

Pavin, the Birthplace of French Limnology (1770–2012), and Its Degassing Controversy (1986–2016)

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Michel Meybeck

Abstract

Lake Pavin is located in the Auvergne Mountains, central France, at 1300 m a.s.l. This small lake (0.44 km²), partially fills an explosive volcanic crater in the Cezallier, a young volcanic area south of the Mont Dore. Its deepest part, from 65 to 92 m, is permanently anoxic, a very rare limnic phenomenon termed *meromixis*. Pavin is the cradle of French limnology, having been first surveyed in 1770, and then regularly studied since 1880 by local botanists and zoologists from Clermont-Ferrand, along other pristine lakes of the Cezallier. Pavin scientists, such as Delebecque the founder of French limnology and his friend Martel the founder of speleology, visiting the area in 1892, always used up-to-date sampling techniques and methodologies, often borrowed from other disciplines. Meromixis at Pavin was described for the first time in the 1950s and after 1970, its deep waters attracted new teams of isotope geochemists, water chemists, microbiologists and sedimentologists, often from foreign origin. After the unexpected and deadly limnic explosion of Nyos Lake (Cameroun) in 1986, the possibility of Pavin degassing was investigated and concluded to a lack of risk under present conditions. Pavin exceptional history and corpus of legends, referring to its repeated misbehavior and latent fear, perceived locally and in the greater area (Chaps. 2 and 3), remained unknown to contemporary scientists until now. To allow for the re-interpretation of these complex sources, a sensory grid of maar-lakes degassing is proposed here, based on scientists' observations or reports at other maar-lakes very similar to Pavin, Nyos (1986) and Monoun (1984) in Cameroun, Albano (398 BC) and Monticchio (1770s–1820s) in Italy.

Keywords

Pavin Lake • Limnology history • Lake degassing • Maar-lake • Nyos lake • Degassing grid

“This lake, located on the top of the Mont Dore Mountain is, by its shape and its details, one of the most beautiful and most singular lakes of our country and adds to the many beautiful monuments that nature has provided Auvergne with.” (Depping 1811)

“Crater lakes can be used as useful test tubes to elucidate transfer processes in aquatic systems... It is a giant rain-gauge to register atmospheric fallout.” (Martin 1985)

“Why a dramatic event [as the one that occurred at Nyos] could not have happened in the volcanic ranges of Massif Central?” (Tazieff, 2 September 1986, La Montagne, daily newspaper)

1.1 Introduction

Pavin Lake in Auvergne province is different from all other French lakes. It combines a rare origin, a *maar-lake*, i.e. a lake filling a crater lake resulting from a volcanic explosion, with an exceptional mixing type, the *meromictic character*, i.e. its bottom waters do not mix with the surface waters. In addition Pavin Lake presents a lack of direct human impacts

M. Meybeck (✉)
METIS, CNRS-Université Paris 6, UMR 7619,
Place Jussieu, 75252 Paris Cedex 05, France
e-mail: michel.meybeck@upmc.fr

and a long Human history including a rich corpus of legends characterized by latent lake fear. It is also considered as the most beautiful lake of the Massif Central (see above, Depping 1811). For geochemists it is a hydrosystem with limited forcing from its watershed that could be considered as a test tube (see above, Martin 1985). These points make it an exceptional lake in many fields of Earth Sciences and of Humanities.

“Pavin”, as its visitors have called it for centuries, has also been identified soon after the catastrophic lake degassing at Nyos (Cameroon), in August 1986, as a lake with a potential degassing risk, a matter still debated today (see above Tazieff, the French volcanology leader). Pavin has also attracted over the last 140 years scientists from many countries: in the last 30 years they have found very specific chemical and microbiological features that will be addressed in more than twenty chapters of this book, so that Pavin is now one of the most investigated lake in Europe.

The first three chapters of this book present Pavin from the point of views of three different actors: (i) the scientific community at Pavin, from the beginning of scientific exploration to the recent degassing controversy (Chap. 1), (ii) Pavin neighbors and visitors on which Pavin history is based (Chap. 2), (iii) the local population and their perception of Pavin through its multiple legends, stories and associated beliefs (Chap. 3). These points of view cover both scientific and non-scientific knowledge concerning this natural entity. In each chapter the introductive sections and the conclusions are presented to the lay reader in each of these fields, including synthetic tables or figures. The core of the chapters provides the detailed argumentation on which this analysis is based. A preliminary analysis about Pavin resulted in some new hypotheses and led to the conclusions that Pavin had probably degassed at the sixteenth century (Meybeck 2010), which could be related to the fear that Pavin inspired over centuries, to its exceptional name – the terrifying- and to its relation with intense local religious practices.

This first chapter briefly sets up the Pavin scene, in comparison to other lakes in Auvergne and to other maar-lakes in Europe, and then presents the works of scientists at Pavin, from 1770 to 1986. Finally, the controversy on degassing risk opened by Tazieff at Pavin, after the Lake Nyos catastrophic event in 1986, is presented. This concern was one of the focuses of the international workshop convened in 2009 at Besse (Jezequel et al. 2010a, b). At each period the study of Pavin by scientists is placed in its historical context: Pavin has often been at the forefront of French limnology, then of international limnology. The new findings at Pavin after 1986, in geology and volcanology, limnology, biology and microbiology, are only shortly mentioned here as they are fully developed in the many chapters of this volume.

1.2 Analysis of Pavin Actors, History and Perception Through an Interdisciplinary and Intercomparative Approach

History and legends are so entangled at Pavin that a specific interdisciplinary approach has been needed to collect, analyze and synthesize hundred sources on which this work is based. This analysis has also required, in these chapters, an inter-comparison with few other maar-lakes located in Cameroon (Nyos and Monoun), in Italy (Averno, Albano, Nemi and Monticchio) and in Germany (Eifel lakes). There is no temporal limit to our analysis: we are aiming to analyze the societal connexion to such dangerous places as Pavin and its companions over the *Longue Durée*. This extends over 2500 years for some lakes. These comparisons have permitted to decipher some of the Pavin attributes, well known since centuries, sometimes still ignored by Earth Scientists and Social Scientists.

There is no current standard approach to investigate the history of lake degassing, although we have been preceded by Italian volcanologists, geologists and geochemists working on Lake Albano (Funicello et al. 2002, 2003, 2010) and Monticchio Lakes (Caracausi et al. 2009). We have also used many works on legends and degassing impacts to populations made at Lake Nyos by Evgenia Shanklin (1989, 2007). In order to make a significant progress we worked through a non-linear and iterative approach: (i) assembling a maximum of written sources, of religious, archeological, folkloric and iconographic elements, and re-attributing a first set of these sources to Pavin, (ii) gaining from the knowledge of other maar-lakes, particularly for the degassing description, (iii) re-interpreting a second set of Pavin sources with the degassing sensory descriptors (see Table 1.2, this chapter), (iii) re-interpreting legends, fantastic stories, local religious history and iconography (Chap. 3).

The main steps of this research are the following.

Step 1. Preliminary analysis (Meybeck 2010)

Our preliminary analysis led to the following conclusions and working hypotheses:

- (i) Pavin had degassed during the sixteenth century,
- (ii) The generated fear, well documented during at least the late XVIth and the seventeenth centuries, was important,
- (iii) Pavin legends are complex. The commonly accepted legend in the twentieth century, the *Sunken City* legend, has been forged at the end of the nineteenth century,

- (iv) Catastrophic events that occurred in Pavin area in the 1300s could be related to Pavin Lake but are not documented by historical sources,
- (v) Pavin Lake “*misbehavior*” – a term referring to the maar-lake abnormalities perceived by locals, coined at Nyos by Shanklin (1989) – and the nearby Vassivière Christian pilgrimage could be linked.

Step 2. In-depth material collection

Works on Pavin and its area were collected first, then those on nearby Vassivière mountain and its pilgrimage and nearby Creux de Soucy cavity, the towns of Besse and Mont Dore (see Fig. 1.2c). The research has also been extended to major texts on Auvergne history and description (sixteenth to nineteenth centuries), to all Auvergne maps until the mid-1800s, to Auvergne tales and legends collected in the XIXth. The quest has also been extended to other recent scientific findings, myths and tales on feared lakes in France and in Switzerland, and on maar-lakes in Italy and Germany (developed in Chap. 3), in connexion with their limnological characteristics (Chap. 1). Major *Cosmographiae*, i.e. early global geography descriptions and geography works (sixteenth to nineteenth centuries) have also been considered. The regional outlook has been completed by the guidebooks on Besse and Mont Dore areas, on Auvergne (nineteenth to twenty-first centuries). Relevant articles on Pavin in the local newspapers and magazines (*La Montagne*, *La Galipote*, *Eruptions*), focused on 1986–1987 and 2009–2012 were also considered. The resulting corpus includes more than 300 references.

Step 3. Sensory description of lake degassing (Nyos Lake and Italian lakes)

Nyos publications and oral presentations of the French team members gathered at the international workshop held in 2009 at Besse were analyzed to find witness description of the post-event lake, soon after the peak degassing and of the damages to Humans and livestock's. In addition we used the historical descriptions of past degassing in Italian maar-lakes in the early 1800s found by volcanologists of the INVG (Istituto Nazionale di Geofisica e Vulcanologia, Palermo) for the Piccolo and Grande Monticchio Lakes (Basilicate) and by Rome Earth Scientists (Geological Sciences, University Roma Tre) for the degassing event that occurred in 398 BC in Lake Albano (Latium) (Chiodini et al. 1997; Caracausi et al. 2009; Funiciello et al. 2003, 2010; De Benedetti et al. 2008). The combination of these scientific assessments

results in a set of sensory degassing descriptors (Chap. 1, Table 1.2).

Step 4. Re-analysis of Pavin textual material

The re-analysis of the Pavin textual material is done here with several assumptions: (i) Pavin is a gaz-containing maar-lake; as such its degassing is not impossible, as reported in other similar lakes, (ii) past degassing can be triggered by occasional event- slumps, rock fall, earthquake- or related to local variability of CO₂ emissions; it might have occurred any time, (iii) if it occurred with enough intensity to be noticed by local people, this non-scientific knowledge could have been reported, orally transmitted or expressed through local beliefs and customs, including religious, (iv) reporting, representation and explanation of these events are specific of their time and should therefore be interpreted in their historical context (Chap. 2), (v) this re-analysis can be done through a grid of sensory descriptors, established on other degassing lakes, Nyos, Monticchio, Albano Lakes mainly. The Pavin material has then been split into two categories: the perfectly contextualized sources, well dated, written by identified, educated people, which are discussed at Chap. 2 and all other sources as myths, legends, fantastic stories, miracles, religious iconography, which are discussed at Chap. 3. [*Original citations, in English, German and Italian, have been translated in French by the author*].

Step 5. Legends, beliefs and fears in Pavin and other maar-lakes

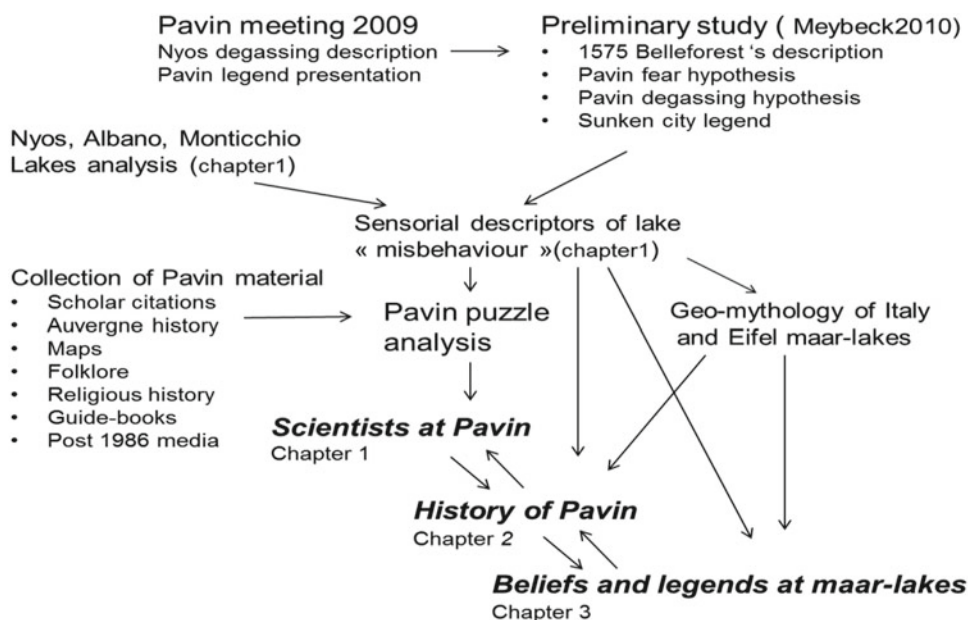
All traditional Pavin stories were analyzed: some of them can be considered as distorted descriptions of past Pavin state, others, as the Sunken City legend, are very recent (end of the nineteenth century). A fantastic story, published in 1632, so far not attributed to Pavin, and a legend featuring Pagan times, collected in the late nineteenth century, are re-attributed to Pavin. Similarities with legends, pagan and/or early Christian cults, from other mountain lakes and maar-lakes, in Italy and at Eifel, in Germany, are discussed in Chap. 3.

Step 6. Chronological presentation of Pavin state

A tentative chronology of Pavin state and of Pavin perception by different actors, local populations, scholars and scientists is proposed.

Several recursive loops from steps 2–5 have been necessary: most texts have been analyzed several times as new findings were made (Fig. 1.1).

Fig. 1.1 Simplified methodology applied for the analysis of Pavin Lake history and degassing



1.3 Pavin, a Typical Maar-Lake Above any Contamination Source

1.3.1 Pavin General Features

Pavin lake is located in Auvergne, one of the few recent volcanic provinces in Europe (Fig. 1.2a). It is adjacent to the Mont Dore volcano massif (named *Mons Aureus* in the Antiquity period, then Mont d'Or) and belongs to the Western Cézallier volcanic district (Fig. 1.2b). It is located just at the hydrological divide between the Loire and the Dordogne watersheds, at an altitude of 1197 m. It is only topped by the Montchal volcano (also Montchalme) (1417 m), 0.5 km further south (Fig. 1.2c).

Pavin is a typical maar-lake, i.e. a lake located in an explosive crater depression. Maar-lakes are rare when considering the global distribution of lakes (Meybeck 1995a, b) and have in common several features: (i) the aerial lake basin is annular, (ii) they do not receive stream waters and their water balance is realized through direct rainfall or snowfall and groundwater inputs, (iii) many of them have no natural outlet, (iii) their detrital inputs are often limited to shore erosion, so that lake sedimentation is limited and/or controlled by internal sources. Pavin, with an area of 44 ha, 400 m in diameter, almost round in shape, with a present depth of 92 m, probably 4 m deeper before the excavation of natural aerial outlet in the late 1800th, is a sort of giant pluviometer, mostly fed by atmospheric inputs and few springs within the crater. It is frozen each year during 3–4 months and partially mixes twice a year (dimictic lake), when the water column is at 4 °C, but the mixing does not affect the whole water col-

umn, its bottom waters, termed *monimolimnion*, are therefore permanently anoxic, a characteristic of *meromictic* lakes. It has an aerial outlet flowing in a steep notch.

Until 1980 Pavin was in ultra-pristine conditions and oligotrophic, i.e. with very limited algal production. Today it is regarded as a natural laboratory for the study of the oxic-anoxic water interface, for the iron cycle during Precambrian period or for archeobacteria analysis (Jezequel et al. 2010a, b). Its classification as a unique European natural site has been proposed (Meybeck 2010).

The nearest town is Besse, some kilometers downstream, located since the twelfth century on the south side of the Couze Pavin River thalweg. Throughout the Middle Age until the mid-1800s the lake was isolated and largely avoided by local people, only coming in winter to take away some wood, due to their long-lasting fear of the *Lacus Pavens*, the terrifying lake (see Chap. 2). This reputation possibly originated since the Antiquity (see Chaps. 2 and 3). Until the mid 1800s Pavin was practically devoid of any fishes and there was no direct access by a carriage way, the lake was essentially observed from the rim until the mid-1800s (Lecoq 1835a, b). The first path to Pavin was traced in the mid-1800s by Henri Lecoq, an Auvergne naturalist who also brought the first boat and introduced chars to the lake (Chap. 2). The present circular pedestrian path around the lake has been built up in 1909 by the city of Besse and the access paved road in the 1960s. During centuries the pedestrian access to the nearby Vassivière mountain, where an important pilgrimage is located, was passing in the valley beneath the lake where the outlet meets the Couze Pavin river, probably on the left bank of the Couze Pavin (Fig. 1.2c).

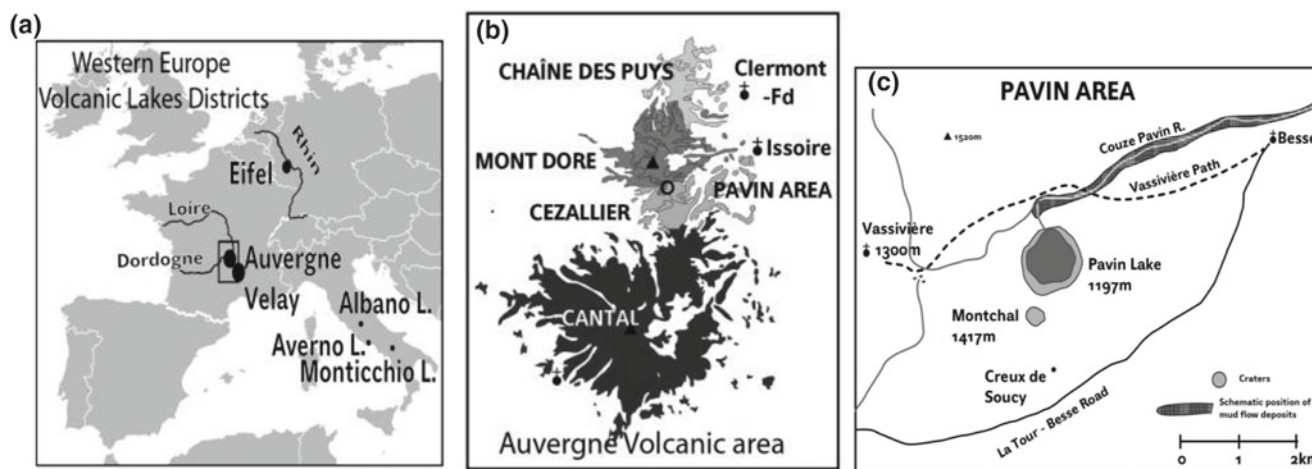


Fig. 1.2 (a) Position of European volcanic lake districts. (b) Auvergne volcanic districts. (c) Pavin area with Besse, Vassivière and Creux de Soucy, ancient roads and footpaths (early 1800s)

Until the mid-1950s the Pavin area was nearly void of permanent populations, excepted for few shacks and a chapel on top of the “Vassivière Mountain”, at an altitude of 1300 m, the history of which could be connected to Pavin (Meybeck 2010 and Chaps. 2 and 3). From there, one can see the edge of the crater, but not the lake.

Pavin explosive crater has been formed on the side of Montchal volcano (Fig. 1.2a), slightly younger, characterized by a small crater and a scoriaceous lava flow. The whole Pavin area corresponds to a relatively recent volcanism (see Chap. 7), in which CO₂ degassing evidence has been found since the mid-nineteenth century (Martel 1894; Bakalowicz 1971; Lavina and del Rosso 2009; Gal and Gadalia 2011).

Many aspects of Pavin characteristics are very rare, some were noted since 1892: its water balance, its very special chemistry (richness in silica; extreme iron levels in anoxic deep waters), its deep groundwaters inputs, its thermic anomaly with slightly warmer deep waters. They are similar to some other volcanic lakes located in more active volcanic district as in Japan (Yoshimura 1937; Touchart and Ishiguro 1999). The meromictic nature of Pavin, now unique in France, is also commonly found in Japan (Yoshimura 1938), in Eifel (Germany) and in Latium (Italy), see further.

1.3.2 Pavin Compared to Other Lakes of the Céallier Lake District

Pavin is surrounded by several lakes of major scientific and / or ecological importance. They are all located between 1050 and 1300 m, on the watershed divide between the Dordogne and Allier rivers (Fig. 1.3a). These lakes are in pristine condition with very limited Human pressures, excepted for pas-

ture: the population density on their basin is less than 1 person per km². The diversity of these lakes, their origins and morphology is known since the survey of Delebecque (1898) (Table 1.1). Pavin, Chauvet, and La Godivelle d'en Haut are considered as maar-lakes, while Montcineyre results from the recent damming of a post-glacial depression by a volcanic cone. There are many post-glacial peat-bogs with residual lakes as Chambédaze, La Godivelle d'en Bas and Bourdouze, all with high biodiversity value with numerous relict species of the last glaciation, some well-known for their paleolimnological records of Holocene climate and vegetation, others protected at the national and European level (Meybeck 2010).

The *Creux de Soucy* Lake, located in a cavity within the Montchal lava flow, some 35 m deep, one kilometer South of Pavin, is a steep underground pond, 10 m deep, still under exploration by speleologists (Bakalowicz 1971; O. Pigeron, pers.com) (Figs. 1.2c and 1.3b). It is near 2 °C all year round and is so far unique in continental Europe. This cavity has been described in 1575 by a royal cosmographer, Belleforest, and has been thought since that time to feed Pavin with groundwater (See Sects. 2.3.3 and 2.3.5). The cavity has been visited for the first time in 1892 (Sect. 2.3.6) and its exploration still continues today: a vertical drowned corridor, found in the late 1960s, now extends the lake depth to 50 m.

La Godivelle d'en haut Lake has been intensively equipped in the 1960s for the study of lake evaporation in altitude (1300 m asl) and of water budget (snow and rain inputs, groundwater outputs) (Jacquet and Mandelbrot 1966). The Chambédaze Lake and peatland is famous for its palynological and tephra studies (Guenet and Reille 1988; Juvigné et al. 1993).

Fig. 1.3 The Cézallier lake district in Auvergne (Berthoule 1890) with the 1050 m altitude contour line in red and a possible delineation of the most pristine lakes in green. Blue dotted line: watershed divide between Dordogne and Allier Rivers (Meybeck 2010, based on Berthoule 1890). 3b North-south cross section Pavin-Montchal- Creux de Soucy by Gobin (1896) (BCU library, Clermont-Ferrand)

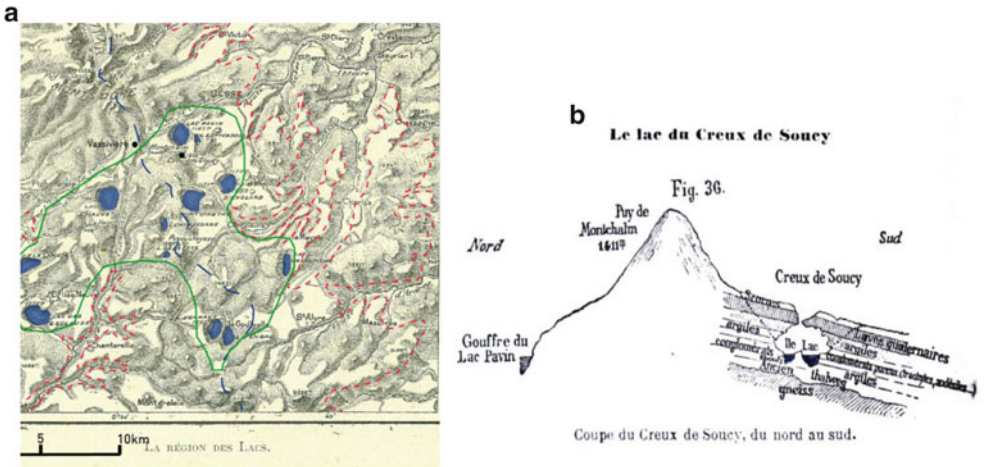


Table 1.1 Lmnological characteristics of Cezallier lakes, Pavin and other European maar-lakes in Central and South Italy and in Eifel

Lake	L.A.	ZM	V	Zm	Alt	C.A.	H.I.	Origin	Outlet
Cezallier									
Pavin	0.44	92	23.0	65	1197		Low	maar	aerial
Chauvet	0.54	64	17.3	N.A.	1162		Very low	maar	aerial
Godivelle Haut	0.15	44	2.74	N.A.	1239		Very Low	maar	subterranean
Servièrès	0.15	26		N.A.	1202		Very low	maar	
Montcineyre	0.4	18		N.A.	1182		Very low	volc. dam	subterranean
Chambedaze	0.02	(2)	(0.04)	N.A.	1180		Very low	peat bog	aerial
Bourdouze	0.15	4.5	(0.6)	N.A.	1168		Very low	peat bog	aerial
Godivelle Bas	0.16	(3)	(0.5)	N.A.	1200		Very low	peat bog	aerial
Central and South Italy									
Albano	5.8	167	450	70	293	3.68	Medium	maar	Tunnel (398 BC)
Nemi	1.7	32	30	15–20	316	10.3	Medium	maar	Tunnel (400 s BC)
Monticchio Grande	0.41	36	3.27	15	654	2.4	Medium	maar	Dug-out canal
Monticchio Piccolo	0.14	38	2.4	15	656	1.07	Medium	maar	Dug-out canal
Averno	0.55	34	6	7	<10		High	maar	Tunnel (500 s BC)
Eifel									
Pulver	0.38	74	14.3	N.A.	411	0.8	Low	maar	Subterranean
Weinfelder	0.17	51	4.3	N.A.	484	0.35	Low	maar	Subterranean
Ulmen	0.055	39	1.12	20	420	0.155	High	maar	Medieval tunnel
Laacher <1164	4.83	65	167	N.A.	289	12.2		maar	
Laacher >1854	3.32	51	103	N.A.	275	12.2	Low	maar	Tunnel (1164)

L.A. lake area (km²), ZM present maximum depth (m), V volume (Mm³), Zm present monimolimnion depth (m), C.A. catchment area (km²), H.I. human impacts, N.A. non applicable

The Cézallier lake district (Fig. 1.3a) has an exceptional level of naturalness index, as defined by Maichado (2004), (Meybeck 2010). The diversity of lake origin and morphology, water and sediment chemistry, hydrology, sedimentology, trophic status, fauna and flora, is exceptionnal as already noted by Berthoule (1890), Delebecque (1898), Bruyant and Eusebio (1904). However, this rare ensemble is not yet recognized as exceptional by geologists or naturalists (Sabouraud 2004; de Wever et al. 2006; Michel 2008) although some of its elements have been individually protected, mostly on ecological criteria (PNRVA 2004; Meybeck 2010).

1.3.3 Pavin Compared to Other European Maar-Lakes

Western continental Europe has three major volcanic lakes districts: Auvergne, Central Italy (Latium and Campania) and Eifel, between the Mosel River and Aachen (Fig. 1.2a) (Table 1.1). All Eifel lakes are termed “maars”.

1.3.3.1 Eifel Lakes

The Eifel volcanic district, located in Germany, West of the Middle Rhine Valley, is famous for its deep round lakes

which fill volcanic explosion craters (Buchel 1993). These depressions, termed locally maars, gave their name to other crater lakes of similar origins. Many of them are now completely filled with sediment, some of them remain filled with water, among them some famous ones: Laacher See, Pulver Maar, Ulmen Maar, Weinfelder Maar (Table 1.1). They are characterized by their round shape, circular drainage basin, absence of natural aerial outlet. This region, between 300 m and 500 m a.s.l., is exposed to Human pressures from villages and agriculture: many of these lakes have received a nutrient excess and have been eutrophied, with the exception of Laacher See, Pulver and Gemündener Maars (Scharf and Björk 1992).

The Eifel lakes have been first studied by August Thienemann, the father of German limnology (Thienemann 1914–1915), who found the permanent anoxia of Pulver Maar which was used later to define the lake meromicticity (Findenegg 1935). More recently they have been intensively studied for their chemistry and ecology (Scharf and Björk 1992). Although this synthesis was realized after the catastrophic Nyos event which occurred in 1986 (see further), no consideration was given to their CO₂ content in bottom waters and/or potential degassing risks. These studies were performed later (Aeschbach-Hertig et al. 1996). Unlike for the Italian maar-lakes no use of geomorphology has yet been realized in this legend-rich region (see Chap. 3).

The Laachersee Lake is well known among earth scientists. It was formed 12,900 years ago by a sudden explosion which sent into the atmosphere about 6 and 20 km³ of ashes hundreds of kilometers away within a few days. This ash layer is now used as a sedimentological tracer in many western European lakes (Bogaard et Schmincke 1995). The residual lake, now 51 m deep, has no natural aerial inlet or outlet. On its shore there is still evidence of a gentle degassing activity.

1.3.3.2 Italian Lakes

In Latium half a dozen lakes of volcanic origins are found (Margaritora 1992; Niessen et al. 1993; Chondrogianni et al. 1996; Elwood et al. 2009; Carapezza et al. 2008) (Table 1.1). Albano and Nemi Lakes are found in maars aged 38,000–40,000 years. Albano Lake, 3.5 km long by 2.3 km wide, is located in an important maar with twin underwater depressions forming a single lake. Albano waters are anoxic below 50 m. Lake Nemi is some 3 km SE of lake Albano, on the other side of Monte Cavo. In both lakes drainage basin is annular and their hydrological budget is therefore exceptional, with regards to most other lakes (Pourriot and Meybeck 1995) with a dominance of groundwaters inputs and outputs: there are neither stream inputs nor natural aerial outlet, a peculiarity also found in most other maar-lakes. Albano crater rim is today at 70 m above the water level. These two meromictic lakes have been drained by dug-out

tunnels in Antiquity (see Sects. 3.5.3 and 3.7). Both lakes have been eutrophied.

The twin meromictic maar-lakes, Lago Piccolo di Monticchio (LPM) and Lago Grande di Monticchio (LGM), are located in the Mount Vulture, an isolated volcano, between Campania and Basilicate (Southern Italy), also known for its deep forest. These lakes are located in a remote environment and are separated by a narrow exundated isthmus of 50 m. Both are anoxic below 15 m today, characterized by a marked positive thermal gradient in deep waters (+1.1 °C/10 m) and contain important amount of CO₂, from mantelic origin (Chiodini et al. 1997; Schettler and Alberic 2008; Mancino et al. 2009; Caracausi et al. 2009).

Averno Lake, *i.e.* the lake without birds for the Greek colony in Italy in Antiquity, is a small maar lake located in the Phlegrean Fields, a very active volcanic district West of Naples. The lake is meromictic and a few years ago a massive fish kill has been reported (Caliro et al. 2008) suggesting a rollover, a partial mixing of deep anoxic waters. As in Pavin, microbiologists are studying its very peculiar bacteria communities (Bianchi et al. 2010). Antique tunnels and an outlet canal have also been dug-out on Averno shores (see Sect. 3.5.3). Averno has received sewage effluents in the past so that is present bottom anoxia can also be related to this pollution.

1.4 Pavin Scientific Exploration (1770–1985)

1.4.1 Chevalier's Expedition (1770)

Pavin scientific history begins in September 1770. Before that year Pavin is still thought to be bottomless and the origin of its waters, their linkage with the nearby Creux de Soucy cavity, are one of its many mysteries, as reported by local people (See 2.3.3). A high-rank royal civil engineer, Chevalier, is asked to make an expedition to disprove these “tales”. He comes to Pavin on September 27 and 28, 1770, fully equipped with a sounding line and a lead weight, as those used by marine engineers, with a Réaumur thermometer, and with material to measure relative altitudes, but he has to make his own raft. His objectives are multiple: (i) to measure the depth of Pavin and of the nearby Creux de Soucy, (ii) to measure their relative altitudes, to check the Soucy-Pavin connection, (iii) to measure the temperatures of these lakes. All objectives are fulfilled: Pavin depth is measured at 288 ft (96 m), the Creux de Soucy lake level is determined to be above Pavin level, allowing a possible subterranean connection. Chevalier sends a bucket into the Creux de Soucy water: to his surprise the water is extremely cold for the summer season (5 °R or 6.25 °C). He also finds a set of springs, hidden in the vegetation, opposite the lake outlet, at the bottom

of “a volcanic cliff whose lava layer was recovered by ashes”, one of the first report of the volcanic nature of Pavin crater. Chevalier has not made a thermal profile of Pavin, as De Saussure did in 1767 for Lake Geneva (Touchart 2003), but he is the first French scientist to have studied the major components of a lake system: its origin and basin rock composition, its water inputs, its depth and temperature. His measurements are still valid today, if one considers the lowering of the lake, from 96 m to 92 m, when the natural sill was dug out in the late 1800s.

Soon after Chevalier's expedition the first accurate maps of Pavin region were realized by Cassini de Thury, within the general mapping of France, and published between 1775 and 1815. They included four other crater lakes, within 20 km from Pavin, Chauvet, Godivelle d'en Haut, Servières – and two volcanic dams lakes – Chambon and Montcineyre. In these official maps, Pavin is still referenced in his original spelling, *Paven* (see Sect. 2.3.4). Few years after, the altitude of the lake is measured by L.F. Ramond, a mathematician topographer and prefect of Puy-de-Dôme: Pavin Lake water level is at 1203 m (today 1197 m) and the Montchal Volcano at 1411 m a.s.l.

This expedition is as soon widely celebrated by the Auvergne scholars (Legrand d'Aussy 1788; Delarbre 1795; 1805). For them it is the scientific proof of the lack of grounded truth of “Pavin stories” (see Sect. 2.3.5): Pavin has a definite depth, it is fed with groundwaters, and it can be connected with the Creux de Soucy. Legrand d'Aussy (1788) is particularly fascinated by Pavin and would like to know the “*shape and verticalness of the slope, composition of the water, where do these water come from, what is the temperature profile with depth, what is the water pressure at 48 toises, the density of water at different depth, the light penetration in lake bottom, etc*”. This visionary program will only be started 100 years later and is still the main research objectives of dozens of scientists that are studying Pavin today.

1.4.2 Lecoq, the Great Auvergne Naturalist, Normalizes Pavin... with Fishes (1847–1871)

Henri Lecoq (1802–1871), a botanist, geologist and hydrologist is attracted by Pavin since his first visit in 1831, during which the marvelous Pavin stories were still narrated by local people (See 2.3.6 and 3.3). Lecoq will spend his life to refute these tales one by one. In 1847 he manages to have the first boat to be assembled at the lake and makes soundings which confirm those of Chevalier (95 m), a decade later he introduces fish to the lake.

This operation, one of the first ever in France, is realized with his colleague Barnabé Rico, who is charged by Lecoq of the new and innovative piscicultures at Clermont, then Besse. This required building a pathway up to the lake, then bringing

materials, boats and juveniles to Besse from the Clermont pisciculture facility, some 50 km away. In January 1859 the first fish juveniles are introduced: “92,000 trouts (*Salmo trutta*), 20,000 common salmons (*Salmo salar*), 18 Heusch salmons (*Hucho hucho*), 8000 chars (*Salvelinus Umbla*), some coregons (*Coregonus Fera*): 120018 salmonidae; 130 Cyprinidae and 200 adults crayfish (*Astacus fluviatilis*), in total” (Rico 1876; Berthoule 1890).

Before these introductions only gudgeons were present at Pavin. They were very peculiar by their size and their speckles (Rico 1876) and “*unique by their spotted and flecked colours*” (Bruyant and Eusebio 1904) but no attempt is made to further study them. In another isolated maar-lake in Mount Vulture (Italy), similar fish speciation had been observed for a small fish, *Cyprinus Vulturius* Tenore, although the reason for this speciation, as isolation or specific water chemistry, was not discussed by Gussone and Tenore (1838).

The pisciculture facility, soon constructed at Besse by Lecoq and Rico, is followed by another one in the nearby crater lake Chauvet (Berthoule 1890). At Pavin, it turns to be a great scientific, commercial and touristic success. Three years after the introduction, the first salmons (as big as 1100 g and 58 cm), trouts (1700 g for 54 cm, aged 38 months) and chars (up to 750 g for 43 cm), are caught and crayfish population is now developed. Some specimens of extraordinary sizes are reported: one 18.5 kg eel (1873), two salmons (8 kg and 12 kg, 80 cm, caught in 1874 in the same net) and one of the Heusch salmons, a 105 cm female weighting 14.5 kg with its eggs, from the juveniles introduced at only 9 cm some 15 years before. The rapid growth of these species probably benefitted from the lack of fishes before the introduction. The average catch for the first 10 years is 157 kg / year, i.e 3.7 kg/ha/year. Fishes are sent to the best hotels in Mont Dore, Clermont and Besse.

This successful salmon introduction is first challenged by Paris scientists in charge of the national fish introduction plan, then gradually recognized by them, but Rico remained hurt by the deny of his successful work until his last day. During the Lecoq-Rico period (1859–1873), the lake outlet is leveled and lowered; a little stone cabin is built by the lake. It will be used by Clermont scientists who are working on Pavin in the late 1870s and will attract tourists until the 1950s (See Fig. 2.7).

Lecoq has not realized important limnological studies at Pavin, except the description of a fresh water sponge *Euspongilla lacustris* (Lecoq 1859), maybe the first-ever limnological publication in France. Lecoq's last book, on the Massif Central waters (Lecoq 1871) provides some descriptions of Pavin, termed by him the *Auvergne Dead Sea*, due to its initial lack of fish. It is one of the first works on general hydrology in France, although also much less quantitative than Belgrand's book on the Seine River basin (1869), which benefited from the support of highest state authorities, including observations of dozens of imperial civil engineers

that were lacking to Lecoq. Considering that the Auvergne scientist had interest in many fields of science, botany, hydrology, geology and even global carbon cycling, his limited study of Pavin can raise questions. He was already 57 years old in 1859 and Pavin access from Clermont was still difficult. Most of all, he was missing the technical instruments and the laboratory facilities that were gradually being developed on Lake Geneva (Léman) by François-Alexis Forel, the founder of limnology. Forel had his own laboratory and boat by the lake shore in Morges (Vaud canton) and his monography on Léman (1892), is also much more quantitative than Lecoq's work in hydrology. Modern scientific exploration of French lakes begins with André Delebecque, who worked besides Forel on Léman and comes to Pavin in 1892, fully equipped.

1.4.3 The First Golden Age of Science at Pavin: Berthoule, Delebecque, Martel, Bruyant (1880–1914)

A few years after Lecoq died in 1871, botanists and zoologists from Clermont Faculty of Sciences initiate the first flora and fauna inventories of Auvergne lakes, which correspond to the start of French limnology, particularly at Pavin. These scientists are now well equipped and are essentially focusing on surface waters. Their research is much facilitated by

Amédée Berthoule, at this period mayor of Besse (Berthoule 1896). He is well recognized for his master book (*Les Lacs d'Auvergne. Orographie, faune naturelle, faune introduite*, 1890) on Auvergne lakes and their halieutic potential, which he developed in with many quantitative data and fauna lists (Fig. 1.4), a major improvement of Lecoq's work, 20 years before. It can be considered as the first limnology textbook published in France.

1.4.3.1 Clermont Botanists and Zoologists Establish the Limnological Station at Besse

The first hydrobiologist at Pavin is Girod, a zoology professor at the Faculty of Science in Clermont-Ferrand, who makes the first fauna inventory, specifically on sponges (Girod 1877–1878). His students are extending this inventory to the other lakes of the region. They are using the plankton net developed at Monaco by Prince Albert for the ocean research vessel “Hirondelle”. Richard studies the cladocerans (Richard 1887), Eusebio the pelagic fauna as entomostracae and rotifers, Bruyant focusses on phytoplankton, making vertical profiles and horizontal catches and studying seiches. Between 1887 and 1912 this team publishes 25 papers, fully listed in the analysis of Wurtz (1945). In total Berthoule, Girod and their colleagues study 20 lakes. Their work demonstrates for the first time the great variety of Auvergne lakes, as foreseen by Lecoq and Berthoule.

TABLEAU SYNOPTIQUE DE LA FAUNE DES LACS.												
NOMS DES LACS. —	NOMS DES ESPÈCES.											
	Brème.	Brochet.	Carpe.	Chevenne.	Corégone.	Écrevisse.	Épinoche.	Gardon.	O. Chevalier.	Perche.	Tanche.	Traite.
Anglard.....	**	*						*		*	*	
Aydat.....	**	*	**	*		*		*		**	*	○
Chambédaze.....	**	*	○			*		*		**	*	
Chambon.....	**	*				*		*		**	*	*
— Couessat.....	**	*				*		*		**	*	*
Chauvet.....		*			○				○	**	*	○
Esclauzes.....		*								**	*	
Godivelle inférieur.....			**							**	*	*
— supérieur.....										*		
Guéry.....							*					**
La Crégut.....										*	*	*
La Faye.....										*	*	*
La Landie.....			*			○			○	*	*	○
Pavin.....						○			○	*	*	○
Servière.....										*	*	○
Tazanat.....	*	*	*							**	*	

Les signes ** désignent les espèces appartenant à la faune naturelle.
— ○ — — introduite.
Leur nombre indique la prédominance de chacune d'elles.

Fig. 1.4 Fish distribution in Cezallier and Mont Dore lakes. It only features introduced species at Pavin and one native species at Chauvet Lake (Berthoule's 1890)(BCU library Clermont-Ferrand)

The most innovative scientists is Charles Bruyant (1894). Together with Eusebio, he publishes in 1904 the “*Introduction à l’aquaculture générale. Matériaux pour l’étude des rivières et des lacs d’Auvergne*”. This book goes further than Lecoq’s and Berthoulet’s, including rivers, their hydrological and thermal regimes and their chemistry in relation to the various basin rock types. It is a major analysis realized at a time when all these aquatic systems were still in a quasi-pristine state. In 1908 Bruyant becomes director of the *Pisciculture départementale*, initiated by Lecoq and Rico. He does not belong to the department of zoology of the Faculty of Sciences, as most of his colleagues, but is professor at the School of Medicine and Pharmacy where he studies phytoplankton. Following Eusebio (1896) he develops the Hydrobiological Station at Besse, also named the Limnological Station, on the model of the Marine Research Stations. Its official opening takes place in August 1908 during the meeting of the French Association for the Advancement of Sciences, at Clermont. From there a group of French and foreign scientists comes to Besse, surprised by the new facility and struck by this new scientific center (Reynouard 1909). The limnological station, i.e. the pisciculture and the hydrobiology station, acquires a high scientific visibility. Its objectives combine the fish introduction in rivers and lakes and the study of the complex relations between animal and plant species and their physico-chemical environment. Bruyant also considers enlarging the scope of the station to mountain environments, with geology, mountain vegetation and also local history (Bruyant 1910). He launches a scientific journal, the *Annales de la Station de Limnologie de Besse*, with a first volume of 400 pages including an important selected bibliography. Bruyant also promotes this new science, in an eight-page introduction to limnology for a remarkable guidebook (Cany et al. 1916), probably his latest work as he will disappear in World War one. The Besse Annales will be stopped and will reappear only in the 1950s. Bruyant and Eusebio are two pioneers of limnological concepts as for the vertical structure of lakes (Fig. 1.5b, c).

In summer 1892 Pavin is hosting two other prominent French scientists: André Delebecque, a young limnologist who has collaborated on Lake Geneva with Forel, the “father of limnology”, and Edouard-Alfred Martel, the “father of speleology”, attracted by the Creux de Soucy.

1.4.3.2 André Delebecque at Pavin (1892)

André Delebecque (1861–1947) is a young state civil engineer from the most prestigious schools of engineers, Ecole Polytechnique and Ecole des Ponts et Chaussées. Unlike his comrades he chooses in 1887 to develop the newly established Thonon-les-Bains pisciculture. There, on Lake Geneva shores, he contributes to the bathymetry of Léman (Lake Geneva) and meets Forel. Few years later he initiates the first

in-depth survey of French lakes: bathymetry, thermography, sedimentology, water and sediment chemistry. He uses his own portable skiff equipped with a winch and up-to-date sampling equipments (Touchart 2002) as Secchi disk, Negretti and Zambra thermometer, sediment grabs, comparable in many ways to those used in oceanography. His chemical analyses are performed by two specialized laboratories, at the Geneva University (Pr. Duparc) and in Paris (Laboratoire des Ponts et Chaussées). Although he is not making biological inventory, he is the first limnologist, in France and elsewhere, to compare more than 300 lakes of different origins and types.

In Auvergne, the young limnologist makes the sounding and survey of all lakes including the seven major crater lakes of the Massif Central: Pavin (92 m now), Servièrès (27 m), Chauvet (63.2 m), Godivelle d’en Haut (43.7 m) and Tazenat (66.6 m), all in Auvergne, and Le Bouchet (27.5 m) and Issarlès (108.6 m) in Velay. He also describes the many peat-bog lakes in Pavin region (Chambédaze, Bourdouze, Godivelle d’en Bas). With Ritter, a young geochemist from Geneva, probably the first foreign scientist at Pavin, he works on Pavin from June 19 to 24, 1892, and makes important discoveries (Delebecque 1898):

1. Pavin bottom is flat and regular, with steep slopes, near cliffs on the eastern side; it is the second most “hollow” lake in France, after Issarlès (Fig. 1.5a),
2. The water transparency in June is one of the highest he had measured in French lakes, 8.5 m; nearby peat bogs have less than 1 m,
3. Sediments are highly siliceous, corresponding to a “*randammite*”, now *diatomite*, i.e. only composed of diatoms siliceous remains,
4. Two temperature profiles are made, every meter in surface, then every 10 m; below 25 m waters are very cold, less than 5 °C, reaching 4.6 °C at the bottom. Another measurement provides 4.8 °C: Delebecque attributes this slight increase to organic matter decomposition. Pavin is a typical dimictic lake (two mixing periods and two stratification periods),
5. Pavin waters are less mineralized compared to Jura lakes or others, but more mineralized than other Auvergne lakes, reaching record dissolved silica levels (22.1 mg/L at outlet).

Delebecque is a pioneer of comparative limnology. While Forel (1892) has spent his lifetime to study Léman (Geneva Lake), Delebecque completes, in few years time, the first standardized survey of all French lakes for all their physical and chemical attributes: lake morphology with detailed bathymetric map, lake origin, thermal stratification, water chemistry, lake sediments origin and chemistry etc. He sets typologies, which are still used today (Dussard 1966;

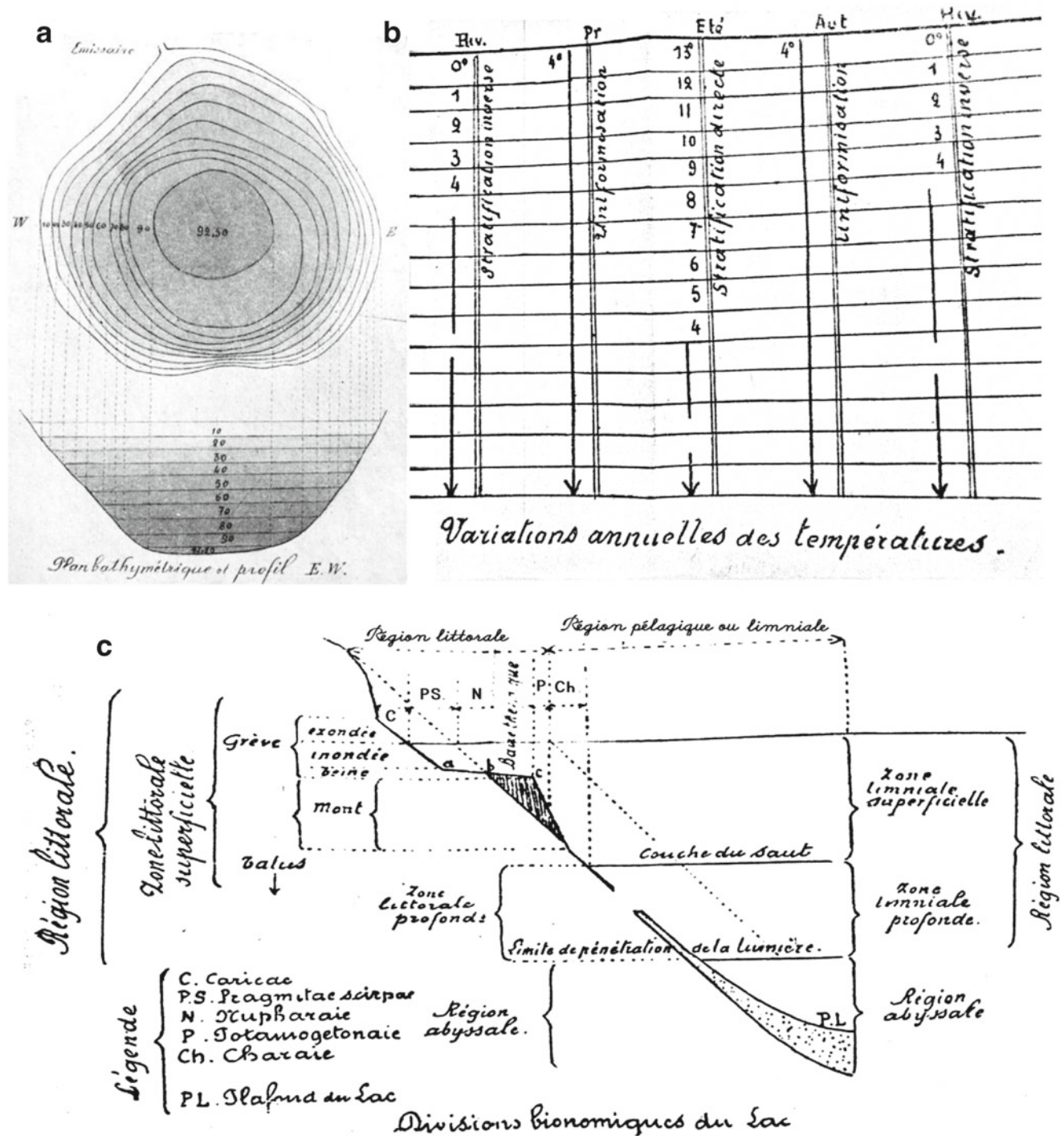


Fig. 1.5 Some of the pionnier limnological works at Pavin (Eusebio and Reynouard 1925). (a) First bathymetric map of Pavin by Delebecque (1898). (b) First representation of Pavin thermal structure. (c) Vertical “bionomic” structure of Pavin (author’s collection)

Touchart 2002). He does not measure dissolved oxygen, a part of Léman: this new approach initiated by Gérardin in the Seine basin (1875) is used in this period for rivers suspected to be polluted. Delebecque does not focus on bottom waters – limnologists have not yet found that few lakes can be anoxic. At Pavin, he does not record any abnormality, except for the

peculiar smell from bottom sediments, and completely misses the absence of O_2 in the bottom waters, the *meromixis* which will be “discovered” 60 years later.

Delebecque’s work on Pavin appears to be complementary to the hydrobiological studies performed by Berthoulet, then by the Clermont team. His master work on French lakes

did not get the international recognition he deserved, particularly in the history of limnology (Touchart and Dussard 1998) but his work contributed to get Pavin recognized by prominent limnologists such as G.E. Hutchinson (1957). Many of his observations are still used today by French limnologists (Pourriot and Meybeck 1995).

1.4.3.3 Edouard-Alfred Martel at Creux de Soucy (1892)

Edouard-Alfred Martel (1859–1938) comes to Besse in June 1892 with his team and his special equipment including a foldable skiff. He is a friend of Delebecque, with whom he worked in Savoy (Touchart and Dussard 1998). Both have planned to explore the Creux de Soucy cavity together. Delebecque and his young colleague, Ritter, would be in charge of the study of the bizarre *tiny lake, with near freezing waters in summer*, according to Chevalier (1770). They benefit from the full support of Amédée Berthoule, the mayor of Besse, whose father has tried to explore the cave some 30 years before without success, being stopped by a CO₂ layer which caused him headaches and dizziness. The expedition mobilizes eight people.

Martel is attracted by the famous cave, the only one in a volcanic setting and previously described by Belleforest in 1575 (See Sect. 2.3.3). The cave is some 1.3 km south of Pavin, together with few other depressions already mapped by Cassini in the late 1700s. It is 35 m deep and the small lake in the bottom of the cave is believed by all to be related with Pavin (Figs. 1.2c, and 1.3b), a scientific possibility established by Chevalier (1770). The cave is hidden in the Montchal scoriaceous lava flow so that Martel (1894) has difficulties finding the very small opening, only few meters wide and he needs to be guided. Unfortunately he is also stopped at 4 m above the small lake by the absence of oxygen and must go back. The cavity bottom will only be reached that year in August 1892 by Berthoule, and then it will fully be explored by the Clermont naturalists, Gautier and Bruyant, a few months later, in November 1892, when CO₂ is totally absent from the cave. These attempts to unveil the Creux de Soucy mysteries, highly anticipated in Auvergne for more than 300 years, correspond to major scientific expeditions and their preliminary results are published at once.

The small Soucy Lake is very peculiar (Gautier 1892; Martel 1892, 1894; Gautier and Bruyant 1896): its temperature is around 2 °C all year round, *i.e.* it is a “polar lake” always below 4 °C (Delebecque 1898; Touchart 2002) although it very rarely freezes, unlike all other polar lakes. In such extreme conditions, without light, with minimal temperature and with very limited nutrients inputs – from the snow melt – aquatic biomass and biodiversity are extremely limited: the aquatic plant community is very simple, essentially the diatom *Asterionella Formosa*, also dominating in Pavin. The lake depth is around 9.5 m and seasonally variable, with highest levels at the spring melt.

In the late 1960s new underwater exploration revealed a near vertical corridor some 40 m deep, still being investigated. The Soucy Lake level is 45 m above the one of Pavin, making the connexion between the two possible, but the groundwater circulation remains debated today. As for Pavin, the scientific and patrimonial value of the Creux de Soucy is worthy of recognition and full protection.

1.4.4 Pavin Meromixis Discovery by Olivier and Pelletier (1950–1960s)

After 1918 the limnological survey at Pavin is slowed down but does not stop. Eusebio publishes with Reynouard, a local historian and former Besse mayor, the first scientific guidebook devoted to Pavin (Eusebio and Reynouard 1925). In this remarkable brochure they combine the presentation of Pavin long history and pioneer scientific observations as the many vertical divisions of Pavin surface waters, combining temperature, morphology, sedimentology and plant communities (Fig. 1.5b, c). In 1936, Luc Olivier, a Clermont hydrobiologist, makes repeated vertical plankton profiles at Pavin between 0 and 20 m. He is using Richard water sampling bottles with a reversing thermometer. He also innovates, making profiles of pH and of dissolved oxygen, by the Winkler method, between 0 and 50 m. They are among the first profiles at such depth in France, after those made on Léman. But he does not find any peculiarity in the oxygen profile (Olivier 1939). In 1943 another survey by Wurtz (1945) confirms the occurrence of O₂ at 70 m (8.34 cm³ O₂/L) for 4.4 °C. On May 24, 1951 Olivier makes new profiles, every 10 m, down to 92 m, and finds for the first time a marked O₂ depletion at 65 m, confirmed again on August 16: 2.3 cm³ O₂/L at 60 m, 0 at 70 m, 9.1 cm³ at 80 m and at 90 m. He reports at once this extra-ordinary profile to the French Academy of Sciences (Olivier 1952). For him an anoxic layer has just been established around 70 m, “in contrast to Wurtz’s opinion”.

In summer 1962 Jean Pelletier, a young limnologist from Thonon-les-Bains hydrobiological station, makes another vertical profile for temperature, oxygen, dissolved iron and H₂S. It is followed by five continuous temperature profiles from 1963 to 1967 measured in situ with a Metrix thermal probe (Fig. 1.6): another French premiere at Pavin (Pelletier 1963, 1968). He confirms Olivier findings and adds new extraordinary Pavin features (Fig. 1.6):

1. There is no oxygen below 70 m,
2. There is a marked yet moderate thermal increase in bottom waters, from 4.2 °C at 60 m to 5.2 °C at 90 m (a thermal inversion),
3. H₂S is present below 70 m,
4. Dissolved iron is 100 times more concentrated in deep waters,

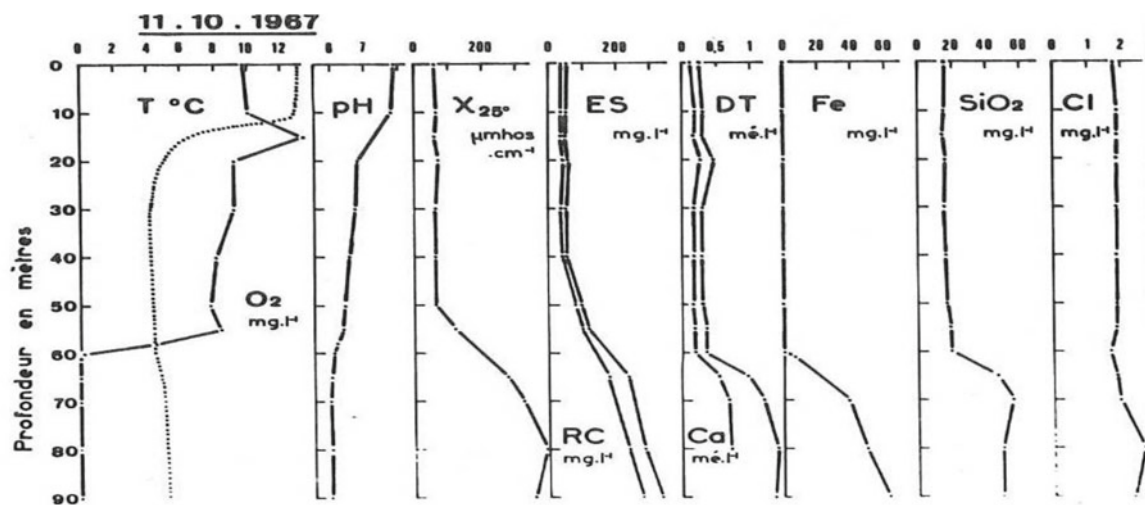


Fig. 1.6 Pelletier's vertical profiles showing Pavin meromixis in October 1967: temperature, O₂, pH, conductivity, total dissolved solids (ES), total hardness (DT), dissolved iron, silica and chloride (1968). (Ann. Stat. Limnologie Besse-en-Chandesse)

5. Bottom waters are very mineralized, with silica exceeding 50 mg/L
6. Pavin is termed “meromictic” by Pelletier, with an upper layer, the *mixolimnion* mixed twice a year, and a bottom layer, the *monomolimnion*, that is never mixed, according to Findenegg (1935).

The discovery of Pavin meromixis is surprising: according to the current geochemical models the quantity of dissolved salts present in deep waters, which originate from more mineralized hydrothermal inputs, corresponds to multisecular hydrothermal inputs (Jezequel et al. 2010b). This suggests that the meromixis should have occurred long ago but was not correctly identified for lack of focus on deep waters and/or for difficulties in dissolved oxygen measurements. It is also possible that the anoxic bottom layer has been much reduced from 1937 to early 1950s due to a soft degassing and partial mixing event in 1936, still debated (see further). After Pelletier's first profiles, all oxygen profiles will show anoxia and a temperature increase below a certain depth, which may fluctuate.

Meromixis, with its associated mixolimnion and monimolimnion, is a rare limnological feature that can only occur when lakes are very “hollow” and/or when deep waters are denser than surface waters, thus limiting vertical water mixing. The primary cause of meromixis combines lake hydrodynamics and oxygen balance: (i) inputs of waters with higher dissolved salts contents (sea water intrusion, saline groundwater) and/or (ii) inputs to deep waters of organic algal detritus from surface waters, in excess of the mineralization capacity of deep water, thus consuming dissolved oxygen. Many European maar-lakes in Italy (Albano, Nemi, Monticchio, Averno) and in Eifel (Scharf and Björk 1992) are meromictic (Table 1.1), most probably due to hydrothermal

inputs, although this is still debated for the Eifel lakes. The Girotte Lake in the French Alps was another meromictic lake (Dussart 1952, 1966), due to gypsum-draining groundwater inputs, but it has been transformed into a hydropower reservoir in the 1950s: Pavin is the only meromictic lake still found today in France.

1.5 Pavin Acquires a Status of International Field Laboratory (1965–2000)

1.5.1 International Projects Select Pavin as a Pristine Lake (1965–1975)

In the 1960s Pavin is still in a quasi-pristine state, with very limited nutrients inputs. Nicole Omaly-Lair who now heads the Clermont limnology group continues the tradition of technical innovations at Pavin. She uses a Cambridge oxygen probe for a continuous in situ O₂ profile, for the first time in France (Omaly 1968). She defines the transition layer, or *mesolimnion*, later decomposed by geochemists into an *oxi-cline* and multiple *chemoclines* for each redox couples: sulfur, iron, manganese, arsenic, nitrate etc. She is the only post WWII limnologist to mention the possibility of strange legendary Pavin behaviour, which will be mocked by local historians (Fournier 1971): Pavin stories, as reported by Lecoq, will never be considered or mentioned by scientists until 2009 (See Sect. 1.8). Pavin also becomes part of several national and international programs on lakes.

As field and laboratory facilities are found at Besse and previous limnological surveys are numerous, Pavin becomes a land mark for foreign limnologists, looking for a mountain oligotrophic lake with high transparency and low nutrient

levels, particularly nitrate, and a very high natural silica content, as already noted by Delebecque (Persoone et al. 1968; Flik et al. 1973, Paanaker and Hallegraef 1987). Pavin is also selected within the global scale Aqua project of SIL (Societas Internationalis Limnologiae) and Unesco which aims to “*get international recognition for a list of freshwater and brackish water area which are of agreed international importance for research, education, training and conservation*” (Luther and Rzoska 1971). Pavin is put on this world list, along with a handful of French lakes, by Bernard Dussart (1922–2008) the head of French limnology at this time. Unfortunately this project, which was conceived to be managed by UNESCO, will not be effective.

The second program is the famous OECD network of lakes trophic status, established by Richard Vollenweider (1922–2007), the world specialist of lake eutrophication for which he received the Tyler price in 1986. His contact for Pavin is Nicole Omaly-Lair and the Clermont team greatly benefits from this international collaboration. Their work focuses on seasonal variations in Pavin mixolimnion (Fig. 1.7a), the phyto-zooplankton relationships, nutrients cycle, lipid markers, occurring within the *mixolimnion*, between 0 and 50 m (Lair 1975–1976; Restituto 1984; Restituto and Lair 1975–1976; Devaux and Lair 1976; Devaux 1980a, b; Devaux et al 1983; Amblard 1986; Amblard and Bourdier 1990).

In the 1980s Pavin is one of the six lakes included in the French national program on lake research – named the GRECO Lacs – headed by Roger Pourriot (ENS Paris). The results of this program are finalized by a collective textbook on limnology in which Pavin is often highlighted, as the complexity of its vertical structure (Pourriot and Meybeck 1995; Meybeck 1995b).

Many old Pavin descriptions highlight its rare transparency, even in summer during the algal growth period. Delebecque measured an average Secchi depth of 8.5 m in June 1892. The 20 measurements made between 1892 and 1970 (Olivier 1939; Würtz 1945; Omaly 1968; Devaux 1980) show a maximum of 15.5 m and an average of 8.5 m. For Wurtz (1945) Pavin is meso-eutrophic due to the *Anabaena* blooms occurrence he has observed: “Pavin is beginning to get eutrophied”. This occurs at a period of absent human impacts and could be linked to internal sources of nutrients, if the 1936 partial mixing of deep waters, unknown until 1986-see further- is accepted.

In the mid-1980s Clermont limnologists begin to attract the attention of authorities on trophic state change at Pavin due to the artificial fertilization of grassland drained to the lake by groundwaters inputs. Nitrogen and phosphorus levels increase subsequently, enhancing the algal development. Pavin was joining other Auvergne eutrophied lakes as Aydat and Chambon (PNRVA 2004). The societal response to Pavin degradation will be slow: the origin and pathway of

excess nutrients had to be demonstrated first to farmers. It took more than 20 years for Jean Devaux, from Clermont University, who is studying Pavin since 1970, to convince all authorities to regulate nutrient use. In 2012 a first agreement is finally reached between all parties, land owners, farmers, Besse, Puy-de-Dôme department and Auvergne region with some European funds. When considering the water renewal time in the monimolimnion, the Pavin recovery might take decades.

1.5.2 Pavin, a Laboratory for Innovative Lake Research (1965–1986)

In the 1960s and 1970s Pavin attracts isotope geochemists looking for lake systems suitable to test their stable or radioactive isotopes toolbox: oxygen-18, tritium, cesium-137, lead- 210, silicium –32, plutonium, some of them natural, others being artificial radionuclides. These teams come from Bordeaux University, Ecole Normale Supérieure (ENS-Paris), Centre de Recherches Géodynamiques of Thonon-les-Bains (CRG-University Paris 6) and Tata Institute for Fundamental Research (TIFR- Ahmedabad, India). At Pavin they benefit from the scientific and logistical expertise of their Clermont colleagues, Nicole Omaly-Lair and Jean Devaux. The international reputation of Pavin is once more boosted and new peculiarities are found.

Tritium study in Pavin Lake by Alevinerie et al. (1966), a team from Bordeaux, is one of the first in Europe. This new approach in hydrology is developing fast in the 1960s, following the injection of this radioisotope in the atmosphere by nuclear tests. It also provides relative dating: waters without tritium predate 1950. On December 1965 the first depth profile of tritium is realized at meromictic Pavin. Surface waters from 0 to 50 m are rich in tritium (180–220 Tritium units, TU) while bottom waters have much less (<20 TU), highlighting the great contrast of their residence time: bottom waters are at least aged 12 years, according to authors. This profile is confirmed by the Thonon team (Crouzet et al. 1969; Meybeck et al. 1975) but the very last 20 cm layer of water, sampled with a special Jenkins-Mortimer corer, shows an increase of tritium, suggesting the possible and very limited input of more recent waters at the bottom. The renewal of the monimolimnion is complex and may include hydrothermal inputs (Krishnaswami et al. 1971; Martin 1985; Viollier et al. 1997; Aeschbach-Hertig et al. 2002). The last hydro-geochemical model is considering the input of 1.6 L/s of highly mineralized water (Assayag et al. 2008; Jezequel et al. 2010b) responsible for the peculiar ionic chemistry of deep waters found in the late 1960s (Pelletier 1968; Meybeck et al. 1975), unique in French lakes (Meybeck 1995a).

In 1970, a 20 cm Pavin sediment core and a Lake Geneva core, taken by the ENS team, is shipped to India at TIFR to

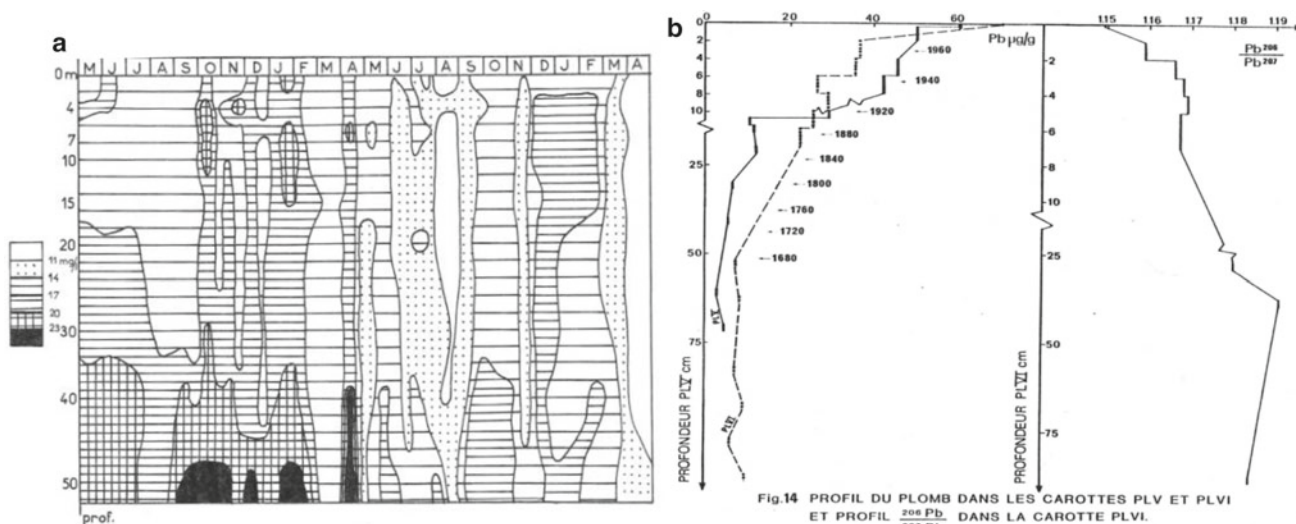


Fig. 1.7 Spatio-temporal complexity at Pavin. (a) Time- depth profile of dissolved silica in Pavin mixolimnion (0–50 m) from May 1973 to April 1975 (Restituto and Lair 1975–1976, Ann. Stat. biol. Besse-en-

Chandesse.) (b) Profiles of total lead content ($\mu\text{g/g}$) and lead 206/lead 207 isotopic ratio in Pavin deep sediments (Elbaz-Poulitchet, 1982)

measure and compare lead-210 and cesium-137. This results in a new method to date recent sediments widely used today (Krishnaswami et al. 1971). Pavin is essentially fed by rain and groundwater inputs and biogenic diatomite sediment is presently forming (Gasse 1969) as in Lake Myvatn in Iceland (Kristmannsdottir and Armansson 2004). The silica content in sediments is close to world records with maximum SiO_2 up to 90 % of organic-free material – while Al and Ti, mostly brought to the lake as atmospheric dust, are very low, (Meybeck et al. 1975; Meybeck 1995a), confirming the original findings of Delbecque (1898). As such it is an excellent site for the study of the formation of diatomite, an economic material. This lake system is also very well suited to study the silica cycle and to test the silicium –32 dating, a natural cosmogenic isotope, now used to date Himalayan glaciers (Nijampurkar et al. 1983; Martin et al. 1992). The ENS team also complements the geochemical profiles (e.g. 55, 60, 65, 70, 90 m) with new redox couples as manganese and arsenic (Figuères 1978; Seyler and Martin 1989) and the mercury profile is studied by ocean geochemists (Cossa et al. 1994). These profiles reveal the complex structure of the mesolimnion, the transition layer where each couple is reduced at a different depth (Martin 1985; Viollier et al. 1995; Olive and Boulègue 2004; Chaps. 10, 11, and 12).

Such studies also show that Pavin, as many other maar-lakes, is an exceptional giant rain and dust collector with very limited runoff and river inputs, in comparison to all other lake types (Martin 1985; Meybeck 1995a).

The fine laminated sediments archive the evolution of Pavin area climate (Stebich et al. 2005; Schettler et al. 2007; Chapron et al. 2010, 2012; Chassiot et al. 2016; Chaps. 22 and 23). They also register the past atmospheric pollution, as

for plutonium and lead: Catherine Jeandel (1981) finds ultra-trace of plutonium contamination, originating from far-away nuclear industry sources and Françoise Elbaz-Poulitchet (1982 and in Martin 1985) realizes the first lake profile of lead isotopes in France, showing a two-steps increase of atmospheric Pb from different pollution sources: the first one in the nineteenth century, due to far away industrial sources emissions, and the second in the 1960s due to leaded gasoline, as cars are now frequent at Pavin (Fig. 1.7b).

After 1986 another page of research is opened at Pavin when water chemists from the IPG-Paris, lead by Gil Michard and Gérard Sarazin, begin a long-term study of Pavin, which is still in progress (Michard et al. 1994; Viollier et al. 1995, 1997; Assayag et al. 2008). They are specialized in redox couples analysis and are amazed to find such an exceptional natural laboratory. Their multiple results over the last 25 years are synthesized in this volume (Chaps. 10, 11 and 12). Meanwhile Clermont scientists continue to innovate at Pavin, 100 years after Berthoule, Delebecque and Bruyant: they are now developing new tools in microbiological analysis of the anoxic monimolimnion (Carrias et al. 1996, 2001; Colombet et al. 2006). Their work is revealing a new world, the Archaea, largely unknown so far (Lehours et al. 2005, 2007). Pavin monimolimnion waters, iron-rich and devoided of oxygen and rich in mantle gases (Aeschbach-Hertig et al. 1999), possibly for a long period, are holding communities that are similar to those of past geological time, billions years ago (Lehours et al. 2010; Fonty et al. 2010; Chaps. 14–20).

While this second golden age of Pavin research, started 30 years ago, is developing, another issue suddenly emerged in August 1986, triggered by the Lake Nyos catastrophe in

Cameroon, where a limnic explosion caused extreme Human damages in few hours. Reactions in the scientific community are rapid at Pavin. Let us first consider the evidence of maar-lakes degassing before exposing the degassing controversy at Pavin.

1.6 Maar Lakes Degassing Evidence in Cameroun and Italy

The explosion of Lake Nyos triggers specific research, first at Nyos then on other meromictic maar-lakes in Italy, Germany, South America and in Pavin, leading progressively to a new vision of the long-term functioning of these rare systems. Several Italian teams of volcanologists and limnologists find that in some maar-lakes past degassing activity, 100–1000 years ago, have been previously observed and reported in historical archives, particularly in the Monticchio Lakes and in the Albano Lake- all meromictic maar-lakes.

1.6.1 Nyos (21 August 1986) and Monoun (15 August 1984) Degassing Events and Their Effects on Populations

The Nyos event occurs on August 21, 1986 in Cameroon. In one night at least 1700 people living in valley villages downstream of the maar-lake (1.58 km², 208 m deep) were suddenly killed along with 3000–6000 cows (Le Guern and Sigvaldasson 1989; Sigvaldasson 1989). Lake waters degassed violently and emitted CO₂ escaped the crater rim and went down the thalweg over more than 20 km in distance, with an estimated velocity of 70 km/h. Eyewitnesses who were fortunate enough to survive the disaster gave a detailed account (Kling et al. 1987; Le Guern et al. 1992).

The Nyos event began the day before with minor upwelling of hot water. On August 21 a small explosion occurred in Lake Nyos followed in the evening by an intermittent jet of water topped by a white plume. At 10 p.m. a major detonation – a series of rumbling or bubbling sounds lasting 15–20 s for other witnesses – occurred in the lake. One observer walked to the crater rim and saw a white cloud or mist rise from the lake then a large water surge and soon after carbon dioxide invaded the low lying valleys. Although people smelled the odour of rotten eggs or gunpowder, they lost consciousness owing to the lack of oxygen in the dense, ground-hugging cloud of CO₂ mixed with water vapour and droplets, which smelled bitter and acidic. Other animals, birds and insects also died in the Nyos eruption. Vegetation was mechanically damaged but no thermal or chemical damage could be identified with certainty. In addition, the surface of the lake turned reddish brown just after the event owing to the oxidation of dissolved iron mixed to the surface from depth. International teams from USA, France, Italy, Japan

and Cameroon converged within few days to Nyos. The mechanism of the event remained disputed for some time. At the international conference on Nyos held in Yaoundé in 1989 (Le Guern and Sigvaldasson 1989) two hypotheses were presented: (i) the volcanic hypothesis, in which a magmatic eruption occurred through the lake (Tazieff 1987, 1989; Tazieff et al. 1987) and (ii) the limnic hypothesis, where gas was stored in the lake prior to the event and released during a lake overturn or mixing of surface and bottom waters (Kling et al. 1987, 1989). Scientists advancing the volcanic hypothesis cited as evidence, the violence and localized nature of the process, the color of the lake and the smell of the gas. However, surveys of the lake and surroundings failed to discover fresh volcanic rock, heat inputs to the lake, volcanic vents. Whether these gas eruptions were volcanic in nature, and therefore impossible to stop, or whether they were limnological in nature, and therefore possible to identify and mitigate through gas removal, had direct political and socioeconomic consequences (Le Guern et al. 1992; Zhang and Kling 2006).

The medical symptoms on the Nyos victims and survivors have been analyzed by a specialized team (Baxter et al. 1989). Their study, focused on 845 hospitalized survivors, out of the 5000 total survivors, recorded: coughing (31 %), headache (26 %), skin lesions resembling burns (19 %), fever (12 %), weakness/malaise (11 %), limb weakness (6 %), severe eye symptoms, vomiting, diarrhea, dyspnoea (5 % each). Many of them had a sudden loss of consciousness with coma lasting few hours, followed by rapid recovery that could be related to anesthetic concentration of CO₂ mixed with air. No persistent respiratory disability was noted in survivors, implying low concentrations of SO₂ or H₂S. The most common abnormalities were erythema, big skin bullae, more than 5 cm, and other skin changes resembling burns, often developed 2 or 3 days after the degassing. The skin lesions were most often present on the face and many over the zygomatic region, in other cases on the leg, the abdomen or back. Only five patients – out of 161 – attributed their skin lesions to burns. Neurological damages could not be estimated.

The Monoun event, also in Cameroon, which occurred 2 years before, in 1984, at the nearby Monoun Lake (0.53 km², 96 m) and claimed 37 victims, was only described by scientists after the Nyos explosion. Haraldur Sigurdsson, a volcanologist from the University of Rhode Island, made a post-event investigation few months only after the event, performed an array of analyses and found no signs of a volcanic eruption. He detected “*a hitherto unknown natural hazard*” that could wipe out entire towns, and in 1986, a few months before the Nyos disaster, he submitted his study to *Science*, the prominent scientific journal, which rejected the paper as far-fetched (Krajick 2003). Sigurdsson paper was eventually accepted by the Journal of Volcanic and Geothermal Research and therefore published a year after the Nyos event (Sigurdsson et al. 1987) so that no early warning was given

to the scientific community about such type of lakes or to local Cameroon authorities. This rejection by the community is exemplary of the difficulties scientists have to conceive such events.

Lake Monoun was then surveyed by scientists from several countries and one of them, Kusakabe, said: “*if the [surface] waters were stirred up by only three feet, the water could start bubbling and trigger an explosion*”; his colleague, Bill Evans, advised caution: “*Let’s not go splashing around too much out there*” (Krajick 2003). This corresponds to a near-saturation state (97%), very sensitive to any perturbation, as throwing a stone. Monoun rescuers, who came few hours after the catastrophic event, observed “*a misty cloud which did not disperse until three to four hours later*” (Baxter et al. 1989). The Monoun eruption also occurred at night and the gas cloud filled a low-lying area near the lake (Sigurdsson et al. 1987). Travelers on a nearby road were killed as they entered the area, as were people who left higher ground to help those who had fallen in the valley. In the lake the water fountains reached 5 m high.

It is now acknowledged that both Monoun and Nyos violently degassed CO₂ from deep stagnant waters, a process termed “*limnic eruption*” (Sabroux 2007). Pre and post eruptions investigations reported that both Cameroun lakes were meromictic (Kling 1987), anoxic and rich in CO₂, originating from mantle degassing (Sigurdsson et al. 1987; Zhang and Kling 2006). Scientists now agree that the event was limnological in nature and represents CO₂-driven water eruptions owing to the rapid exsolution of CO₂ gas bubbles from dissolved CO₂ stored in the lakes. The degassing process may be triggered by an earthquake, a rockfall, a slump of sediments deposited on steep slopes, a spillover of lake water releasing the gas pressure in sediments, and/or their combination.

1.6.2 Ancient Degassing Events in Italian Maar-Lakes, Albano and Monticchio

In the decades following 1986, other maar-lakes in Italy are also checked for risk analysis at Monticchio Lakes and at Albano Lake (Chiodini et al. 1997; Caracausi et al. 2009; Funicello et al. 2002, 2003, 2010; De Benedetti et al. 2008). During their investigations the Italian scientists are discovering evidence of ancient degassing events from Antiquity period to the early XIXth, which complement the descriptions of Monoun and Nyos events. Meanwhile German scientists do not take reference to past degassing events or legends (Scharf and Björk 1992). This attitude towards lake history may explain the different opinions on degassing risks: Italian volcanologists and geochemists are very cautious and highlight present risks while the risk issue is so far not raised at Eifel.

1.6.2.1 The Albano Catastrophic Degassing and Spillover Event in Latium (398 BC)

Many teams have extensively studied Albano maar-lake in recent years within a major Risk assessment programme. These investigations (Funicello et al. 2002, 2003, 2010; De Benedetti et al. 2008; Cabassi et al. 2013) shed a light on another type of catastrophic degassing that occurred some 2400 years before. Italian scientists compared their current findings with historical sources from Latin authors who have reported a very famous story of a sudden and catastrophic increase of Albano Lake level, that spilled over its banks and forced Romans to dig out a tunnel to prevent future inundations. This catastrophic event, viewed by Archaic Rome contemporary historians as a legendary event, is now regarded as a major spillover due to degassing by Italian volcanologists, as Franco Barberi, a prominent member of this community. The Albano spillover is probably the earliest and one of the most spectacular lake degassing report.

Funicello’s prime source is Dionysius from Halicarnassus (first century BC), who wrote the early Rome history in 20 books (*Antiquitates Romanae*); he is in turn quoted by Livy, Titus Livius (59 BC–17 AD) (*Historiae Romanae*), then by Plutarch (46–125 AD) (*Parallel Lives*, Themistocles–Camillus). The event can be summed up as such:

The event occurred between July 23 and August 24, 398 BC. During that period the water level rose at eye sight. But no precursor of the event such as neither water boiling nor climatic cause could be involved. The water reached the lower part of the crater rim which suddenly collapsed under the weight then an enormous mass of water flooded and destroyed the surrounding landscape. The Romans, who were at that time besieging the Etruscans at Veius, were scared by the prodigy, which occurred very close to Rome, and sent delegates to the Pythia of Delphi [in Greece] who told them that “Poseidon [the Etruscans protector] was angered against Romans” and required to let the lake waters join freely the sea.

This story is not fabricated; it has no fantastical tone and is well dated, detailed and considered as a *prodigium* of nature, with very limited intervention of supernatural forces. The surge is gradual yet however rapid, about 70 m in 1 month, i.e. it could have reached a velocity of several meters per day, a rise visible to the naked eye! There is no mention here of an explosive event, like in Nyos. The surge could not be stopped and probably destroyed any existing human settlements within the crater, one of the possible origins for the *Sunken city* legends for lakes (See 3.3.1). The consequences of the spillover are catastrophic and unexpected.

Italian scientists base their belief of the historical sources on their study of stratigraphic sections on the Ciampino plain, on the north side of the lake. Together with archaeological excavations, they revealed repeated *lahars*, i.e. volcanic mudflows, occurring along the north-western slope of the maar, between 3000 BP and 2400 BP, filling in the paleo-rainage network, blanketing the previous ground surface and

forming a vast plain. Paleohydraulic analyses on fluvial and lahar deposits indicate that water flows that carried these lahars were in excess of hundreds of cubic meters per second, i.e. more than three orders of magnitude higher than normal streamflows on the lake rims. Lahars, now up to 20 m thick in thalwegs, were known by geologists as the Tavolato Conglomerate but until recently, they had no satisfactory explanation for their formation. The catastrophic inundations would be linked to overflows of the lake from its lowest rim, as in the historical sources. A lake rollover phenomenon, caused by the injection through the lake bottom of hot fluids, from mantle origin, in the lake bottom rich in volcanic gases, is invoked as the prime cause of this event. According to the paleomorphology of Albano shoreline and to the sublacustrine archeological findings, such events have occurred previously several times during the Holocene. Paleo shores at -20 m and -64 m of present shoreline have been dated 7.1 and 4.1 ka, an indication of very different lake levels in those periods (Anzidei et al. 2008). Over the last 250 years multiple evidences of degassing have been described around lake Albano and the Alban Hills volcanic district (Funicello et al 2002).

1.6.2.2 Monticchio Lakes (Southern Italy) and Their Pioneer Degassing Studies, 1777–1838

The first scientific study on Monticchio Lakes is realized by Domenico Tata, a Naples ecclesiastic, a noted mineralogist and volcanologist of the late eighteenth century. He reports his work in a remarkable *Lettera sul Monte Vulture* (Tata 1778), dedicated to his friend William Hamilton, representing the British king at the Napoli court, and one of the earliest UK volcanologist, famous for his observations of Etna and Vesuvius eruptions. When Tata visits Vulture in 1777, he has already heard about the marvelous lakes of Monticchio since he comes fully equipped with a sounding line to measure their depths, a water sampling bottle and with instruments to precisely position the latitude and longitude of the lakes. Domenico Tata has a more scientific objective than the one of Chevalier at Pavin, few years before (See 1.4.1) and he has already faced active volcanism and its magmatic degassing processes around Naples.

Tata focus is on Lago Piccolo. There, he does not observe any water movements in the lake and makes some deep water sampling in the middle of the lake but, as he tries to remove its cork with great difficulty, a sudden water and gas fountain rises one meter high above the bottle. It is probably one of the first sampling of deep anoxic waters with dissolved gases. At Monoun the same phenomenon will be reported by Sigurdsson et al. (1987).

After Tata, Monticchio Lakes were studied by two geologists, Giambattista Brocchi (1772–1826) and Riccioli, who analyze the gases emitted by the lakes and identify carbonic

gas and hydrogen sulfide (Ciarallo and Capaldo 1995), possibly the first measurement of this kind, 150 years before the “discovery” of CO₂ degassing at Nyos. Some years later, Michele Tenore, a prominent botanist and the founder and director of Napoli Royal Botanical Garden, arrives to Monticchio with his assistant, Giovanni Gussone. They are mandated by the Naples Academia of Science to explore Mount Vulture area, a *terra incognita* so far. Their reports (Gussone and Tenore 1834; Tenore and Gussone 1838) have enormous scientific recognition. At the Lago Piccolo Tenore finds what he was expecting: a “permanent water fountain” coming out at the lake surface that agitates and mixes with the whole lake. According to Tenore and Gussone, this phenomenon has been going on since the early 1800s. During peak degassing the maximum height of the fountain was estimated to be around 5 m in November 1820 according to Father Paolino Tortonella, probably from the nearby San Michele Abbey (see Chap. 3), and other local witnesses.

In 1851, two Naples geologists make an in-depth study of Mount Vulture region (Palmieri and Scacchi, 1852). They, too, are expecting to see the marvelous water fountain; however they only find some bubbles at a given spot in the lake, where water is 11.4 m deep. Palmieri doubts that the fountain could have been so high in the past but accepts the phenomenon: he imagines that deposited rocks and sediments on the lake bottom probably blocked gases where the spring is located, until the high pressure released them.

A preliminary chronology of Monticchio *misbehaviour* events, as abnormal lake events have been termed at Nyos by Shanklin (1989, 2007), can be proposed as such, taking into account the contemporary analyses of Ciarallo and Capaldo (1995), Chiodini et al. (1997), Caracausi et al. (2009):

1770s: Lago Piccolo is meromictic; its bottom waters are rich in gases, including H₂S

1800, June 1: *Water column* of 6 m high in Lago Grande

1810, May 31: Lago Grande *overflows* with 5.5 m *water column*, then general lake agitation (June 1–23); *strong roar* on July 31, perceived by local people

1810, July 31: an *intense roar* was also heard; the column of water reached a height of about 3 m

1820: *water column* 5 m high in Lago Piccolo, lake agitation with *fish kill*

1830s (?): analysis of CO₂ and H₂S by Brocchi

1838: a *permanent boiling and water agitation* is still seen at a given spot in Lago Piccolo

1851: only few bubbles remain emitted in Lago Piccolo

Tata, Brocchi, Tenore and Palmieri are prominent scientists of their time with experience of volcanic degassing in Latium, Campania and Sicilia. All are also aware about Averno, the famous lake without birds in the Campi Flegrei volcanic district, near Naples, renowned since the Antiquity

Table 1.2 Sensory descriptors of maar-lake degassing events and their impacts on populations

A. Degassing evidence in the lake and its close surroundings (lake examples)
(i) <i>Lake surface boiling</i> (Monoun, 1984),
(ii) <i>Lake storm</i> (at Nyos, 1986; Monticchio, 1810; Monoun 1984): the lake surface is very agitated with spurts, occasional jets. At Nyos, the erosion marks on South lake shore suggest a water jet up to 50 m–80 m,
(iii) <i>Reddish water colour and fluffy aspect</i> (Nyos, 1986): due to the precipitation of ferrous iron into ferric hydroxide or ferric carbonate,
(iv) <i>Gun powder and rotten egg smell</i> (Nyos, 1986): the ambient air has a characteristic sulfur smell,
(v) <i>Detonation, thunder, roars, hissing, rumbling sounds</i> (Nyos, 1986; Monticchio, 1810), reported before, during or after the main event. According to Le Guern and Chevrier, 48 h after the main event, three violent detonations are heard within 5mn (Tazieff et al. 1987); other Cameroon witnesses recall gun shots. Big roars are heard at Monticchio,
(vi) <i>Lightning and/or luminescence</i> (Nyos, 1986; Monticchio, 1810): one detonation at Nyos is accompanied with brief lightning with a powerfull light jet, as a flash light without centre (Tazieff et al. 1987),
(vii) <i>Degraded lake water taste</i> (Monticchio, 1770s): deep water tasted by Tata is “awful and one cannot bear it”.
(viii) <i>Corrosive lake water</i> (Monticchio, 1770s): after drinking the tongue turns black and the water causes skin damages, “as for vitriol” (sulfuric acid)
(ix) <i>Reduced lake buoyancy</i> (Nyos, 1986), since the water density can be as low as 0.1 kg/L (Sabroux 2007),
(x) <i>Misty cloud</i> (Monoun, 1984), or <i>white plume</i> (Nyos, 1986) observed above the lake surface, probably CO ₂ clouds,
(xi) <i>Permanent water fountains</i> generated from deep waters (Monticchio, 1800s; Monoun, 1984) [Deep water sampled in Monticchio Lago Grande by Tata are degassing when brought to the surface producing a kind of permanent, 1 m high jet. A similar effect is noted at Monoun by Sigurdsson],
(xii) <i>Lake spillovers</i> (Albano, 398 BC): during such type of paroxistic degassing events the lake. Level can raise at a rate exceeding 1 m/day and overflow the lower part of maar rims.
(xiii) <i>Lake fish kills and absence of fishes</i> (Nyos, 1986; Monticchio, 1810): due to the mixing with anoxic waters, also containing toxic gas or substances, fish kills can be observed. Lake Nyos was devoid of fishes before the catastrophic event (Sabroux, 2007)
B. Spatial extend and temporality of degassing events.
(xiii) <i>Spillover lahars</i> (Albano, 398 BC): these mud-flows deposited in downstream thalwegs may exceed 10 km long, they are eventually transformed into conglomerates,
(xiv) <i>Degassing temporal variability</i> . Degassing may take various forms intensity and temporality: permanent light bubbling, permanent boiling at specific position in the lake; degassing and spillover episodes (day to months, Monticchio, Albano), sudden violent rollover, explosive events (Nyos, Monoun),
(xv) <i>Degassing period duration</i> (Monticchio, Albano): temporal variability of degassing processes can be studied at different scales: subdecadal (Albano, 1997–2008), multi-decadal (Monticchio, 1770–1850), multi-millenary (Albano, Holocene and 3000 BP–2400 BP).
C. Damages to human populations and to the environment
(xvi) <i>Asphyxia and lethal CO₂ intoxication</i> (Nyos, 1986, Monoun, 1984): CO ₂ degassing caused massive animal and human killing, including birds and insects in downstream valleys,
(xvii) <i>Health damage</i> to survivors in downstream valleys (Nyos, 1986): skin damages with bullae developed few days after the event, mental shock and temporarily loss of consciousness, sight and speaking capacity,
(xviii) <i>Mechanical damages to thalweg vegetation</i> (Nyos, 1986), due to the power of the CO ₂ flow.

period for its release of deleterious gases and its absence of birds (See also Chap. 3) and they do not seem so surprised about this very unusual lake behavior at Monticchio. Their descriptions are in many ways similar to those made 160 years later at Nyos, yet the Monticchio degassing is much less violent, it lasts for several decades and no Human victims are reported during that period. Today there is no sign of degassing in neither of both lakes. The degassing evidence at Monticchio has been gradually forgotten by the scientific community until the late 1990s, possibly because it was not catastrophic enough. Any records of Monticchio “misbehaviors” are still not found today in the local touristic information. However older dramatic events may persist in local memories through the exceptional millenary religious history of this remote and isolated place (See Sects. 3.5.3 and 3.7).

1.7 Sensory Grid of Degassing in Maar-Lakes

The Nyos event characteristics from *witness accounts* have been published by many scientists (Tazieff et al. 1987; Sigvaldason 1989; Le Guern et al. 1992; Zhang and Kling 2006), some of them reported at the Besse meeting. Other types of degassing symptoms and intensity have been described at Monoun, Monticchio and Albano. These qualitative data, generated or collected by scientists, have mobilized all senses: sight, vision, smell, taste, touch and hearing. They refer to the lake itself, its waters, its ambient air, its fauna, its surroundings (spillovers), and its impacts on populations, animals and crops, particularly in valleys downstream of the lake. These degassing descriptors, synthesized on Table 1.2, do not require an advanced scientific

knowledge or training and can just be observed by riparian populations and lay people. They will be the basis for the re-interpretation of Pavin historical sources (Chap. 2) and of its legends and beliefs (Chap. 3).

1.8 Pavin Degassing Controversy (1986–2016)

The Nyos explosion in 1986 takes all volcanologists and limnologists by surprise, excepted Sigurdsson, and shed a sudden light on meromictic maar- lakes accumulating dissolved gases in deep waters. Lake degassing events, violent or not, are at that time undescribed by the modern scientific community and are not covered in major limnology textbooks (Hutchinson 1957; Wetzel 1975), or in volcanology and volcanic hazards textbooks and guidebooks (Kraft 1974; Hewitt and Burton 1971; Blong 1984). It must be recognized that maar-lakes are quite uncommon: their proportion is of the order of one per 1000 to one per 10,000 of all lakes (Meybeck 1995a).

A few days after the Nyos event (late August 1986), Haroun Tazieff (1914–1998), the famous French volcanologist and former head of the new French Natural Hazard Commissariat, questions the possibility of a degassing risk at Pavin (See quotation at the beginning of this chapter). He sends his team at Nyos at once and rings the alarm bell in the national and Auvergne media, demanding immediate research on this new type of hazard. Few days after Tazieff's call for immediate action, Renaud Vié-Lesage, the Natural Hazard commissioner, also an Earth scientist, asks Clermont volcanologists, Kornprobst and Camus, to perform a preliminary inventory of a potential degassing risk in Auvergne: the answer arrives within two months and the focus is set on Pavin. Meanwhile, from September 1986 to January 1987, local and national French media follow the ongoing observations made at Nyos by the French team and question these local volcanologists about explosion risks at Pavin (La Montagne 1986a, b; 1987a, b, c).

Vié Le Sage asks for an immediate study of Pavin in November 1986, Guy Camus assembles in summer 1987 a multidisciplinary team – volcanologists, water chemists, isotope geochemists – which makes in-depth geochemical inventories and innovative dissolved CO₂ measurements, with special samplers to preserve Pavin deep waters from degassing. Preliminary results are as soon communicated to the local press which reports in June 1987: “*The CO₂ contents between 80 and 90 m deep are minimal and of the same order than those found at the surface, tells us Renaud Vié Le Sage, professor at Paris 7 University, in charge of Natural Hazards*” (La Montagne 1987c). The full investigation will take much longer to be published and will be much more balanced: “*Pavin does not present any limnic hazard as it*

receives a little amount of endogenous CO₂ [from mantle degassing] and that most CO₂ originates from the dismutation of the organic matter produced in situ” (Camus et al. 1993). Pavin neighbours are reassured, but not for too long.

In 2005–2006, the question of Pavin degassing and risk management is revisited by Pierre Lavina, a volcanologist, and Thierry Del Rosso, an hydrogeologist, while they realize new field observations for an updating of the local geological map of Pavin area and estimate nutrient inputs to Pavin by groundwaters. They found evidence of CO₂ degassing spots in many places in the area (Lavina and Del Rosso 2009). This confirms both the observations on CO₂ fluctuations made before at Creux de Soucy (Martel 1892, 1894, see Sect. 1.4.3.3) and the common knowledge of degassing spots in the area by local Besse people (Boyer-Vidal 1888), an evidence forgotten in the 1990s and recently confirmed (Gal and Gadal 2011). They also mapped for the first time a 9 km long mudflow deposit in Couze Pavin thalweg, downstream of the lake, which they attribute to a violent lake spill-over around 1300 AD (Del Rosso-d'Hers, 2010) (Schematically presented on Fig. 1.2c). Their findings reactivate the risk assessment at Pavin: local authorities suppress the release of this information while installing a set of security measures, landslides surveys within the crater, stabilization of crater slopes to prevent rockfalls, laser-telemetry survey of crater etc. But the findings are eventually leaked to the local press, reactivating the risk concern at Pavin.

In June 2009 Pavin geochemists, limnologists and microbiologists organize a meeting in the town of Besse to discuss Pavin and other meromictic lakes (Jezequiel, Amblard and Fonty, 2010). It is attended by 120 scientists during 5 days, including by members of the Nyos French team, François Le Guern (1942–2011), Tazieff's closest collaborator, and Jean-Christophe Sabroux (Sabroux 2009), and by Michel Halbwachs, the initiator of current Nyos degassing by pipe. Leguern and Sabroux had come at a few days only after the main event, at a time when Lake Nyos was still exhibiting some degassing features and report at the Besse meeting its unusual features with witness accounts from survivors. Lavina presents the mudflow deposits he found in the Couze Pavin thalweg and Del Rosso also shares the past “Pavin stories” with this scientific audience and links some legends to past catastrophic events in Pavin area, either of volcanic origin or of limnic origin, a thesis he had just exposed in the local press (Del Rosso 2009a, b) but which is strongly challenged by the rest of scientific community. Pavin legends are actually quite complex (See Chap. 3).

The Besse workshop, published in 2010, includes papers on lake sedimentary archives (Chapron et al. 2010), hydrological balance (Jezequiel et al. 2010a), carbon cycle and current risk of gaseous outburst (Jezequiel et al. 2010b) microbial communities (Fonty et al. 2010), forest history around Pavin (Lathuillière 2010) and on Pavin patrimonial value and preliminary history

(Meybeck 2010). Few other meromictic lakes were discussed at Besse; however none were maar-lakes with the exception of Lake Nyos. In their analysis of Pavin carbon cycle, Jezequel et al. state that “*no spontaneous gaseous eruption can take place... the present situation is stable and only important landslides, disturbing bottom sediments, could generate a partial degassing*”. After this meeting our preliminary analysis of Pavin history (Meybeck 2010) reveals a long history of possible “misbehaviour” events at Pavin.

Anomalies found in Pavin sediment records led to further investigations and to the evidence of two major catastrophic events (Chapron et al. 2010, 2012; Chap. 23): (i) around 600 AD, corresponding to a large subaquatic slide, a spillover of the lake with a drop of lake level by 13 m, due to the sill erosion, (ii) a second subaquatic slide occurred around AD 1300 in Lake Pavin and several other lakes in the area (Guéry, Chauvet, Moncineyre, see their position in Fig. 1.3a) supporting a regional earthquake triggering (Chassiot et al. 2016). According to Chapron et al. (2012) subaquatic slides in Pavin were “*large enough to be associated with violent waves in the lake. 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 spillover of a debris flow downstream in the Couze Pavin valley. Such violent waves may also result from a limnic eruption. 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 m³. 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)*”. The 600 AD and 1300 AD events can be considered as the first paleolimnological evidence of past Pavin degassing and/or catastrophic events, recorded in sediment archives. The long mudflow deposit found in the Couze Pavin thalweg could originate from this Pavin spillover (Lavina and Del Rosso 2009).

1.9 Conclusions

Pavin has a long and rich common history with lake scientists, placing it on a top level of the development of limnology. Scientists have been attracted there since 1770, when an expedition organized by one king engineer succeeded to measure its depth, a major challenge at this time. However during the next 90 years, naturalists were lacking sampling apparatus and other means of observation, faced lake access difficulties, had no boat for their investigation and they mainly observed Pavin from its rim. They probably received limited support by local population who feared the lake to be bottomless and fishless (See the next two chapters). This ended with the construction of a pathway to the lake outlet, the construction of the first boat (1847) then the successful

fish introduction in 1859, all by Lecoq, the prominent naturalist of Auvergne.

From 1880 to 1914 scientists from Clermont University, backed by Berthoulet, the Besse mayor, are at the forefront of French limnology. They establish the limnological station of Besse, the first of its kind in France. Charles Bruyant models the Station after the oceanographic stations and presents it to an international audience in Besse in 1908, but its development is limited after the death of Bruyant in World War I.

In June 1892 Pavin is studied by André Delebecque, the most inventive French limnologist, who develops comparative limnology on more than 300 French lakes for all geographical, physical and chemical aspects. He highlights many of the exceptional Pavin characteristics but does not notice any peculiarity in bottom waters. Meanwhile, his friend Edouard-Alfred Martel, the founder of cave science, explores the tiny Creux de Soucy cave and its unique lake.

In the 1950s, Luc Olivier, a Clermont hydrobiologist, measures anomalous O₂ profiles for the first time at Pavin and, in 1963, Jean Pelletier confirms the permanent absence of oxygen in deep waters, the meromixis, and the inverted thermal gradient in bottom waters. UNESCO selects Pavin among the world's remarkable lakes and OECD, includes it in its network of alpine oligotrophic lakes set up by Richard Vollenweider.

Since the 1970s Pavin attracts scientists, for its unique morphological, hydrological and geochemical characteristics. They come with up-to-date material, test new theories and develop innovative approaches, benefit from the cumulated scientific results and have excellent local working conditions. Today several dozens of scientists from half a dozen countries have chosen Pavin as a natural laboratory, particularly for its chemocline and its microbial diversity, all of them fully convinced about its uniqueness in their own field (Jezequel et al. 2010a; Meybeck 2010).

The Nyos event in 1986, which took the whole volcanologists and limnologists' communities by surprise, has not been the first case of lake degassing described by scientists. Actually, prior degassing observations had been already recorded at the Monticchio Lakes in Italy, 150 years before, by prominent scientists of their time. Italian scientists are now acknowledging another catastrophic event that occurred at Lake Albano near Rome in 398 BC, reported by Greek and Latin historians, as a major spillover due to a degassing process. Both degassing evidences were then forgotten until Italian volcanologists and geochemists from INVG and Roma Tre university reconsidered them as a potential degassing risk (Chiodini et al. 1997; Funicello et al. 2002, 2003; Caracausi et al. 2009) and took these historical descriptions into consideration (Caracausi et al. 2009; De Benedetti et al. 2008; Funicello et al. 2010).

A first outlook on Nyos, Monticchio and Albano lakes shows that lake degassing may take multiple forms and

intensities. Gentle and harmless limited degassing may only be reported by some curious and/or educated persons, particularly when the lake is not found in its normal state. More violent and/or dangerous degassing events, the *misbehavior* (Shanklin 2007), are reported provided they are witnessed by someone, or evidenced by their damages on populations, animals and crops, near the lake or far away in the valley. Degassing events and their effects on the environment and populations are described by witnesses by a set of sensory criteria (Table 1.2). This set shows a wide variety of indicators, depending on the degassing intensity and types, on mobilized senses, on the position of witnesses.

The most catastrophic degassing events, as the Albano overspill (398BC) may be recorded, like other types of natural hazards, by local populations for hundred of years or more. They can also be transformed into myths, legends, fantastic stories and local fears that may leave traces in local iconography and toponymy, as discussed in Chaps. 2 and 3. In their conclusions on risk assessment in the Colli Albani volcano where Lake Albano is located, the Italian volcanologists from Roma Tre state: “*The acquisition and verification of archaeological and historical data are essential to support hazard analysis*” (Funicello et al. 2010). Meanwhile German scientists working on Eifel maars do not take reference to past degassing events or legends (Scharf and Björk 1992). Today maar-lake degassing is still poorly covered in specialized textbooks and Monticchio and Albano events are not yet reported in them (Smith 2003; Rouwet et al 2015).

At Pavin the degassing issue has been quickly put on the scientific agenda in 1986 and remained a matter of discussion since then. The survey made for the authorities reported that degassing risk was non-existent in normal conditions (Camus et al. 1993). This opinion was confirmed during the 2009 meeting at Besse on Pavin. However, the preliminary historical analysis of Pavin (Meybeck 2010) and the new palaeolimnological findings at Pavin (Chapron et al. 2012; Chassiot et al. 2016) suggest that major degassing events have actually taken place in the past, before the start of regular limnological surveys at Pavin in the 1880s (a possible misbehavior event reported for summer 1936 has not been considered by the scientific community, see the next chapter).

The historical, iconographic and folkloric analyses, realized by us between 2010 and 2016, while paleolimnologists were finding evidence of degassing at Pavin, reveal a very rich and largely ignored corpus of sources, since Antiquity. This corpus, re-interpreted through the sensory indicators grid of degassing unveils many ignored misbehaviour events of Pavin, some confirming the paleolimnological analysis, other apparently not recorded in sediments, a latent fear of the lake over two millennia and a complex interaction

between local populations and *Lacus Pavens*, i.e. the terrifying lake, as it was actually called since at least 1605. Aside from the complex history of Pavin (Chap. 2), many forgotten or mis-attributed legends and fantastic stories provide new clues of past Pavin misbehavior (Chap. 3).

Aknowledgements of chapters 1, 2, 3 are clustered and presented at the end of chapter 3.

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