

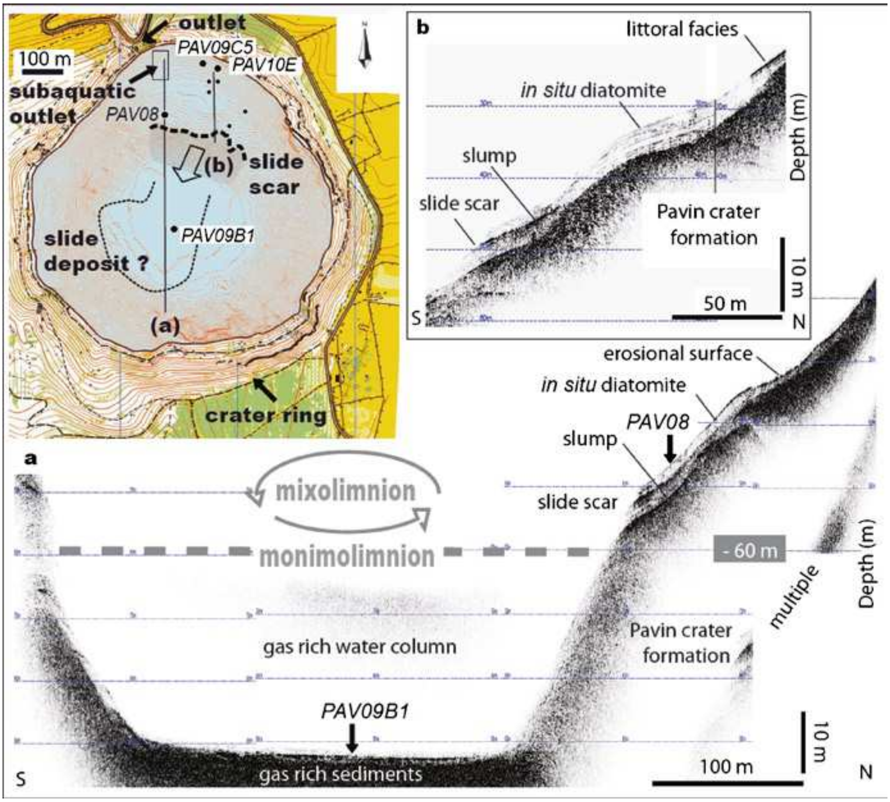

Fig. 23.4 Lake Pavin geomorphology (*upper panel*) and seismic sections (**a** and **b**) illustrating contrasting deposits in the deep basin, on a sub aquatic plateau and along the littoral. Also shown are the locations of the studied sediment cores and the occurrence of a monimolimnion rich in gas in the deep waters of the lake

develops a transparent facies and a high-amplitude reflection at the water-sediment interface; (ii) an up to 5 m thick acoustically well-stratified facies composed of continuous and high-frequency low-amplitude reflections draping the underlying morphologies and (iii) an up to 3 m thick and 100 m wide chaotic to transparent lens-shaped body deposited above the acoustic basement hummocks. At the southern edge of the plateau, the sediment depocentre ends abruptly and an up to 4 m high slide scar (well-identified in the bathymetry) returns diffractions on seismic profiles.

23.2.2 Basin Fills Lithologies and Chronologies

Lake Chauvet basin fill lithologies were previously documented by Juvigné (1992) with two piston cores retrieved in the north-western part of the basin at 13 and 20 m

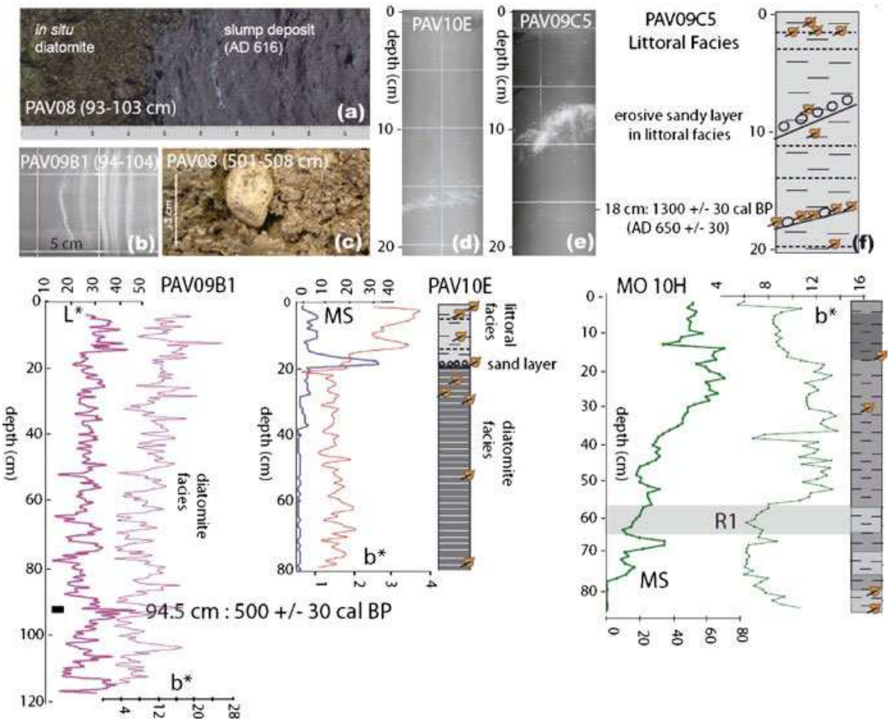

Fig. 23.5 Multiproxy characterization of sedimentary facies from cores retrieved in lakes Pavin and Montcineyre. Core photographs (**a** and **c**), radiographs (**b**, **d**, **e**), lithological log (**f**), sediment lightness (*L**) magnetic susceptibility (*MS*) and diatomite content (*b**) allows distinction of background sedimentation from sedimentary events

water depths (Fig. 23.2, black arrows), respectively. They consist (from top to base) in (i) dark mud rich in diatoms and organic macro remains where the Pavin, Montcineyre and Taphanel regional Holocene tephra layers are not systematically in chronological order ; (ii) light grey clays, slightly organic, bearing the Godivelle T4 (ca. 12,250 cal BP) and T5 (ca. 12,730 cal BP) regional Late Glacial tephra layers (in chronological order); and (iii) a mixture of silts and trachyandesite stones of variable size similar to the moraine deposits identified in trenches T1 and T2 near the lake. These lithologies are in good agreement with the seismic data. Glacial deposits can be correlated to the ridges of the acoustic basement. The basal basin infill can be related to Late Glacial sediments essentially observed in between moraine ridges, and the upper draped deposits can be linked to Holocene organic-rich sediments (Fig. 23.2). The reworked tephra layers are suggesting that subaqueous MWDs identified on seismic sections occurred after the most recent regional volcanic event (i.e. the Pavin eruption, ca. 7,000 years ago). Since these MWDs are identified near the lake floor, they are probably much younger in age.

Lake Montcineyre recent sedimentation is only documented by cores MO 10H and MO 10B (Figs. 23.3 and 23.5), which consist of light- to dark-brownish mud rich in organic terrestrial leaves. Several sub units are identified based on sediments' MS and diffuse spectral reflectance (Fig. 23.5), especially with the b* parameter, which is considered as a good proxy for diatom content in bioturbated or anoxic sediments (Debret et al. 2006). In core MO 10 H, fluctuations in b* and in MS may thus reflect recent environmental changes. Between 55 and 65 cm, abrupt changes in b* and MS can be correlated to horizon R1 on seismic sections. Similarly, R1 occurs between 50 and 60 cm in core MO 10B. A rough estimation of the age of horizon R1 can be based on the most likely age of the formation of this lake (ca. 7495 ± 565 cal BP), on the depth of R1 and on the thicknesses of the basin infill at coring site MO 10H. This estimate suggests a mean sedimentation rate of ca. 0.3 mm/a and an age of around 1,900 cal BP (ca. AD 50) for R1. Taking into consideration dating uncertainties (±565 years), this MWD in Lake Montcineyre could be contemporaneous to a slump deposit dated to AD 610 ± 30 (1340 ± 30 cal BP) on the plateau of Lake Pavin (Chapron et al. 2010a). On going radiocarbon dating on samples from core MO 10 H will be used to test this assumption.

In Lake Pavin, three main sedimentary environments identified on seismic profiles can be ground-truthed by sediment cores and their chronologies are either constrained by radiocarbon dating, pollen and diatom assemblages or by biochemical varve counting from a freeze-core (Stebich et al. 2004; Schettler et al. 2007; Chapron et al. 2010a). The acoustic basement has been sampled (Fig. 23.5c) by piston core PAV08 and related to the formation of the Pavin crater (Chapron et al. 2010a). The lacustrine sedimentation developing a stratified facies on seismic profiles is characterized by the *in situ* diatomite facies, made of biochemical varves in the basin (core PAV09B1, Fig. 23.5b) and on the plateau (PAV08, PAV10E, Fig. 23.5a, d). This facies is characterized by a dark brown to greenish colour, very low MS values but finely fluctuating values of sediment lightness (L*) and b* throughout PAV09B1 and below 20 cm core depth in PAV10E (Fig. 23.5). The varve chronology developed on thin sections in the deep basin (Schettler et al. 2007) is in agreement with the age of leaf debris sampled at 94.5 cm in core PAV09B1 (500 ± 30 years cal BP). This further supports that a plurimetric MWD covered by a large turbidite deposit documented in the deep basin by piston coring between 650 and 220 cm below the lake floor (Schwab et al. 2009) dates around AD 1200 (Chapron et al. 2010a) and is related to the slide scar identified at the edge of the plateau (Fig. 23.4). Littoral facies identified on seismic profiles down to 26 m water depths have been sampled in core PAV09C5 and in the upper 20 cm of core PAV10E. In this environment, the sediment is generally composed of light brown to greenish homogenous fine-grained mud rich in diatoms (high values in b*) and with frequent thin layers made of leaves and leaf debris (Fig. 23.5f). Two erosive horizons are also identified on PAV09C5 (Fig. 23.5e): a 1 cm thick sand layer at 10 cm core depth, and a stricking 1 cm thick layer at 18 cm, very rich in leaves and also containing few pebbles and some fine sands. This organic and erosive layer is dated to 1300 ± 30 cal BP (AD 650 ± 30). On core PAV10E, a 2 cm thick sandy layer (identified visually, on radiographs and from MS data) matches the transition from a littoral facies to a diatomite facies. This abrupt change in sedimentation from a deeper to a shallower environment occurring below 17.5 m water depth indicates a rapid lake level drop of ca. 6.5 m at that time (taking into consideration that first human infrastructure around 1855 at the outlet induced a lake level rise of ca. 2 m).

23.3 Discussion and Conclusions

This study highlights a range of Late Holocene MWDs in three small lakes of volcanic origin dominated by authigenic sedimentation. The largest events are found in meromictic Lake Pavin and well-dated at ca. AD 610 and AD 1200. Radiocarbon ages from gravity cores in the two other lakes are still needed to establish if MWDs are contemporaneous and regional. This will be essential to identify a triggering factor for these MWDs and to carry out risk assessment in this young volcanic province.

MWDs in Lake Pavin were previously related to high gas content in authigenic sediments and possibly to abrupt lake level changes associated with crater outburst events (Chapron et al. 2010a). The erosive layer at 18 cm in core PAV09C5 identified at 20 m water depth in the littoral environment is contemporaneous with the slump deposit on the plateau. This confirms that this slump in ca. AD 610 was large enough to be associated with violent waves in Lake Pavin. Such exceptional waves can favour erosion at the outlet and a rupture of the Pavin crater ring resulting in: (i) abrupt lake level drop and (ii) the spill over of a debris flow downstream in the Couze Pavin valley. Such violent waves may also result from a limnic eruption. Another striking erosive layer at 10 cm in core PAV09C5 is rich in littoral sands and probably resulted from violent waves or abrupt lake level drop. This second erosive event may be associated with the second MWD identified on Lake Pavin. Abrupt lake level drop of ca. 6.5 m identified in core PAV10E by a sand layer at the transition from a diatomite to a littoral facies may either result from the first or the second MWD identified in Lake Pavin. This abrupt lake level drop can be related to a rupture of the crater ring (outburst event) and imply a sudden discharge of ca. 2.8 million m^3 (2.8 billion litres) down stream Lake Pavin in the Couze Pavin River (Fig. 23.1). Such outburst event would trigger a large debris flow in the Couze Pavin River and could also favour a limnic eruption (abrupt release of gas due to pressure drop). Radiocarbon dating just above erosive layers in the littoral facies is in progress and will be used to determine the impact of MWDs in Lake Pavin. Finally, the identification of a significant reservoir age in radiocarbon dates from bulk sediment in core PAV08 above the AD 610 slump suggest that MWDs in Lake Pavin may have supplied significant amount of gas in the deep waters and favoured the onset of its meromicticity (Chapron et al. 2010b).

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