Télesphore Sime-Ngando · Pierre Boivin
Emmanuel Chapron · Didier Jézéquel
Michel Meybeck *Editors*

# Lake Pavin

## History, geology, biogeochemistry, and sedimentology of a deep meromictic maar lake

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# Preface

The volcanic mountain Lake Pavin (45°29′41′ N, 002°53′12″E) enjoys an increasing amount of interest both in terms of touristic activities, with more than 200,000 persons attracted each year by the beauty of the site, and in terms of scientific research with hundreds of references published in peer-reviewed international journals. Remarkably studies go back to the eighteenth century (Montlosier 1789, http://www.edition-originale.com/-MONTLOSIER-Essai-sur-la-theorie-des-volcans-d-Auvergne-Clermont-1802.html,35329). These publications resulted from the works of scientists from Europe but also from around the world (USA, China, Japan, etc.), attracted by the geomorphological and biological peculiarities of the deep ($Z_{max} = 92$ m) meromictic Lake Pavin. This maar lake offers a unique environment characterized by (i) a permanently anoxic monimolimnion from about 60 m downwards, (ii) a small surface area (44 ha) about equal to the drainage basin area (50 ha), and (iii) a substantially low human influence with no river inflow.

We propose the first multidisciplinary scientific volume centered on a maar lake (Lake Pavin) but importantly in comparison with other similar temperate lakes. The work groups different chapters in five main parts, reflecting the scientific research and disciplines conducted so far in Lake Pavin: (i) general limnology, history, and comparative legends (Chaps. 1, 2, and 3); (ii) origin, volcanology, and geological environment (Chaps. 4, 5, 6, 7, 8 and 9); (iii) geochemistry and biogeochemical cycles (Chaps. 10, 11 and 12); (iv) biology and microbial ecology (Chaps. 13, 14, 15, 16, 17, 18, 19, 20 and 21); and (v) sedimentology and paleolimnology (Chaps. 22 and 23). The biological part refers to the study of the biology of the lake, including pelagic and benthic communities. However, most of the chapters in this part mainly deal with microbial ecology, which has been extensively studied in Lake Pavin during the past decades. Major methodological, conceptual, and empirical advances in environmental sciences during the past decades indeed are known from the molecular study of uncultured microbes and viruses in natural environments.

Much more than a local interesting study site, we aim to provide an extensive rigorous limnological text centered on Lake Pavin, of value and interest for an international scientific audience. The syntheses of the main characteristics of Lake Pavin are, for the first time, set in a firmer footing comparative approach, encompassing regional, national, European, and international aquatic science contexts. In this book we synthesize heretofore very scattered knowledge on a unique site whose characteristics make it an ideal reference site to examine questions on freshwater lake origin, physics, geochemistry, biogeochemistry, sedimentology, biology, and variability in time and space. The targeted audience is researchers and advanced students, primarily in the fields of limnology, biogeochemistry, and aquatic ecology. Because the book is an outgrowth of an extensive teaching experience of the main authors, it can also serve as a useful reference for aquatic resource scientists, professionals, and engineers.

We thank all the contributing authors and coauthors of the book, some of whom also have reviewed submissions from colleagues. We are particularly indebted to non-anonymous reviewers who work hard for many months and provided invaluable comments. Thanks are owed to A. Cheronet (publishing editor for Environmental Sciences, Springer) and her staff for their precious assistance at different steps of the editing process. Finally, F. Rieu conducted the preliminary bibliographic research on Lake Pavin, on which the contents and organization of the book are based upon.

Aubière, France Télesphore Sime-Ngando

# Contents

## Part I Limnology, History and Comparative Legends

1 **Pavin, the Birthplace of French Limnology (1770–2012), and Its Degassing Controversy (1986–2016)** ........ 3
Michel Meybeck

2 **Pavin, A Rich but Fragmented History (200 AD–2016)** ........ 29
Michel Meybeck

3 **Dragons, Fairies, Miracles and Worship at Pavin and Other European Maar-Lakes** ........ 53
Michel Meybeck

## Part II Origin, Volcanology and Geological Environment

4 **Volcanism of the Monts Dore (French Massif Central)** ........ 83
Alain Gourgaud

5 **The Origin of Lake Pavin: Two Centuries of Controversy** ........ 91
Pierre Boivin and Sylvaine Jouhannel

6 **Characterization of Phreatomagmatic Deposits from the Eruption of the Pavin Maar (France)** ........ 105
Hervé Leyrit, William Zylberman, Pascale Lutz, Alexis Jaillard, and Pierre Lavina

7 **Magmatic Evolution of Pavin's Group of Volcanoes: Petrology, Geochemistry and Modeling of Differentiation Processes. A Preliminary Study** ........ 129
Benoît Villemant, Benoît Caron, Pauline Thierry, and Pierre Boivin

8 **Distribution, Tephrostratigraphy and Chronostratigraphy of the Widespread Eruptive Products of Pavin Volcano** ........ 143
Etienne Juvigné and Didier Miallier

9 **Geology, Geomorphology and Slope Instability of the Maar Lake Pavin (Auvergne, French Massif Central)** ........ 155
Jean-Claude Thouret, Pierre Boivin, Philippe Labazuy, and Alberic Leclerc

## Part III Geochemistry and Biogeochemical Cycles

10 **Lake Pavin Mixing: New Insights from High Resolution Continuous Measurements** ........ 177
Céline Bonhomme, Didier Jézéquel, Michel Poulin, Mohamed Saad, Brigitte Vinçon-Leite, and Bruno Tassin

11 **Carbon Cycle in a Meromictic Crater Lake: Lake Pavin, France** ...................... 185
Didier Jézéquel, G. Michard, E. Viollier, P. Agrinier, P. Albéric, F. Lopes, G. Abril, and L. Bergonzini

12 **The Iron Wheel in Lac Pavin: Interaction with Phosphorus Cycle** ................... 205
Vincent Busigny, Didier Jézéquel, Julie Cosmidis, Eric Viollier, Karim Benzerara, Noah J. Planavsky, Patrick Albéric, Oanez Lebeau, Gérard Sarazin, and Gil Michard

**Part IV Biology and Microbial Ecology**

13 **The Significance of Transparent Exopolymeric Particles (TEP) for Microorganisms in Lake Pavin** ........................................................................ 223
Jean-François Carrias, Christian Amblard, and Télesphore Sime-Ngando

14 **Lake Pavin: A Pioneer Site for Ecological Studies of Freshwater Viruses** ......... 229
Télesphore Sime-Ngando, Yvan Bettarel, Jonathan Colombet, Stéphanie Palesse, Angia Sriram Pradeep Ram, Marie Charpin, and Christian Amblard

15 **Study of Prokaryotes and Viruses in Aquatic Ecosystems by Metagenetic and Metagenomic Approaches** .................................................... 245
Gisèle Bronner, Didier Debroas, François Enault, Mylène Hugoni, Isabelle Jouan-Dufournel, Isabelle Mary, Viviane Ravet, Simon Roux, and Najwa Taïb

16 **Anaerobic Microbial Communities and Processes Involved in the Methane Cycle in Freshwater Lakes-a Focus on Lake Pavin** .................. 255
Anne-Catherine Lehours, Guillaume Borrel, Nicole Morel-Desrosiers, Corinne Bardot, Vincent Grossi, Benoit Keraval, Eléonore Attard, Jean-Pierre Morel, Christian Amblard, and Gerard Fonty

17 **New Insights into the Microbial Contribution to the Chlorine Cycle in Aquatic Ecosystems** .................................................................................. 285
Eric Dugat-Bony, Pierre Peyret, and Corinne Biderre-Petit

18 **The Importance of Phagotrophic Protists in Lake Pavin** .................................... 307
Jean-François Carrias, Christian Amblard, Gilles Bourdier, and Télesphore Sime-Ngando

19 **Diversity and Biogeography of Picoeukaryotes: New Insights into the Rare Biosphere** .......................................................................................... 315
Cécile Lepère, Isabelle Domaizon, and Didier Debroas

20 **Molecular Diversity Studies in Lake Pavin Reveal the Ecological Importance of Parasitic True Fungi in the Plankton** .......................................... 329
Télesphore Sime-Ngando, Mélanie Gerphagnon, Jonathan Colombet, Marlène Jobard, Emilie Lefevre, Sébastien Monchy, Serena Rasconi, Delphine Latour, Jean-François Carrias, and Christian Amblard

21 **History of the Fish Fauna of Lake Pavin: A Population Heavily Influenced by Man?** .................................................................................... 345
François Desmolles

## Part V Sedimentology and Paleolimnology

22 **Lake Pavin Sedimentary Environments** ........ 365
Emmanuel Chapron, Léo Chassiot, Patrick Lajeunesse, Grégoire Ledoux, and Patrick Albéric

23 **Lake Pavin Paleolimnology and Event Stratigraphy** ........ 381
Léo Chassiot, Emmanuel Chapron, Yannick Miras, Markus J. Schwab, Patrick Albéric, Aude Beauger, Anne-Lise Develle, Fabien Arnaud, Patrick Lajeunesse, Renata Zocatelli, Sylvain Bernard, Anne-Catherine Lehours, and Didier Jézéquel

**Glossary** ........ 407

**Index** ........ 419

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# Part I

# Limnology, History and Comparative Legends

Michel Meybeck

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

# 1

Michel Meybeck

**Abstract**

Lake Pavin is located in the Auvergne Mountains, central France, at 1300 m a.s.l. This small lake (0.44 km$^2$), 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

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and a long Human history including a rich corpus of legends characterized by latent lake fear. It is 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 synthetize 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 (Funiciello 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 $CO_2$ 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).

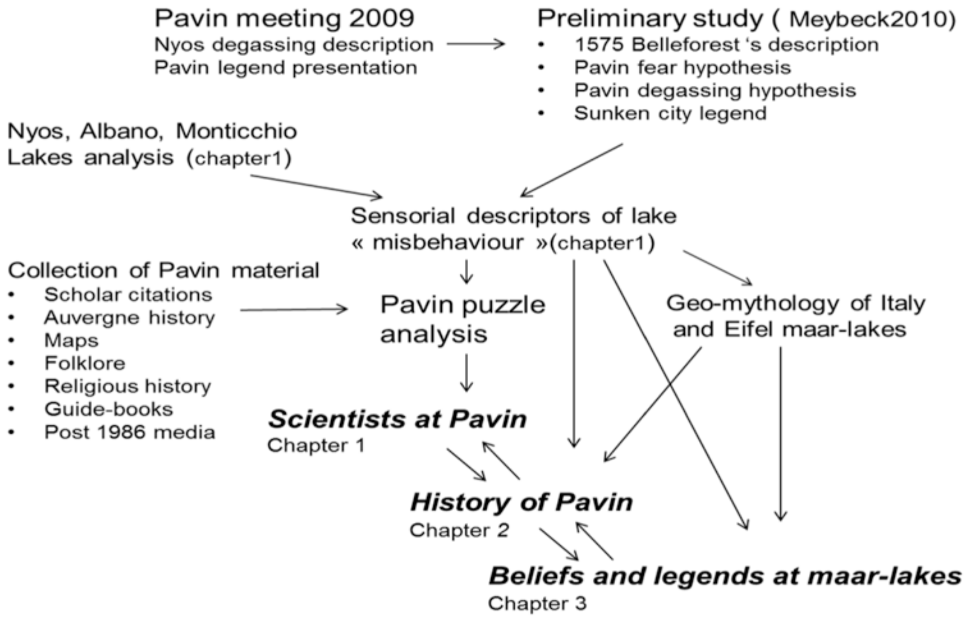

**Fig. 1.1** Simplified methodology applied for the analysis of Pavin Lake history and degassing

## 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 column, 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).

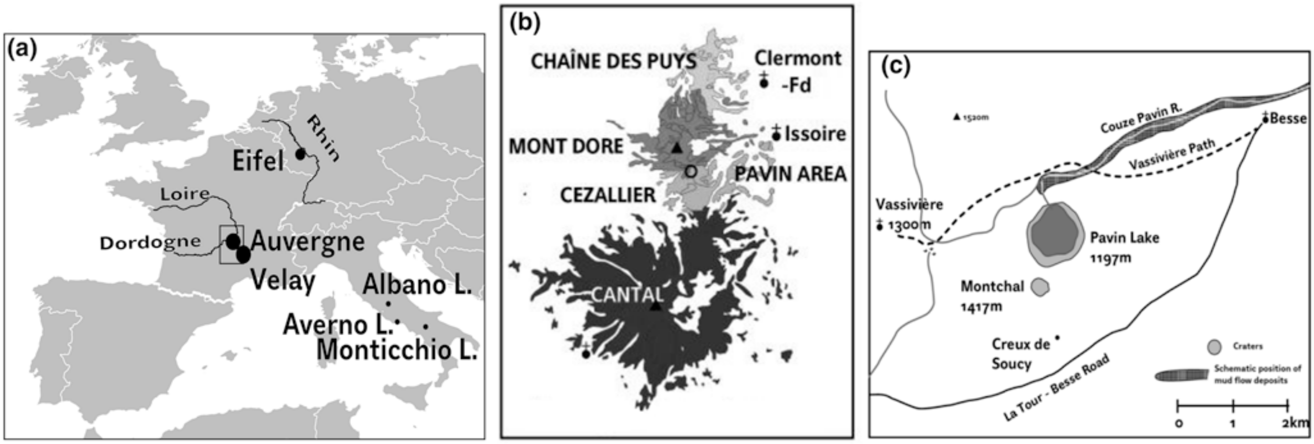

**Fig. 1.2** (**a**) Position of European volcanic lake districts. (**b**) Auvergne volcanic districts. (**c**) Pavin area with Besse, Vassivière and Creux de Soucy, ancient roads and footpaths (early 1800s)

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 $CO_2$ 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 Cézallier 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 pasture: the population density on their basin is less than 1 person per $km^2$. 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 Chambedaze, 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 Chambedaze Lake and peatland is famous for its palynological and tephra studies (Guenet and Reille 1988; Juvigné et al. 1993).

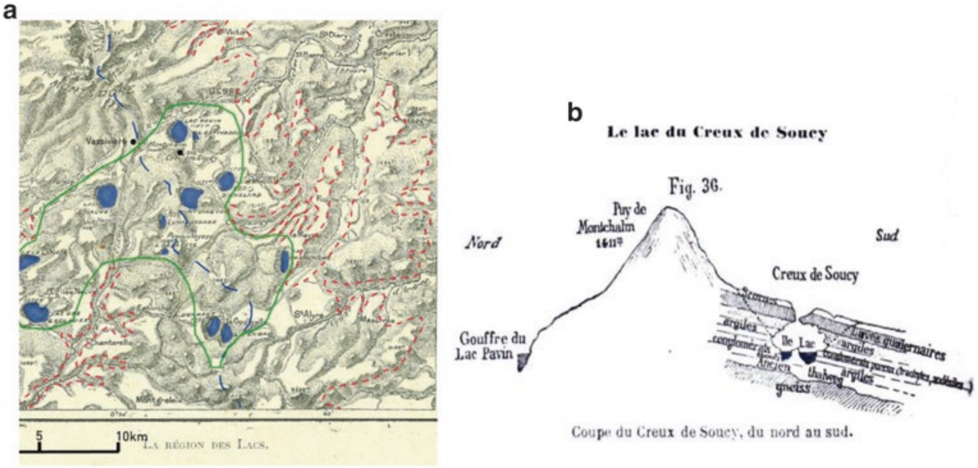

**Fig. 1.3** The Cezallier lake district in Auvergne (Berthoule 1890) with the 1050 m altitude contour line in *red* and a possible delineation of the most pristine lakes in *green. Blue dotted line*: watershed divide between Dordogne and Allier Rivers (Meybeck 2010, based on Berthoule 1890). 3b North-south 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 |
| Servières | 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 ($km^2$), *ZM* present maximum depth (m), *V* volume ($Mm^3$), *Zm* present monimolimnion depth (m), *C.A.* catchment area ($km^2$), *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 $CO_2$ 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 geomythology 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 km$^3$ 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 $CO_2$, 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 disproof 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.

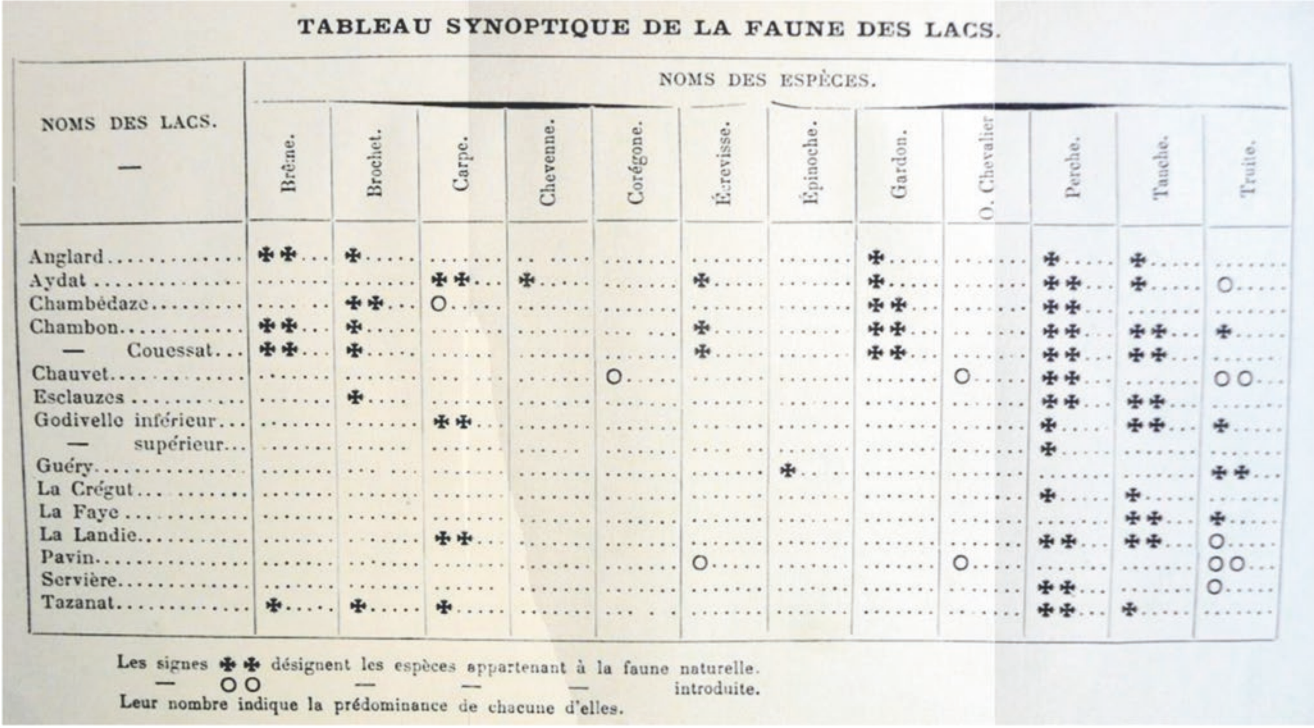

TABLEAU SYNOPTIQUE DE LA FAUNE DES LACS.

| NOMS DES LACS. — | NOMS DES ESPÈCES. | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Brême. | Brochet. | Carpe. | Chevenne. | Corégone. | Écrevisse. | Épinoche. | Gardon. | O. Chevalier | Perche. | Tanche. | Truite. |
| 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 Berthoule'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 Medecine 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 pionners 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), Servières (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 Issarlés (108.6 m) in Velay. He also describes the many peat-bog lakes in Pavin region (Chambedaze, 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 Issarlés (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;

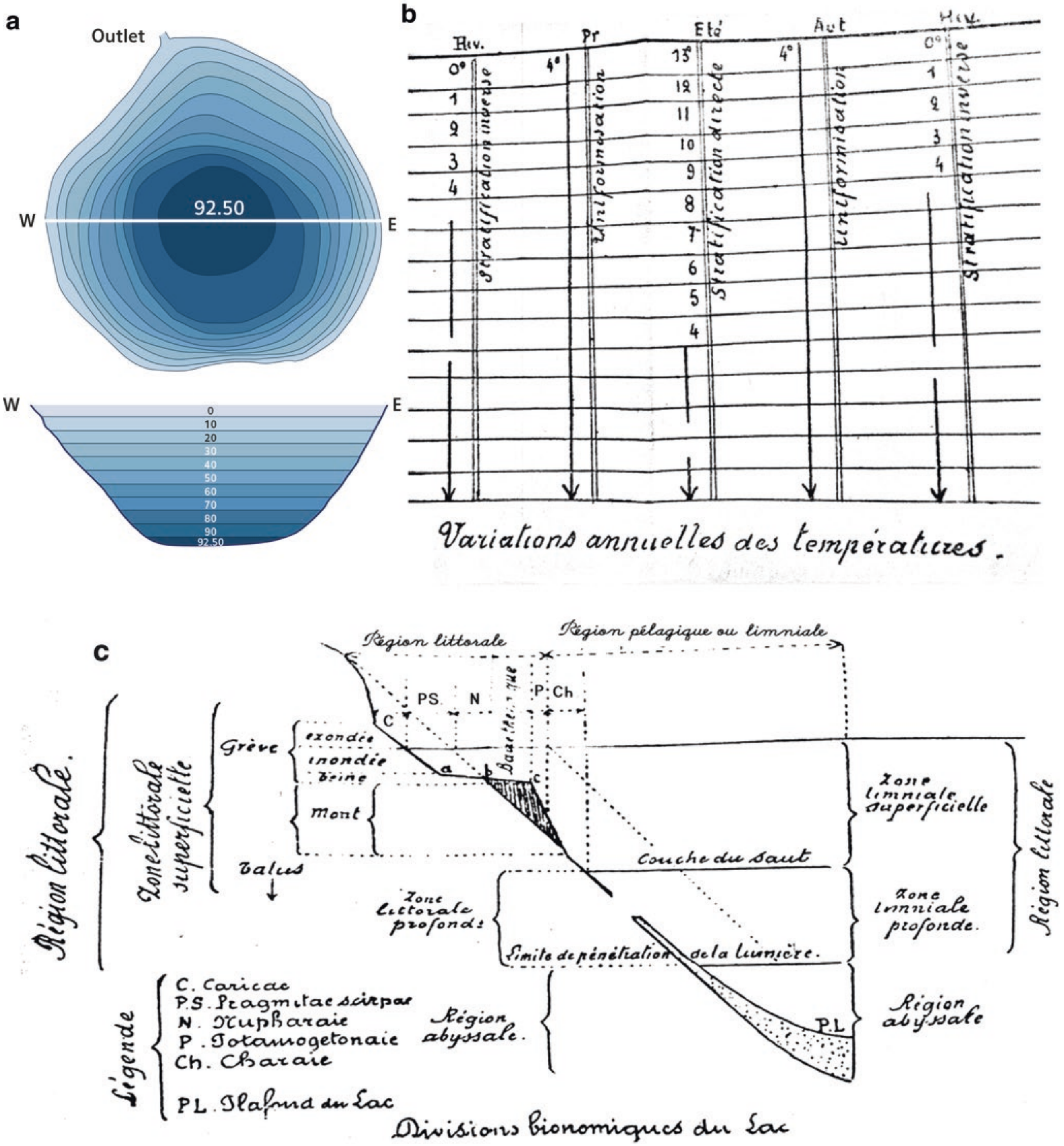

**Fig. 1.5** Some of the pionnier limnological works at Pavin (Eusebio and Reynouard 1925). (a) First bathymetric map of Pavin by Delebecque (1898). (b) First representation of Pavin thermal structure. (**c**) Vertical "bionomic " structure of Pavin (author's collection)

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 $0_2$ 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 Berthoule, 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 $CO_2$ 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 $CO_2$ 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 seasonaly 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 $O_2$ at 70 m (8.34 $cm^3$ $O_2$/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 $O_2$ depletion at 65 m, confirmed again on August 16: 2.3 $cm^3$ $O_2$/L at 60 m, 0 at 70 m, 9.1 $cm^3$ 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 $H_2S$. 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. $H_2S$ is present below 70 m,
4. Dissolved iron is 100 times more concentrated in deep waters,

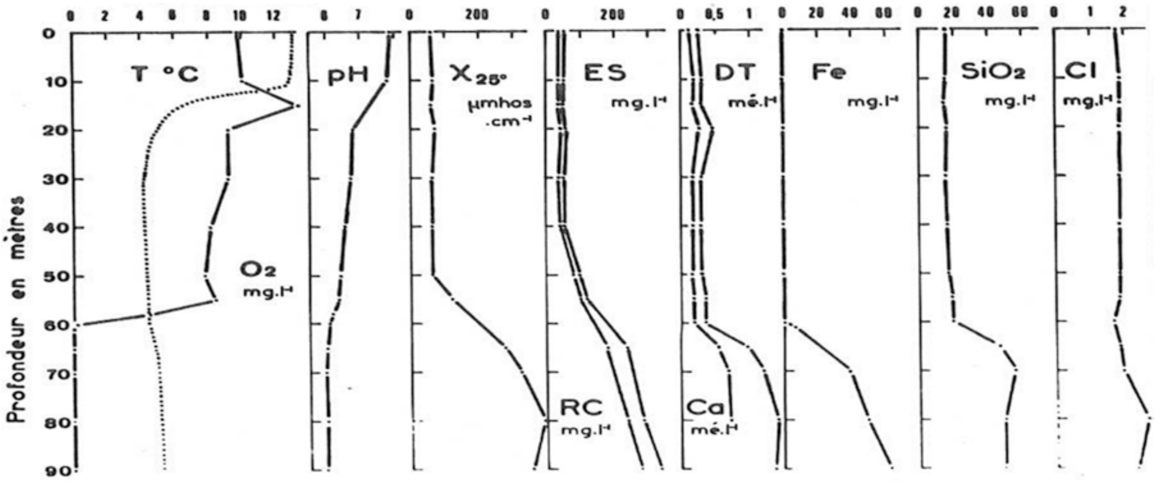

**Fig. 1.6** Pelletier's vertical profiles showing Pavin meromixis in October 1967: temperature, $O_2$, pH, conductivity, total dissolved solids (ES), total hardness (DT), dissolved iron, silica and chloride (1968). (Ann. Stat. Limnologie Besse-en-Chandesse)

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 *monomolimion*, 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 Bjôrk 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 $0_2$ profile, for the first time in France (Omaly 1968). She defines the transition layer, or *mesolimnion*, later decomposed by geochemists into an *oxicline* 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; Restituito 1984; Restituito 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 hydrogeochemical 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

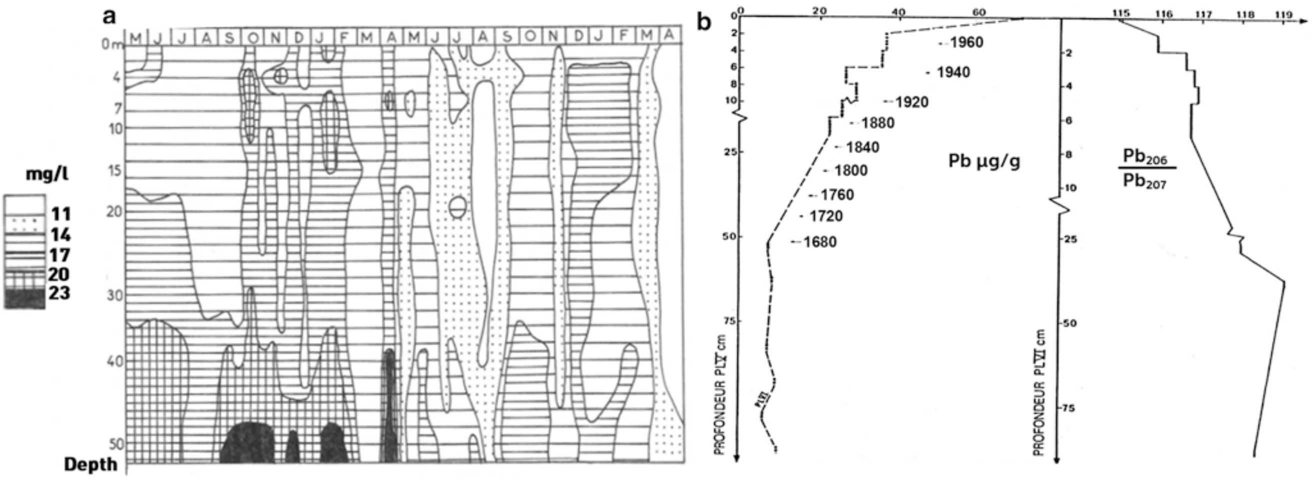

**Fig. 1.7** Spatio-temporal complexity at Pavin. (**a**) Time- depth profile of dissolved silica in Pavin mixolimnion (0–50 m) from May 1973 to April 1975 (Restituito and Lair 1975–1976, Ann. Stat. biol. Besse-en-Chandesse.) (**b**) Profiles of total lead content (μg/g) and lead 206/lead 207 isotopic ratio in Pavin deep sediments (Elbaz-Poulichet, 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 (Kristmanndottir 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 exceptionnal 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-Poulichet (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 synthetized 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 catastrophy in