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# Lake Pavin Sedimentary Environments

# 22

Emmanuel Chapron, Léo Chassiot, Patrick Lajeunesse, Grégoire Ledoux, and Patrick Albéric

**Abstract**

In the recent years, Lake Pavin sedimentary basin has been intensively studied by several acoustic surveys (high resolution seismic reflection profiling, multibeam bathymetry) and gravity coring campaigns. This new data set combining acoustic images and multidisciplinary study of sediment cores allows characterizing contrasted subaquatic sedimentary environments along the littoral slopes, a subaquatic plateau (close to the lake **outlet**), steep slopes and its deep central basin. Two main types of lacustrine sediments are identified (i) between the lake shore and 26 m water depth (massive organic rich sandy silts), and (ii) below 26 m water depth when the lake floor slopes are less than 15° steep (organic rich laminated **diatomites**). A large and recent **slide scar** is in particular clearly identified at the edge of the plateau just above the deep central basin. Evidences of former gravity reworking phenomena within the **crater ring** draining into Lake Pavin also include a large subaquatic **slump deposit** accumulated on the subaquatic plateau and several small scale **rock fall** deposits originating from outcropping **lavas** within the **crater ring**. The identification of two recent outstanding **erosive** sandy layers in Pavin littoral environment also suggests that some of this gravity reworking phenomena have been associated with unusually violent waves and/or abrupt lake level drop. Lake Pavin geomorphology and sedimentary environments are in addition compared to the ones of the nearby Lake Chauvet based on a similar acoustic and sedimentary data base in order to highlight the influence of **maar** age and geomorphology on the development of sedimentary environments and Natural Hazards in this volcanic region of the French Massif Central. Lake Chauvet is comparatively to Lake Pavin characterized by a shallower central basin, less steep slopes and no subaquatic plateaus. A recent and relatively large **mass wasting deposit** is, however, clearly identified along the slopes of a small delta facing the only tributary of this maar lake. This work

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suggest that maar lakes from the study area are concerned by subaquatic slope stabilities, especially in Lake Pavin were slope failures may in addition impact the development or the stability of its **meromicticity**.

**Keywords**
Lake Pavin • Lake Chauvet • Sediment • Slope stabilities • Bathymetry • Seismic stratigraphy

## 22.1 Introduction

Lake Pavin have been intensively investigated in terms of limnology and volcanology (Parts I, II and III, this volume) but little is still known about its subaquatic sedimentary environments and their dynamics (Chapron et al. 2010). Such a characterization of sedimentary environments in this young crater lake (or **maar** lake, see Chap. 5, this volume) can be achieved through a **limnogeological** approach of its sedimentary archives. This chapter aims thus at addressing an up-to date presentation of available knowledge on Lake Pavin sedimentary environments based on the integration of two complementary acoustic mapping techniques (multi-beam bathymetry and seismic reflection mapping) and a multidisciplinary characterization of short sediment cores (sediment color, magnetic susceptibility, total organic carbon content and organic geochemistry) retrieved at key locations.

In this chapter, first results from a similar approach recently performed in nearby **maar** lake, Lake Chauvet, (Fig. 22.1) are also presented in order to highlight the main specificities of Lake Pavin's sedimentary environments and to further discuss their influence on the development of natural hazards in this touristic part of the French Massif Central.

Pavin is the only **meromictic maar** lake in France (Chaps. 1, 6 and 10, this volume) and is surrounded by several contrasting older small lakes of volcanic origin as shown in Fig. 22.1. The other **maar lake,** Lake Chauvet, for example, formed during the last glacial period is today 63 m deep and contains several regional **tephra** layers from the Late Glacial and Early Holocene periods (Juvigné 1992). Lake Montcineyre formed in the Early Holocene is nowadays

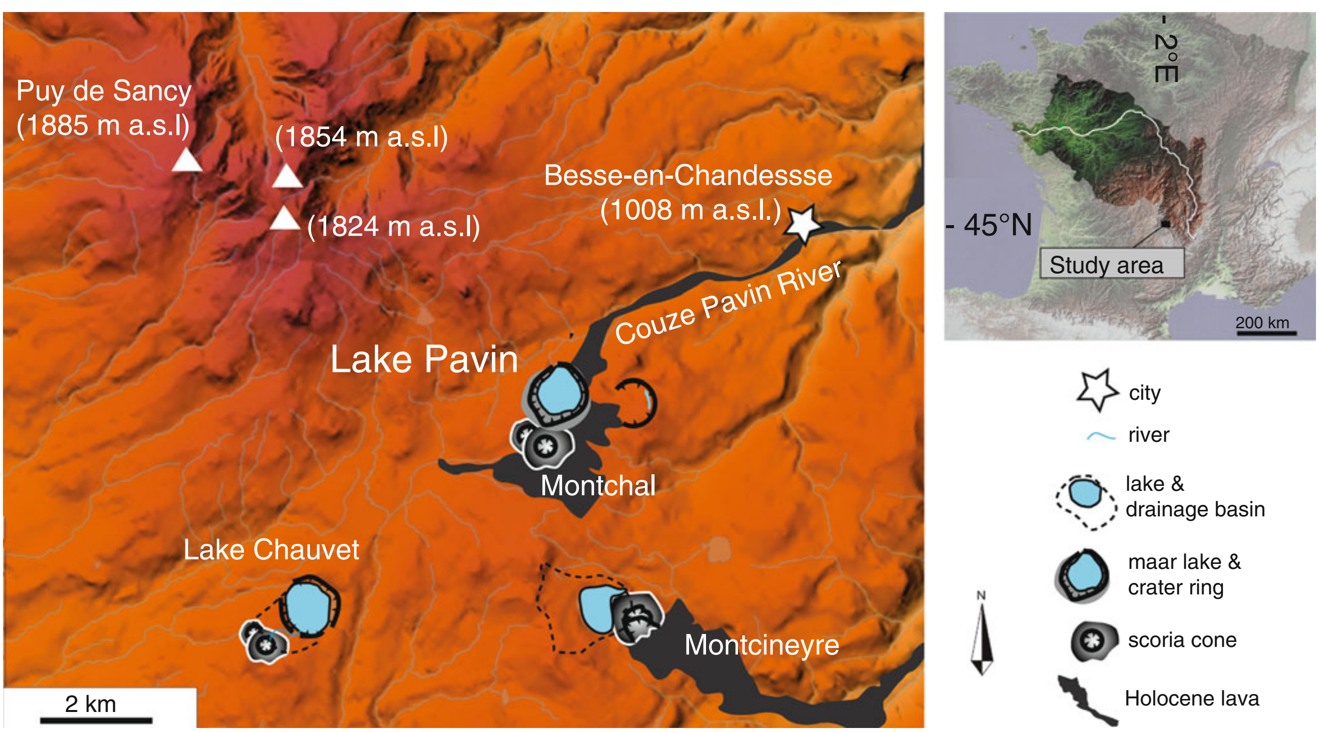


**Fig. 22.1** General location of maar lakes Lake Pavin and Lake Chauvet in the French Massif Central and in the Loire river drainage basin (*right*) and simplified Holocene volcanic context south of the Puy de Sancy strato volcano (*left*) (Note that lakes Pavin and Montcineyre are part of the Allier River watershed draining into the Loire River watershed towards the north east, while Lake Chauvet drains into the Dordogne River towards the west)

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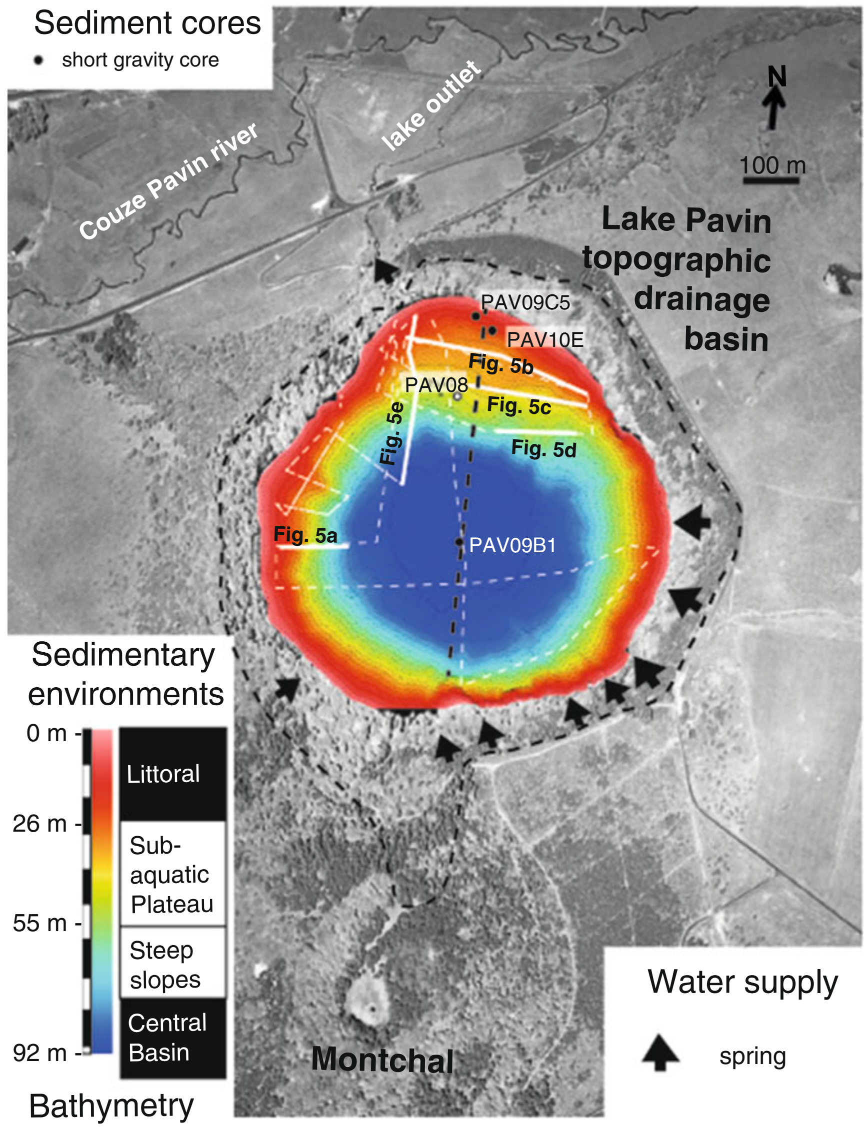


**Fig. 22.2** Illustration of Lake Pavin multibeam bathymetry and location of sub-bottom profiles and short sediment cores. The grid of 12 kHz sub-bottom profiles (*white dotted lines*) and the 3.5 kHz sub-bottom profile (*black dotted lines*) were used together with short gravity cores to identify four main sedimentary environments from the littoral to the deep central basin. The locations of springs within the crater rim (*black arrows*) and of 12 kHz sub-bottom profiles illustrated in Fig. 22.5 (*thick white lines*) are also given

22 m deep and consist in two coalescing small **maars** damned by the Montcineyre **scoria cone** and **lava flow** which developed shortly before the Montchal **scoria cone** and **lavas** (Chapron et al. 2012). The Montchal **lavas** have then been partly destroyed by the Pavin **phreatomagmatic** eruption ca. 7000 years ago (Gewelt and Juvigné 1988; Chap. 6, this volume). This recent volcanic event formed Lake Pavin: a almost circular (750 m diameter) small but 92 m deep **maar** lake, today located at an altitude of 1197 m above sea level (a.s.l.) and draining a steep and well preserved **crater rim** reaching an altitude of 1253 m a.s.l.. As shown in Fig. 22.2, the edge of the Pavin **crater ring** matches the limit of the topographic drainage basin of Lake Pavin. It is however important to keep in mind that this **topographic drainage basin** is smaller than the still poorly defined **watershed** of Lake Pavin draining several subaerial and subaquatic springs (Jezequel et al. 2011).

## 22.2 Limnogeological Data Bases from Lakes Pavin and Chauvet

During the last decade advanced acoustic mapping techniques were applied in Lake Pavin in order to document subaquatic slope stabilities and to optimize the location of sediment cores (Figs. 22.2 and 22.3) to further understand the history and the evolution of this recent volcanic lake.

### 22.2.1 Acoustic Mapping Technics

In 2008, a Reason Sebat 8101 multibeam echosounder used with differential GPS positioning and an inertial navigation system allowed to precisely map the lake floor morphology (Figs. 22.2 and 22.4). This recent map presented in Chapron et al. (2010) significantly improved our understanding of

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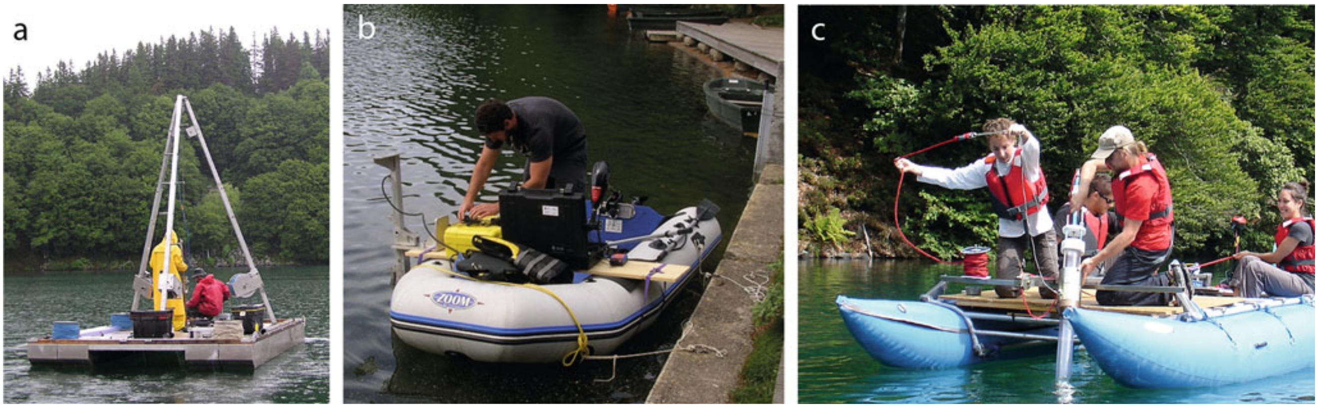


**Fig. 22.3** Recently available geological data from in Lake Pavin and Lake Chauvet discussed in this chapter include short gravity coring performed from an UWITEC platform in 2008 (**a**); high resolution seismic reflection mapping survey from an inflatable boat in 2009 (**b**) and short gravity coring from a Limnoraft in 2009, 2010 and 2013 (**c**)

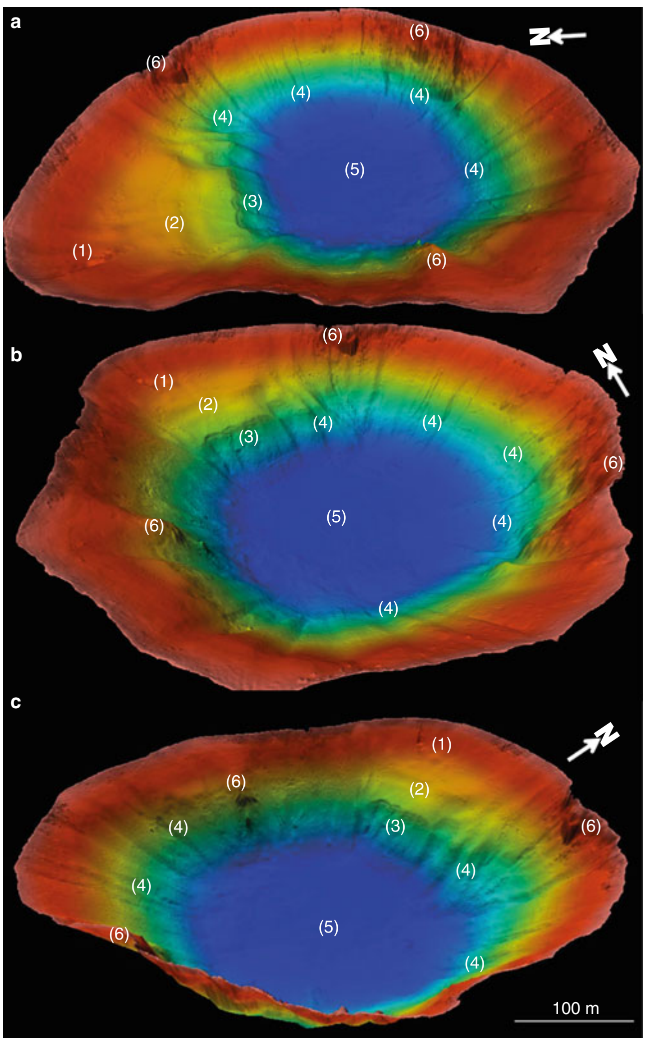


**Fig. 22.4** 3D views of Lake Pavin multibeam bathymetry illustrating a possible subaquatic outlet (*1*), the subaquatic plateau (*2*), the ca. AD 1300 slide scar (*3*), multiple active canyons along steep slopes (*4*), a deep and flat central basin (*5*) and outcropping volcanic rocks (*6*). These geomorphological features are further presented and discussed in the text

Lake Pavin sedimentary environments, in particular because it clearly illustrates the development of a subaquatic plateau between ca. 26 and 55 m water depths in the northern part of the lake. This key feature was not identified on the previous bathymetric map made by Delbecque (1898) on basis of manual water depth measurements along only two perpendiculars transects.

The multibeam bathymetric map of Lake Pavin also allowed optimizing the location of high-resolution **seismic reflection profiles** documenting the sub-bottom geometries developed by lacustrine sediments below the lake floor (Figs. 22.2 and 22.5). The sub-bottom profiling survey realized in 2009 used GPS positioning and a very high frequency (12 kHz) acoustic source in order to provide very high resolution **sub-bottom profiles** (ca. 8 cm vertical resolution) (Chapron et al. 2012). This strategy has been established based on the results of a previous seismic reflection survey performed in 2002 using a lower frequency seismic source (3.5 kHz) and a dense grid of profiles showing (i) that the maximum sediment thickness accumulated above the bedrock on the plateau is limited (ca. 5 m) and (ii) that the acoustic signal is very quickly absorbed by gas rich sediments in the deep flat basin of the lake (Chapron et al. 2010).

An exploratory sub-bottom profiling survey using the same 12 kHz seismic source and GPS positioning in Lake Chauvet (Fig. 22.6) was also conducted in 2009 based on available bathymetric data from Delbecque (1898). This survey allowed mapping lacustrine sediment thicknesses and geometries above the **bedrock** (along the lake shore) or subaquatic **moraine** deposits in the deep central basin were Late Glacial and Holocene sediments are clearly imaged (Chapron et al. 2012). In 2011, further bathymetric data has been collected in Lake Chauvet (i.e. along the shore line and several cross sections in between available seismic reflection profiles) with a single beam echo sounder using a 200 kHz acoustic source. This strategy allowed mapping

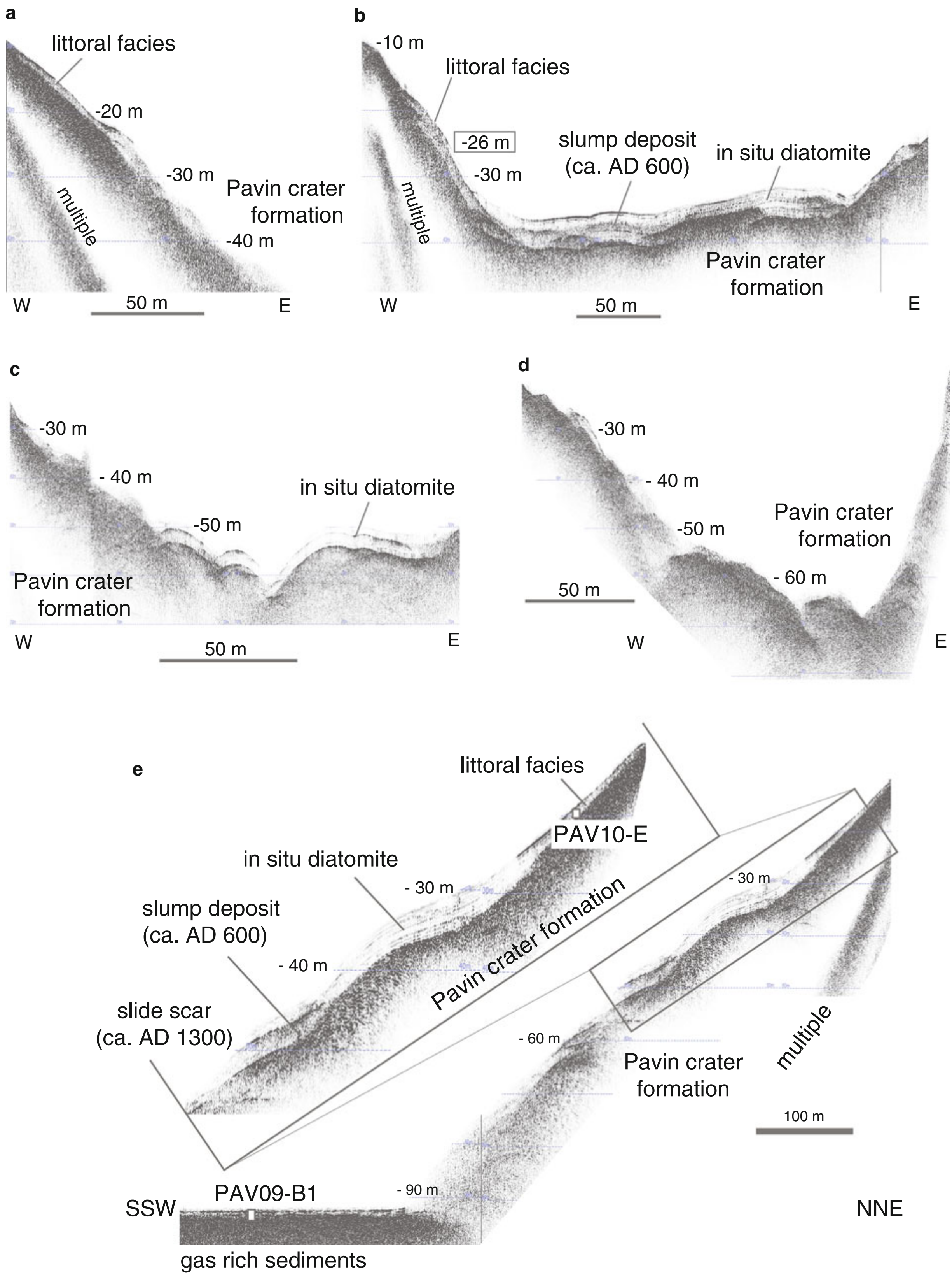


**Fig. 22.5** Lake Pavin sub-bottom profiles illustrating the acoustic facies developed in littoral environments or along the subaquatic plateau (**a**, **b**, **c**, **d**, **e**) and down to the deep central basin (**e**). Note that all these sedimentary environments develop contrasted acoustic facies above the subaquatic plateau formed by the Pavin crater formation. The location of short gravity cores PAV09B1 and PAV10E is also indicated. As detailed in this chapter and in Chap. 23, in situ deposits (diatomites) on the plateau are clearly distinguished from reworked sediments (ca.AD 600 slump deposit and ca. AD1300 slide scar). The location of each seismic section is given in Fig. 22.2

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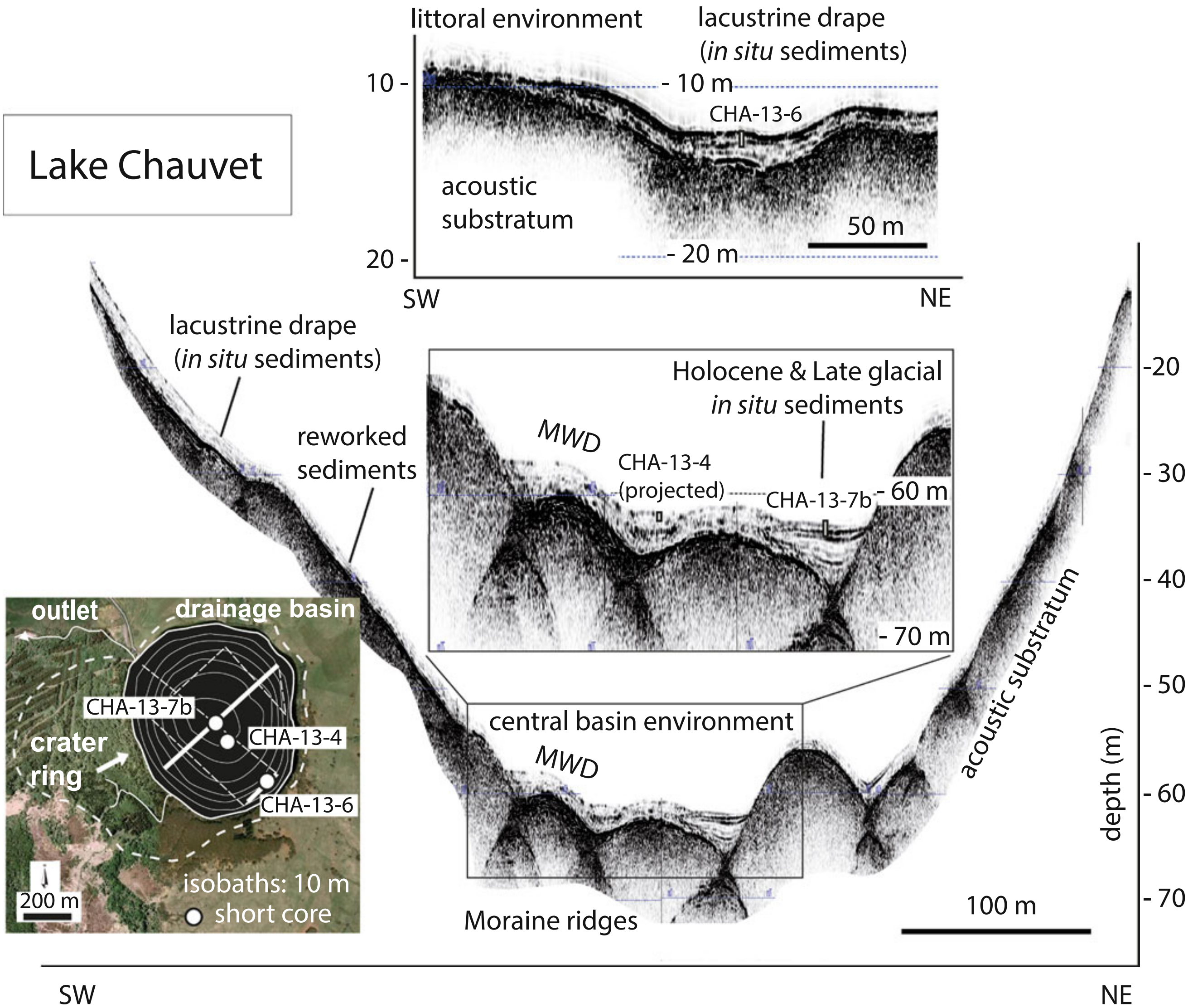


**Fig. 22.6** Lake Chauvet sub-bottom profiles (12 kHz) of a littoral environment and of the central basin. The southwestern slopes of this maar lake are unstable and a recent mass wasting deposit (MWD) can be identified within the deep central basin were moraine ridges are ponded by Late glacial and Holocene lacustrine sediments. The bathymetric map, the location of the crater ring, the outlet, the extension of Lake Chauvet drainage basin, available short coring sites (white circle), seismic reflection profiles (*white dashed lines*) and illustrated seismic profiles (*thick white lines*) are also indicated

more precisely the subaqueous geomorphology of this maar lake.

### 22.2.2 Short Sediment Cores

Based on Lake Pavin multibeam bathymetry and sub bottom profiling, several short gravity cores were retrieved by the ISTO laboratory (i) in 2008 at 46 m water depth on the plateau (PAV08-P1, 33 cm long, 45°29.86′N/2°53.24′E), (ii) in 2009 from a littoral environment at 20 m water depth (PAV09-C5, 51 cm long, 45°29.93′N/2°53.32′E) and in the deep anoxic basin at 92 m water depth (PAV09-B1, 120 cm long, 45°29.74′N/2°53.28′E) and (iii) in 2010 (PAV10-E, 80 cm long, 45°29.92′N/2°53.35′E) at 17 m water depth (Fig. 22.2).

As shown in Fig. 22.6, three short gravity cores were also retrieved in 2013 by the ISTO laboratory in Lake Chauvet within littoral environments (CHA 13–6, 90 cm long) and in the deep basin; one within in situ deposits (CHA 13-7B, 95 cm long) and one within reworked deposits (CHA 13–4, 55 cm long) according to the seismic profiles.

A multi-proxy study of the lacustrine sediments was then conducted once the cores from both lakes were split in two halves. Hand-held measurements of sediment **magnetic susceptibility** (MS) with a Bartington MS2E point sensor and of sediment **diffuse spectral reflectance** with a Minolta 2600D spectrophotometer were both performed following the procedure described in Debret et al. (2010), at a sampling interval of 1 cm. Organic matter content and quality from lacustrine sediments were in addition punctually documented by Rock-Eval (RE) pyrolysis following the proce-

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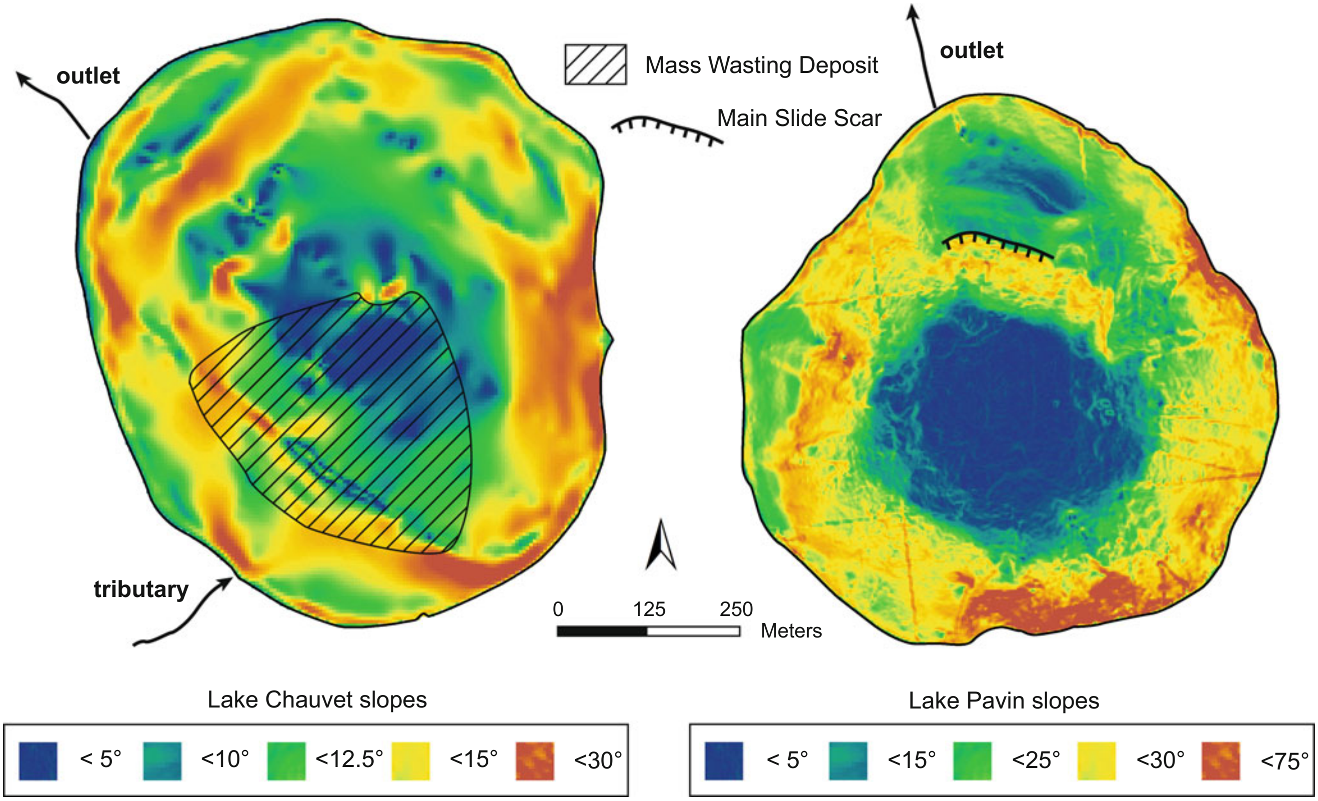


**Fig. 22.7** Slope maps of maar lakes Chauvet (*left*) and Pavin (*right*)

dure described in Behar et al. (2001) and Simonneau et al. (2014).

## 22.3 Signatures of Littoral Environments in Lakes Pavin and Chauvet

### 22.3.1 Lake Pavin

Between Lake Pavin shore line and 26 m water depth, when slopes angles are below 30° (Fig. 22.7) a specific **acoustic facies** is observed on **sub-bottom profiles** (Fig. 22.5a, b, and e). This littoral facies is characterized by a transparent acoustic facies developed above the acoustic substratum and capped by a high amplitude **reflection**. This littoral facies is getting thinner towards the shoreline and can reach a maximum thickness of ca. 4 m in the northern part of the lake (Fig. 22.5e), while it is limited to ca. 3 m and 1 m in the northwestern (Fig. 22.5b) and western (Fig. 22.5a) parts of the lake, respectively.

Sediment cores PAV09-C5 and PAV10-E were retrieved along the northern part of Lake Pavin at 20 m and 17 m water depth, respectively, (Fig. 22.2) and allow characterizing the composition of the littoral acoustic facies.

Lake Pavin littoral sediments are made of massive brownish sandy silts with frequent sandy layers and numerous leaves and leave debris (Fig. 22.8). Sediment **magnetic susceptibility** (MS) is variable and oscillating between 35 and 3 $10^{-6}$ SI. Two distinct **erosional events** producing sandy layers rich in leaves (E5 and E6) in PAV09-C5 were dated by **AMS radiocarbon** (Chapron et al. 2012) and are further discussed in Chap. 23. Only one of such outstanding sandy layer is identified in PAV10-E and characterized by high values of sediment MS. As shown in Fig. 22.8, this **erosive** sedimentary event (labeled E6?) matches an abrupt transition from laminated brownish sandy silts (with low MS values) towards a littoral sedimentary facies in the upper 20 cm of the core. Unfortunately, too little terrestrial organic matter (leave debris) did not allow **AMS radiocarbon** dating of this major change in sedimentation (Chapron et al. 2012). As further discussed in Chap. 23, the depth of this erosive layer in PAV10-E matches the depth of E6 in PAV09-C5 and might thus be contemporaneous.

### 22.3.2 Lake Chauvet

Between Lake Chauvet's shore line and ca. 30 m water depth, when slopes angles are below 30° (Fig. 22.7) a thin and transparent acoustic facies with a draping geometry is observed on **sub-bottom profiles** above the **acoustic substratum** (Fig. 22.6). This littoral facies is getting thinner towards the shore and can reach a maximum thickness of ca. 2.5 m in the southern part of the lake.

Up to five contrasted **sedimentary facies** are, however, identified within this littoral facies in sediment core CHA13-6 (Fig. 22.9). The upper Unit A consists of brown massive sediments with relatively high and fluctuating MS values and is interrupted by three distinct coarse sandy layers developing peaks in MS of a few cm wide with very high values (up to 350

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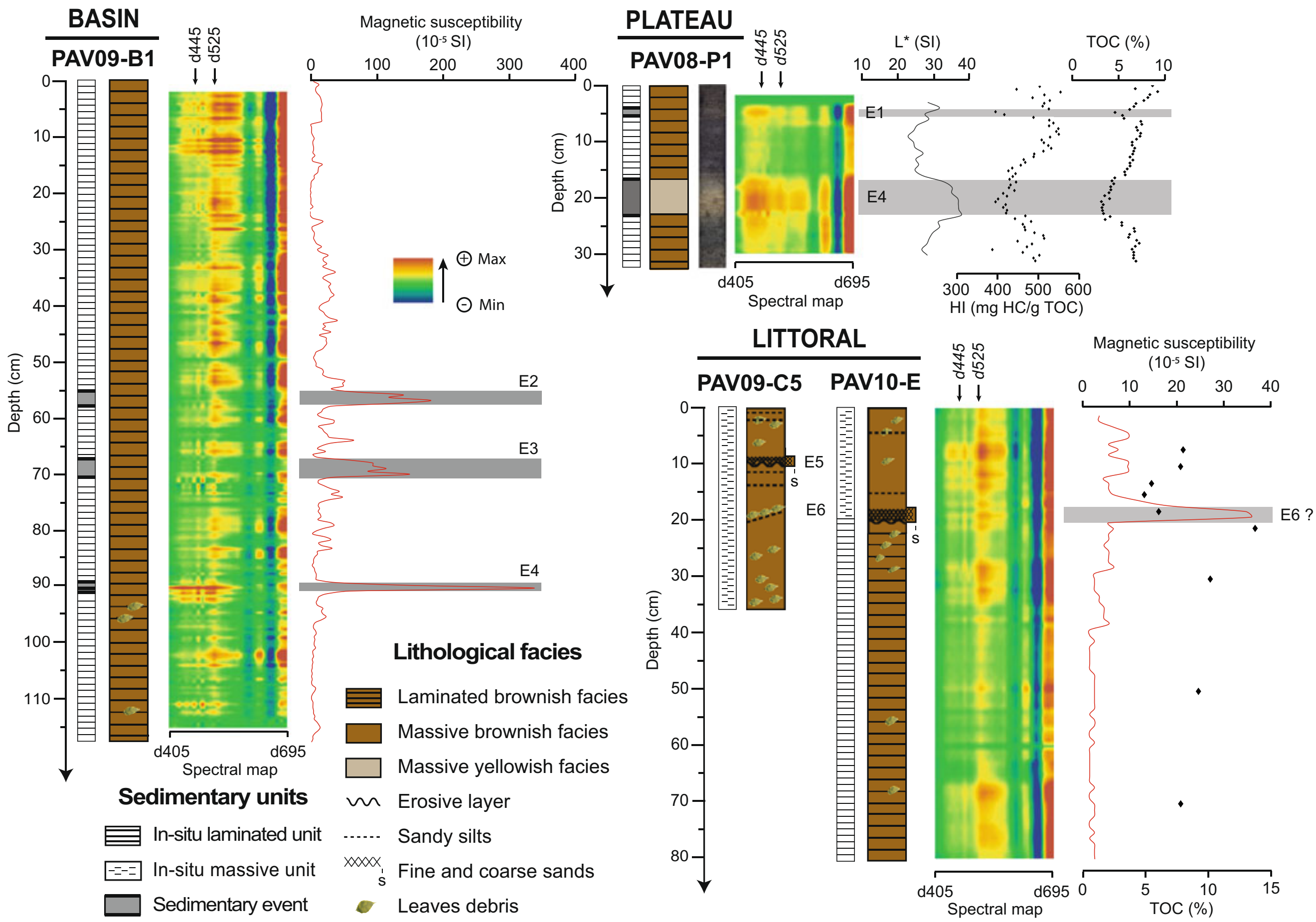


**Fig. 22.8** Multidisciplinary characterization of Lake Pavin sediments retrieved by short gravity cores, in the deep central basin (PAV09-B1), on the plateau (PAV8-P1) and in littoral environments (PAV09-C5 and PAV10-E). Visual descriptions of sedimentary facies are further defined (i) by sediment diffuse spectral reflectance (here plotted on a 3D diagram where the X axis represent the wavelengths, Y is the depth in core and Z the first derivative value for the corresponding wavelength (in nm) expressed by a code of color); (ii) by sediment magnetic susceptibility (for PAV09-B1 and PAV10-E); (iii) core PAV08-P1 is in addition detailed by sediment reflectance (L*), sediment digital picture and organic carbon geochemistry (*TOC* total organic carbon, *HI* hydrogen index). The locations of these cores in Lake Pavin are also given in Fig. 22.2

$10^{-5}$ SI) and labeled E2, E3 and E4. Below, Unit B is, on the contrary, a dark brownish massif unit with lower MS values and is locally interrupted by Unit C. Unit C is a brownish massive unit bearing much higher MS values than Unit B, and also the brownish Unit D identified at the base of core CHA13-6. Several leaves and leave debris founded in Units B and D are suitable for **AMS radiocarbon** dating and on-going analysis will provide some chronological controls on such contrasted sedimentation patterns in this Late Glacial **maar** lake.

## 22.4 Sedimentation Patterns Along the Slopes of Lakes Pavin and Chauvet

### 22.4.1 Lake Pavin Subaquatic Plateau

Between ca. 26 and 55 m water depths in the northern part of Lake Pavin, gentle slopes (below 15°, Fig. 22.7) are draped by an up to 5 m thick sedimentary sequence made of two contrasting **acoustic facies** (Chapron et al. 2010, 2012) as shown in Fig. 22.5b, e: a stratified unit bearing few low amplitude and continuous **reflections** is mainly identified downslope from the littoral facies and on top of a chaotic to transparent lens-shaped body. This chaotic deposit occurring above the Pavin crater formation has the typical signature of a **mass wasting deposit** (MWD). It has been sampled in PAV08 long piston core, interpreted as a **slump deposit** and dated to ca. **AD** 600 as detailed by Chapron et al. (2010) and further discussed in Chap. 23.

The stratified unit has also been sampled in short cores PAV08-P1 and in the lower part of PAV10-E (Fig. 22.2). These sediments are characterized by well-defined sandy silts developing brownish and greenish laminas rich in diatom bloom that are bearing low values of MS. At site PAV08, short core P1 highlight in addition high values of Total Organic Carbon (TOC) oscillating around 8 % and relatively high values of Hydrogen Index HI) between 450 and 550 mg HC/g TOC (Fig. 22.8). Following Schettler et al. (2007), Chapron et al. (2010) and Albéric et al. (2013), these sediments rich in

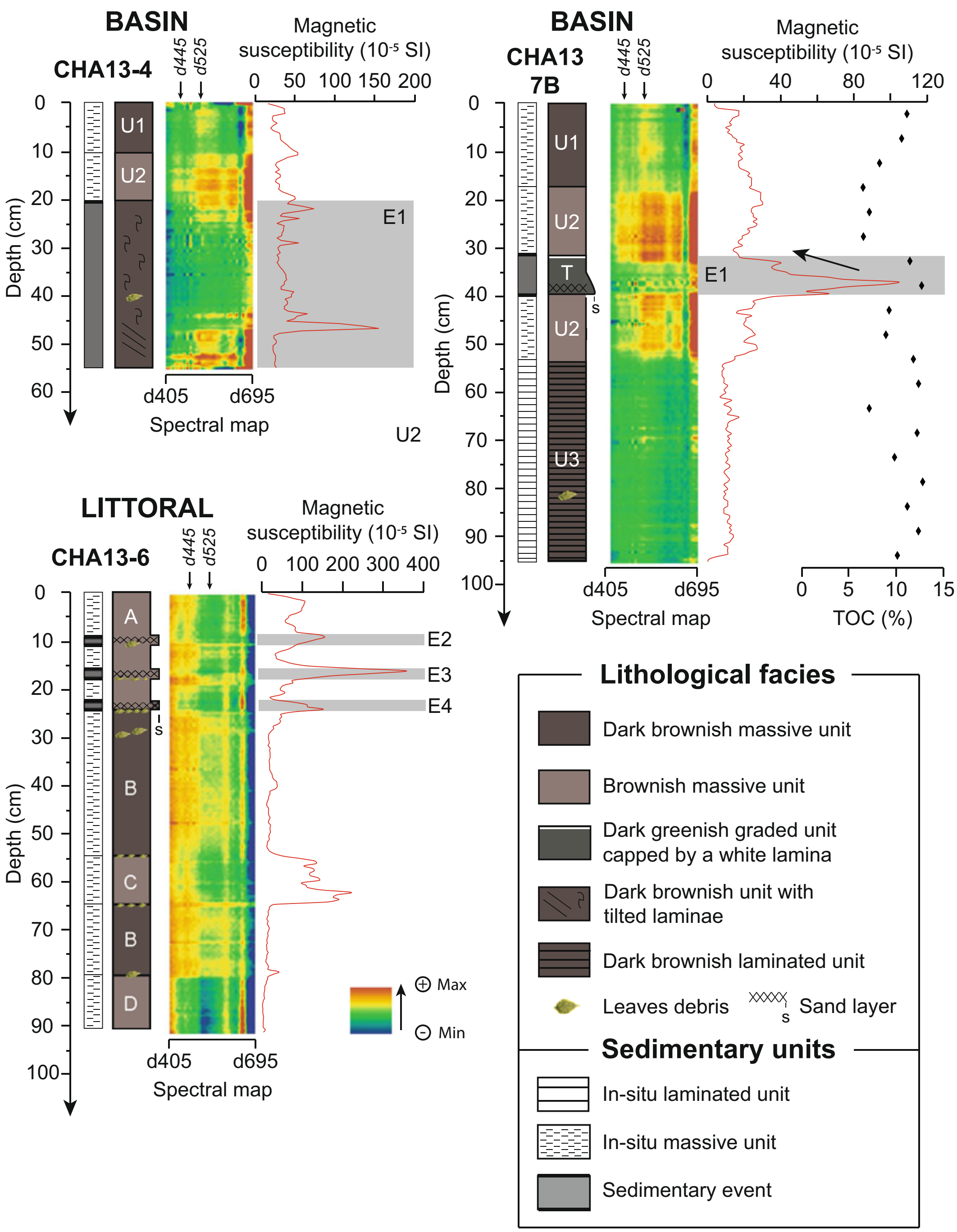


**Fig. 22.9** Multidisciplinary characterization of Lake Chauvet sediments retrieved by short gravity cores in the deep central basin (CHA13-4 and CHA13-7B) and in a littoral environment (CHA13-6). Visual descriptions of sedimentary facies are further defined (i) by sediment diffuse spectral reflectance (here plotted on a 3D diagram where the X axis represent the wavelengths, Y is the depth in core and Z the first derivative value for the corresponding wavelength (in nm) expressed by a code of color); (ii) by sediment magnetic susceptibility and (iii) core CHA13-7B is in addition detailed by measurements of Total Organic Carbon (TOC). The locations of these cores in Lake Chauvet are also given in Fig. 22.6

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organic matter essentially of algal origin developing a stratified sedimentary unit along the gentle slopes of Lake Pavin can be interpreted as in situ annually laminated **diatomite**.

Two **sedimentary events** (E1 and E4) are identified within the laminated **diatomite** at coring site PAV08 by light colored layers (i.e. higher values in **L* parameter**), and lower values of TOC and HI (Fig. 22.8). These characteristics suggest that E1 and E4 are resulting from the remobilization of a mixture of lacustrine and terrestrial material. They might thus correspond to gravity reworking phenomena initiated near the lake shore. Their chronologies and possible sediment source areas are further discussed in Chap. 23.

A fresh **slide scar** ca. 350 m long and 4 m high is identified at the southern edge of the subaquatic plateau (Figs. 22.4 and 22.5e) around 55 m water depth. Below this large **slide scar**, steep slopes (>30°, Fig. 22.7) are free of any sediment. This suggests that these steep slopes of Lake Pavin were unstable and recently submitted to gravity reworking phenomena that reach the deep central basin. This recent event has been dated around **AD** 1300 (Chapron et al. 2010) and is further discussed in Chap. 23.

Several smaller steep slopes breaks (>30°) identified at the lake floor on Figs. 22.4 and 22.7 at the southeastern edge of the subaquatic plateau (where the lake floor is generally characterized by slopes ranging between 15° and 25°) also suggest the development of recurrent regressive **slide scars** and small scale gravity reworking phenomena. This interpretation is further supported by sub-bottom acoustic profiles in this area (Fig. 22.5c) illustrating that in situ **diatomite** is locally incised by several canyons. This suggests that these active canyons may have recently bypassed some sediment from the plateau to the deep central basin.

Finally, a bathymetric anomaly identified between ca. 12 and 26 m water depth just south form the lake outlet (Fig. 22.10) is suggesting the development of a deep but elongated depression at the lake floor. Such a geomorphological feature could highlight the occurrence of a subaquatic outlet in this part of the plateau (Chapron et al. 2010). This outlet could further explain the occurrence of a spring of water downstream from Lake Pavin into the canyon developed by its outlet at ca. 1180 m altitude a.s.l. (Jézéquel et al. 2011).

### 22.4.2 Lake Pavin Slopes

When slope angles in Lake Pavin are above 30° (Fig. 22.7) they are free of any sediment and characterized by the development of numerous steep **canyons** clearly visible on multibeam bathymetric data (Figs. 22.4, 22.7 and 22.10). **Sub-bottom profiles** along these steep slopes are thus only illustrating the morphology of the **acoustic substratum** (Fig. 22.5a, d and e). This acoustic facies has been sampled at the base on a long **piston core** (PAV08) and attributed to the Pavin crater formation (Chapron et al. 2010). It is therefore very probable that all these canyons draining the steep slopes of Lake Pavin crater are still active canyons and are sporadically bypassing sediment to the deep central basin. In such a context it is highly possible that sediment from subaquatic littoral environments, lake shores and sub aerial slopes from the crater ring draining into the lake (Fig. 22.10), can be exported directly to the deep central basin.

Locally very steep slopes at the eastern and southern edges of Lake Pavin are produced by **outcropping lavas** (Chapron et al. 2010). Some of these volcanic rocks are also locally **outcropping** within the inner slopes of the **crater ring** where they develop unstable cliffs (Fig. 22.10). Boulders along the shore lines and steep slopes of Lake Pavin near these **outcropping** volcanic rocks highlight the occurrence of relatively small scale but recurrent **rock falls**.

### 22.4.3 Lake Chauvet Slopes

Lake Chauvet is comparatively to Lake Pavin characterized by a shallower central basin, less steep slopes (Fig. 22.7) and no subaquatic plateaus, but several **moraines ridges** are however locally developing small topographic steps along the northern slopes of the basin (Juvigné 1992; Chapron et al. 2012). This **maar** lake is also quite different from Lake Pavin because it has a small but permanent tributary and a very poorly preserved **carter ring** where gentle slopes are locally incised by gullies draining into the lake.

Consequently, the slopes of Lake Chauvet are generally covered by a thin layer of sediments with a transparent acoustic facies. This facies is thus similar to the littoral facies, but generally only 1–2 m thick, except near the lake outlet, where a well-developed **moraine** ridge favored the accumulation of up to 2.8 m of sediments (Juvigné 1992; Chapron et al. 2012).

Offshore its tributary, a recent and relatively large **mass wasting deposit (MWD)** is in addition clearly identified along the southwestern slopes of the basin and down to the deep central basin (Fig. 22.7). Along the slopes this **MWD** is producing a slightly hummocky and transparent seismic facies (Fig. 22.6). It is thus very likely that this subaqueous slope failure reworked most of the delta deposits that were accumulated offshore the tributary (Fig. 22.11).

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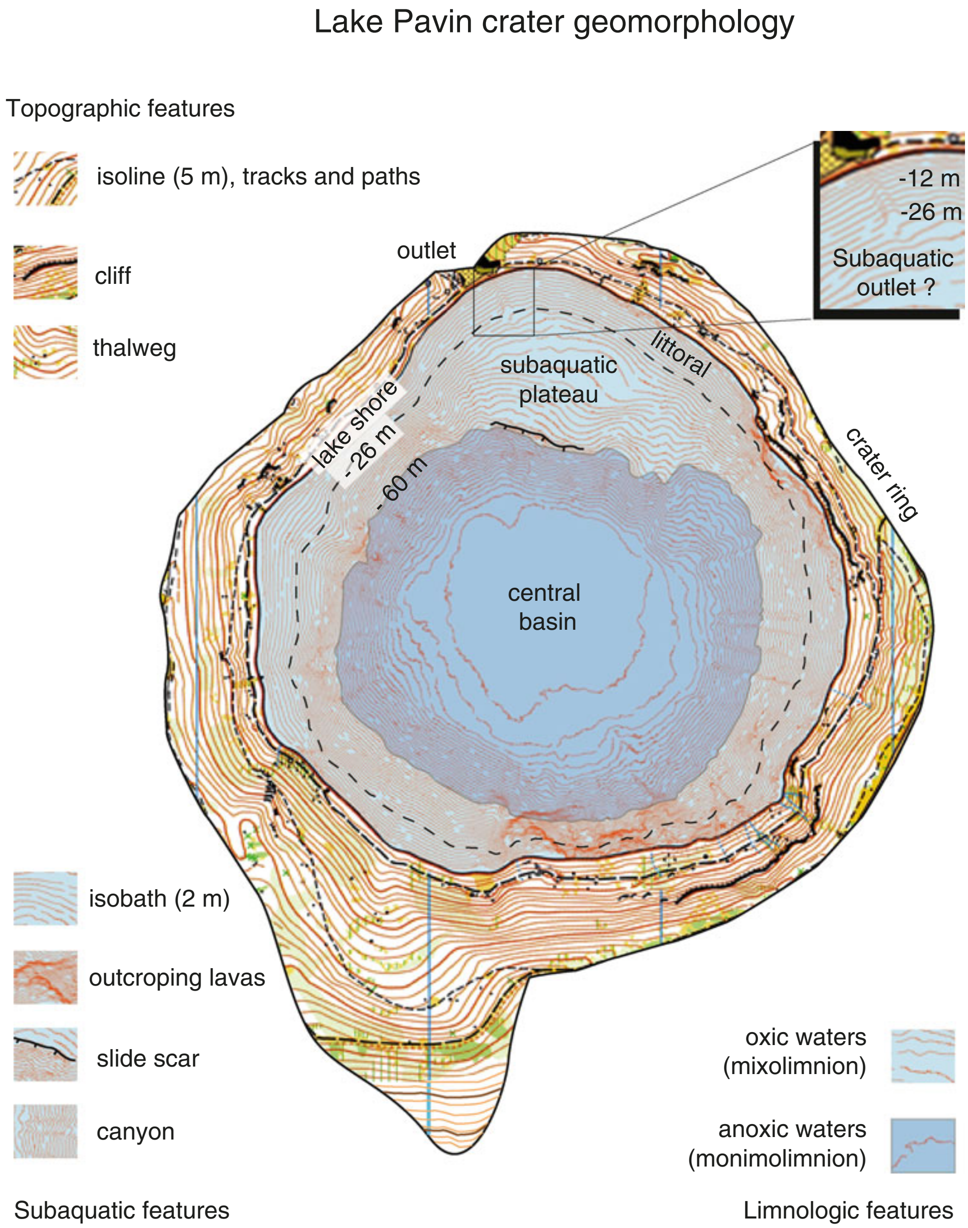


**Fig. 22.10** Lake Pavin crater geomorphology from the crater ring to the deep central basin illustrating key topographic, subaquatic and limnologic features of this young and deep meromictic crater lake

## 22.5 Sedimentary Environments in the Deep Central Basins of Lakes Chauvet and Pavin

### 22.5.1 Lake Chauvet Basin

The deep central basin of Lake Chauvet is clearly imaged by 12 kHz sub-bottom acoustic profiles (Fig. 22.6). It is filled by up to 4.6 m thick well-stratified deposits were few continuous **reflections** are terminate by **onlap** against the edges of the basin and the **moraine ridges**. Locally, **moraine** ridges can also be partly draped by a thin layer of sediment developing a transparent acoustic facies.

Down slopes from the lake tributary, the **MWD** reworking slope sediments forms a lens-shaped body at the edge of the basin where it is characterized by a transparent to chaotic facies. This body is laterally thinning toward the central basin into a distinct high amplitude **reflection** that has been sampled in short core CHA13-7B (Fig. 22.6). Such a succession of acoustic facies is typical of a mass wasting phenomena evolving downslope from a mass movement into a

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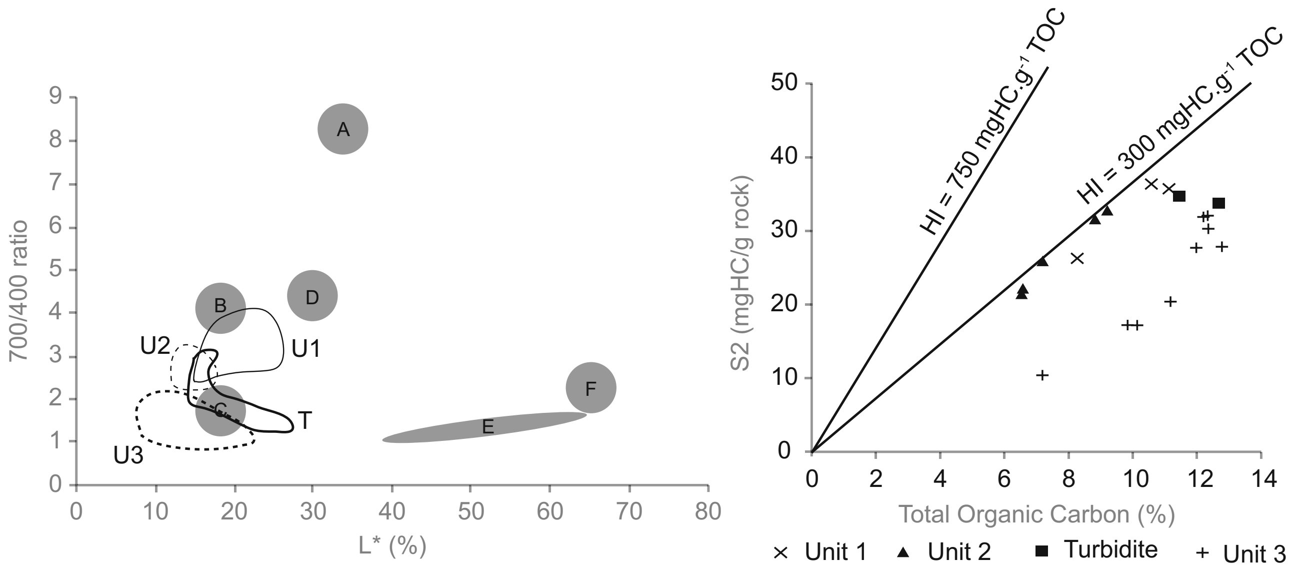


**Fig. 22.11** Characterization of Chauvet sediments origin and sediment sources of sedimentary event E1 based on CHA13-7B sediment spectral diffuse reflectance Q7/4 diagram (*left*) and Rock-Eval pyrolysis results represented by S2 vs. TOC diagram (*right*) where Total Organic Carbon (TOC), together with Hydrogen Index (HI) and S2 (thermal cracking of the hydrocarbon compounds) are illustrated. The two linear domains of the hydrogen index (HI = 750 and HI = 300 mgHCg$^{-1}$TOC) corresponding to algal and terrestrial poles, respectively, are also presented. In the Q7/4 diagram, the diffuse spectral reflectance signature of Lake Chauvet sedimentary units 1, 2 and 3 (U1, U2, U3) together with the turbidite deposit associated with E1 (T) are compared to the five distinct poles of sediments defined by Debret et al .(2011): Iron-Rich deposits (**a**); Organic-rich deposits dominated by Melanoidine type (**b**); Organic-rich deposits dominated by altered organic matter (**c**); Organic-rich deposits dominated by Chlorophyll and by-products (**d**); Clayey deposits (**e**) and Carbonate deposits (**f**)

turbidity current (Mulder and Cochonat 1996; Chapron et al. 2006; St-Onge et al. 2012).

Sedimentary facies retrieved in cores CHA13-4 and CHA13-7B are in addition clearly illustrating the occurrence of a **sedimentary event** (E1) covered by a succession of two distinct **sedimentary units** (Unit 1 and 2, Fig. 22.9): While Unit 1 is a dark brownish massive unit with decreasing MS values but increasing TOC toward the top, Unit 2 is a brownish massive unit with fluctuating MS values and lower values of TOC. In core CHA13-4, E1 is on the contrary characterized by a dark brownish massive facies with locally some tilted laminas associated with strongly contrasting MS values. Following the classification of **mass wasting deposits** of Mulder and Cochonat (1996), this deposit is interpreted as a **slump** deposit. E1 is downslope evolving into a typical **turbidite** deposit in core CH13-7b where MS values and visual descriptions are clearly showing a fining upward structure above a sharp sandy base. Higher TOC content in E1 (Fig. 22.9) at this site are similar to the organic rich Unit 3 retrieved in the lower part of core CHA13-7B. But this dark brown laminated Unit 3 is in addition characterized by lower values of MS than the **turbidite** deposit.

Based on the seismic facies and on the **sedimentary facies** of cores CHA13-4 and CHA13-7B, it is thus possible to explain the formation of a lense-shaped body and the high-amplitude reflection by the deposition of a single **sedimentary event** (E1) that formed a **slump** deposit at the edge of the basin and a **turbidite** in the deep central basin. In addition it seems very likely that E1 remolded older sediments (such as Unit 3 and part of Unit 2) previously accumulated along the slopes and the basin edges of Lake Chauvet. This interpretation is further supported by the spectral signature and the organic geochemistry of Lake Chauvet sediments from core CHA13-7B (Fig. 22.10).

When plotting the spectral diffuse reflectance measurements of Lake Chauvet sediments in a Q 7/4 diagram as defined by Debret et al. (2011), it clearly appears that these maar sediments are organic-rich deposits essentially dominated by altered organic matter (Fig. 22.10). This is here further supported by Rock-Eval data indicating that Chauvet sediments are essentially within the terrestrial pole (especially Unit 3) based on the previous studies of Ariztegui et al. (2001) and Simonneau et al. (2013).

According to these two diagrams given in Fig. 22.10 it is thus possible to precise that Lake Chauvet sediments deposited in the central basin are mainly originating from the remobilization of altered terrestrial organic matter from its **catchment area** (i.e. organic rich soils material). This is particularly the case for Unit 3, but it seems that unit 1 and 2 are also containing some organic matter of algal origin. This is thus suggesting that the trophic state of Lake Chauvet may have recently changed and favored algal production. Based on these two diagrams and on the available seismic reflection

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profiles illustrated in Fig. 22.6, it is also possible to identify that the **turbidite** associated with E1 essentially remolded a mixture of lacustrine sediments rich in organic matter of terrestrial and algal origins typical from deltaic lacustrine environments.

### 22.5.2 Lake Pavin Basin

The deep central basin of Lake Pavin is poorly documented by seismic refection data because the acoustic signal is very quickly absorbed by gas-rich sediments (Chapron et al. 2010, Fig. 22.5e). Bathymetric data (Figs. 22.4 and 22.7) indicate that only the central part of the basin is very flat (2–5°), while its edges are locally affected by numerous small-scales steep slope breaks (<25°). This specific morphology suggests that the edges of Lake Pavin central basin are significantly shaped by sediment (or water) supply originating from the canyons developed along the steep slopes of the crater. Some of these canyons are in the continuity of gullies incised within the inner slopes of the **crater ring** (Fig. 22.10) and some of them are in addition linked with springs in the topographic **drainage basin** (Fig. 22.2).

**Gravity cores** from the deep central basin of Lake Pavin are characterized by organic rich in situ **diatomite** (Fig. 22.8) showing low values of MS but also several abrupt peaks with very high values of MS in core PAV09-B1. As further discussed in Chap. 23, the main peak in MS at 90 cm below the lake floor in the basin has been dated and correlated with **sedimentary event** E4 identified on the plateau at PAV08 coring site. This **sedimentary event** E4 was thus probably large enough to cross the plateau and reach the deep central basin. The two others outstanding peaks in MS identified on core PAV09-B1 can also be dated (see Chap. 23) but were not identified on the plateau at site PAV08. This suggest that these two MS peaks (labeled E2 and E3) might be more local **sedimentary events** supplied by some of the canyons draining Lake Pavin steep slopes and/or the edge of the plateau.

## 22.6 Implications for Natural Hazards in Lake Pavin

**Maar** lakes from the study area are filled with organic-rich lacustrine sediments and are exposed to subaqueous slope failures. It is today well-established that subaqueous slope instabilities in lakes (or in ocean realms) are either due (i) to changes (natural or human-induced) in sedimentation rates favoring sediment overloading; (ii) to changes in lake (sea) level controlling the weight of the water column (and thus loading of underlying sediments); (iii) to earthquake shaking producing an abrupt acceleration of gravity and cyclic loading when the site is impacted by seismic waves; (iv) to cyclic loading by waves; and/or (v) to gas hydrate destabilization within older sediments buried along margins of sedimentary basins (Mulder and Cochonat 1996; Van Rensbergen et al. 2002; Chapron et al. 2006; Girardclos et al. 2007; St-Onge et al. 2012; Phrampus and Hornbach 2012). All these factors may in addition combine with complex interactions in sedimentary basins to increase stresses or lower sediment strength and lead to sediment instability.

The **slump** and associate **turbidite** identified ca. 30 cm below the lake floor in Lake Chauvet are resulting from a recent subaquatic slope failure that affected its deltaic environment along relatively steep slopes (Fig. 22.7). Changes in sedimentation rates in lacustrine deltaic environments can either be due to climate changes or human impact (land use in the drainage basin for example) and could favor slope failure in Lake Chauvet. According to Juvignié (1992), Lake Chauvet has been affected by a significant and abrupt lake level drop, but during the last deglaciation, when glaciers from the Puy de Sancy were retreating outside the Chauvet **crater rim**, out of the lake's drainage area. The outlet of Lake Chauvet is today rather stable since its altitude is controlled by a **moraine** ridge (Juvignié 1992). Lake level change as a trigger for Lake Chauvet **MWD** is thus unlikely. Cyclic loading related with waves seems as well unlikely to explain this **MWD**, since Lake Chauvet is very small and not especially exposed to strong winds. Cyclic loading associated with earthquake shacking seems rather unlikely, but possible, since this volcanic area has a moderate regional seismicity (Boivin et al. 2004).

Ongoing **AMS radiocarbon** dating on core CHA13-7B should allow dating the formation of this **turbidite** in Lake Chauvet and this will be crucial to pinpoint earthquake triggering if this sedimentary event can be related to an historical earthquake and/or to a (prehistoric) period of contemporaneous **MWD** in lakes at a regional scale (Chapron et al. 2006; St-Onge et al. 2012).

Several generations of **MWDs** can be identified within Lake Pavin basin (Chapron et al. 2010, this study). Some small scale **sedimentary events** are identified either in littoral environments, on the plateau or in the basin. **Sedimentary events** affecting several sedimentary environments may however reflect an abrupt environmental change. The establishment of an **event stratigraphy** in a lake basin over longer time scales than historical chronicles or instrumental data can thus provide key elements to evaluate Natural Hazards in a given area.

Over the last millennium, a larger **slump deposit** dated on the plateau of Lake Pavin (at site PAV08) to ca. **AD** 600 (Chapron et al. 2010) can be related to **sedimentary event** E6 dated at site PAV09-C5 (Chapron et al. 2012). The occurrence of such an erosive sandy layer in shallow waters contemporaneous to the **slump deposit** on the plateau suggest

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that this **slump** may have been triggered by an abrupt lake level change or may have induced a destructive wave along the lake shore (Chapron et al. 2012). Similarly, as further discussed in Chap. 23, the correlation of **sedimentary event** E5 at site PAV09-C5, with the formation of the large **slide scar** at the edge of the plateau, suggest that this significant slope failure may also have been triggered by a change in lake level or may have formed and propagated a destructive wave in the lake.

As shown in Fig. 22.10, the large **slide scar** in Lake Pavin occurs at 55 m water depth just next to the upper limit of the **monimolimnion**. It is thus likely that such a slope failure remolding gas rich sediments from the steep slopes and the deep central basin, can significantly impact gas content within these permanently anoxic waters and may favor the generation of a **limnic eruption** (Chapron et al. 2010; Chap. 3 and 23, this volume).

## 22.7 Conclusions and Perspectives

Lakes Pavin and Chauvet are two nearby relatively similar maar lakes, since they are both filled with relatively little amount of organic rich sediments highlighting different **acoustic facies** and **sedimentary facies** within littoral environments and in their deep basins. Both lakes were also relatively recently exposed to subaqueous slope failures.

The different ages of these two nearby **maar lakes** offer the possibility to track in their sedimentary archives regional environmental changes and to better define the exposure of this volcanic area of Western Europe to natural hazards related with subaquatic slides.

Lake Pavin is in addition characterized by the absence of any tributary and the presence of a wide subaquatic plateau located above its **monimolimion**. Such a specific geomorphologic and limnologic charachteristics allows the accumulation of **diatomites** either within the **mixolimnion** and the **monimolimnion**. A challenging perspective in this young volcanic lake is thus to reconstruct is the timing of meromictic conditions in the deep basin and to document how much former subaqueous slope failures from the edges of its plateau may have impacted its limnologic condition. This might as well help to better understand the exposure of volcanic areas to **limnic eruptions**, i.e. one of the less well known natural hazards but potentially very dangerous in a touristic area such the Pavin and the Puy de Sancy area of the French Massif Central.

Future investigations in these deep and steep maar lakes should also concern numerical modeling of subaquatic slope failures in order to better understand the development of **turbidites** and the generation of waves. The identification of a subaquatic outlet in Lake Pavin should also be confirmed by in situ measurements in order to better identify its impact on Pavin limnology and geochemistry.

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