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Chapter

Historical and Paleolimnological Reconstruction of Degassing Maar Lakes: The Case of Lake Pavin (Auvergne, France), for the Last Two Thousand Years

*Michel Meybeck, Emmanuel Chapron, Brice Molo
and Pierre Lavina*

Abstract

Degassing maar lakes were thought to be a new natural hazard until the Nyos Lake catastrophe (1986). Historical degassing events published for Lakes Pavin (France, 1785), Monticchio (Italy, 1770–1820), Albano Lake (Italy, 1829), combined with those of Monoun (1984) and Nyos (1986) in Cameroon, allow to propose a grid of degassing descriptors, on lake and waters changes, on atmospheric disorders and on impacts on populations. Pavin Lake degassing history has then been reconstructed from well-contextualized written source over five centuries, revealing boiling (1783), lake storm (1847), color change (1783, 1936), sudden limnic eruption (1551, 1785), emission of fog, vapors, and thick clouds (1550–1750), associated with reported sudden neurologic diseases, similar to those observed at Albano and Nyos. Their spontaneous healings have been reported as miracles by the church authorities. Pavin, described as a, « *marvelous lake with sudden storms with thunder and lightnings* », is feared and avoided by the local population. When eventually sounded (1770), Pavin is gradually normalized by local authorities who deny its misbehaviors until recently. Since 2005, Pavin geohistory is gradually unveiled by paleolimnology, geomorphology, and geochemistry, revealing sub-lacustrine slides, higher lake levels, overflows events, and its deep CO₂ are beginning to be surveyed. A recent modelling of sudden lake degassing confirms that Pavin area is a potential hazard. Other world maar lakes could benefit from the multiple approaches implemented at Pavin to establish their past degassing history, necessary to risk management.

Keywords: degassing descriptors, maar lakes, Lake Pavin, limnic eruption, geohistory

1. Introduction

When the sudden eruption of Lake Nyos occurred on August 21, 1986, causing 1700 victims and thousands of injuries in the Grasslands of Cameroon [1], this phenomenon

was new to the academic world of limnologists [2] and volcanologists [3–6]. Now termed limnic eruption [4], this phenomenon is interpreted as a violent and sudden degassing of CO₂, of magmatic origin, stored in stagnant deep waters of a very rare type of lake, the meromictic maar lakes, which otherwise behave like other lakes. It is quite different from the phreatic explosions produced by the volcanic magma when in contact with groundwater or surface water, resulting in an explosion of steam, water, ash, and rock debris. Maar is a volcanic term, originated from the Eifel volcanic province in Germany, applied to depressions that have been generated by violent phreato-magmatic eruptions followed by crater floor subsidence, then filled with water [7]. The meromixis is a very rare limnological property of some lakes, which are never completely mixed due to the presence of denser bottom waters originating from groundwater inputs or coastal intrusions [2]. The semantic associations “limnic eruption” and “meromictic maar lakes” reflect the sort of “natural monster” that is encountered throughout this paper, which mixes the permanent quietness that is attributed to still continental waters and the violence and unpredictability of volcanic processes.

The Nyos catastrophic event immediately attracted scientific teams from far away, mostly volcanologists, a few limnologists, and lake geochemists, who mainly worked separately on the field. In 1987, UNESCO organized a conference in Yaoundé to collect these past-event observations and tried to reach a consensus on the origins of the event [1]. Cameroon scientists’ participation was at that time very limited. Also, very few social scientists were present, excepted Evguenia Shanklin, an US anthropologist, who made the first study of the perception of the catastrophe by the Grasslands population [8]. In the conference volume, her paper was the only one to address the question of possible past Nyos events and their perception by the local population through oral transmission and in a context of very limited historical records. She mentioned that actually the local population knew about the “misbehavior” of some lakes, a term that has been later used to qualify various lake deviations from their normal quiet state, such as color change, sudden eruptions, lake displacement, and their representations, often by various types of lake monsters and spirits [9–11].

For limnologists, maar lakes are rare at the global scale, probably one in 1000 or 10,000 lakes worldwide, but they may be common in recent volcanic areas such as Alaska, Japan, Ethiopia, Central America, the Andes, Cameroon, Indonesia, etc. (**Figure 1**). Before the Nyos catastrophe, they had been rarely studied, mostly in Europe: in Eifel (Germany) [7, 12], in Southern Italy [13], and in Auvergne-Velay (France), where they were mixed with other lakes generated by volcanic dams such as lava flows or eruption cones [14, 15].

For volcanologists, the term “volcanic lakes” covers a wide range, from crater lakes still receiving acidic hydrothermal fluids or young maar lakes exposed to phreato-magmatic explosions to quiescent maar lakes and caldera lakes as Crater Lake (Oregon). Their classification can be based on their genesis, their current activity, and their chemistry [16–18]. A classification of volcanic lakes into six classes according to their activity, from volcanic eruptions (class 1) to low activity (class 5) and no activity (class 6) is proposed. Most limnological studies before 1986 were concerning the class 6 lakes; other volcanic lakes were barely mentioned by limnologists. The specificity of Nyos-type lakes was only recognized recently by the community of limnologists [19].

The acidic volcanic lakes have been particularly studied for their singular chemical composition: many of them are extremely acidic, very mineralized, and are still constrained by internal inputs of volcanic fluids [16]. Their access is difficult, dangerous, and often restricted, and their limnological study through vertical profiles is rarely performed between volcanic crises. When the volcanic forces are decreasing,

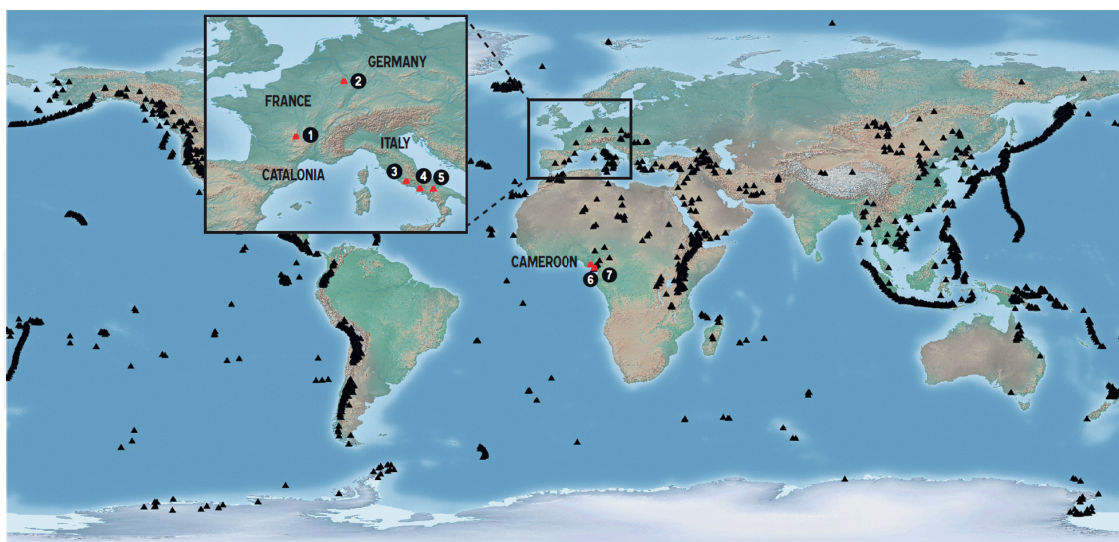


Figure 1.
 World volcanoes and position of degassing maar lakes studied, or mentioned in this paper, in Western Europe and Cameroon. 1 Lake Pavin in Auvergne, France. 2 Laacher See, Ulmen, Weinfelder, Pulver Lakes in Eifel, Germany. 3 Lakes Albano and Nemi in Colli Albani, Italy. 4 Lake Averno in Phlegrean Fields, Italy. 5 Piccolo Lago di Monticchio and Grande Lago di Monticchio in Mount Vulture, Italy. 6 and 7 Lakes Monoun and Nyos in Oku volcanic field, Cameroon Volcanic Line. <https://volcano.si.edu/>. Data: Natural Earth, OpenStreetmap, Global Volcanism Program—Smithsonian Institution.

the aging maar lakes (classes 5 and 6) become gradually controlled by the external forces—solar energy, watershed inputs—as all other lakes. However, they are still marked by their volcanic origin, which controls their morphology, limits the inputs of water and material from their restricted annular drainage basins, and may still be responsible for sub-lacustrine hydrothermal inputs [19]. A recent inventory of African volcanic lakes by volcanologists gave a total of 220 lakes for Africa alone [18]. In this VOLADA data base, maar lakes are by far the dominant type (178 lakes).

Maar lakes sediment archives are characterized by their high resolution, in parts even annual, which gives detailed evidence of paleo climatic variations, regional seismic activity, volcanic activities, and human perturbations, as well as their biotic response within the lakes and their catchment areas, as studied in Western Europe maars [20].

After the Nyos catastrophe in August 1986, other potential degassing maar lakes have been rapidly looked for in Italy, Germany, and Japan and analyzed in hundreds of papers in the fields of volcanology, limnology, and geochemistry. However, their studies by human and social scientists (historians, human geographers, sociologists, anthropologists, literature specialists, and folklorists) are just beginning. Italian volcanologists [21, 22] have been the first ones to refer to pioneer studies of the Monticchio maar lakes in the late 1700s and to the Lake Albano *prodigium*, which occurred in 398 BC, according to Latin authors [23, 24]. More recently, a precious description of Lake Albano degassing in 1829 was found [24]. In Greek and Latin Antiquity, Lakes Nemi, Albano, and Averno have been considered sacred places, and the association between their past misbehavior and their well-known associated beliefs is beginning to be considered [25].

A few weeks after the Nyos catastrophe, Pavin Lake, in the Auvergne volcanic province (France), was rapidly identified as a potential degassing maar lake. A first national expertise of a degassing risk was conducted, including one of the authors (MM): we concluded to the absence of risk in present conditions, considering the relatively low CO₂ concentration in its deep and stagnant waters [26]. This lake has

been the birthplace of French limnology since the 1890s [9] and continues to attract scientists from far away [27]. In the last decades, paleolimnological [28–30] and geological studies have been developed to reconstruct its past geohistory and the extend of its tephras, and CO₂ measurements have been made in the lake and its surroundings to assess the present rate of degassing [31–35]. The first historical analyses of Lake Pavin, over 450 years, revealed complex social responses to its past misbehaviors, lake normalization periods, and scientific controversies [9–11]. The social receptions of degassing risk at Nyos and Pavin reflect cultural and social differences [6]. We are referring throughout this paper to “Pavin” as most local people continue to call this place, which was not always identified as a lake in the past.

In this chapter, the Pavin past is reconstructed from written historical documents since 1551 and from paleolimnology. They show various types and intensities of lake misbehaviors attributed to degassing, none of which were taken into account in the first degassing risk assessment [26], on which the risk management is still based [6]. The local historical description covers the following European history periods: Renaissance, Enlightenments, modern scientific era (1890–1986), and contemporary post-Nyos era (since 1986). The paleolimnological records now extend over more than two thousand years.

Our study includes new historical sources such as the limnic eruption of 1785 and a description of a “Pavin event” in 1847. A companion paper [36] focuses on Pavin geoheritage values and on its geom mythology, based on sources anterior to the 16th, generally in Latin, and on its numerous legends and tales.

We are addressing the following questions: (i) What terms have been used by scientists to report the past limnic eruptions and other major lake degassing events in four European maar lakes and their impacts on nearby populations between 1770 and 1829; are these descriptors comparable with those of Nyos and Monoun? (ii) Can these degassing indicators be used to re-analyze the past written accounts about Pavin since the sixteenth century? (iii) How have the perceptions and representations of Pavin have gradually changed from the eighteenth to twentieth centuries? (iv) How, gradually, the hypothesis of a degassing Pavin has been generated, debated, and accepted based on the paleolimnological, geological, and geomorphological elements? (vi) Which are the perspectives offered by Pavin analysis on the other maar lakes in Europe and other continents?

2. Maar lakes degassing reported in historical sources in Western Europe

Two hundred years before the Monoun and Nyos catastrophes, which have only been studied by scientists after the events, there have been few early descriptions of maar lakes degassing, by volcanologists, geologists, geochemists, and a medical doctor, and published as scientific communications in journals or reports between 1770s and 1829, with detailed contextualization, made in Italy (Monticchio Lakes and Albano Lake) and France (Pavin Lake) (**Figure 1**). The comparison of the different elements of these descriptions provides a coherent and converging set of descriptors of lake degassing and of their effects (**Table 1**). Another very special misbehavior of Lake Laach (Laacher See in Eifel, Germany) has also been reported in 1844 by a local witness, although not identified, therefore not included in **Table 1**. Also, the Albano *prodigium*, a slow lake level rise and overflow that threatened the city of Rome in 398 BC, as reported by many classical historians of Rome, four centuries after the event [23–25], is not part of this list. These historical scientific observations went largely unnoticed, and scientists at Monoun and Nyos thought they were the first to study this phenomenon [41].

	Pavin	Monticchio	Albano	Monoun	Nyos
Date	1785	1770–1820	1829	1984	1986
Ref.	[37]	[21, 22, 38, 39]	[40]	[41–43]	[1, 5, 43–46]
L1		X			X
L2					
L3					X
L4		X			X
L5	X	X			X
L6					X
L7					
L8		X			X
L9					
L10		X			
L11	X				
L12	X	X		X	X
A1		X	X		X
A2		X			X
A3					X
A4	X		X		X
A5	X		X		X
A6	X		X		
A7					
A8	X	X	X		X
A9	X		X		X
A10	X				
A11	X				
I1			X	X	
I2			X		X
I3			X		X
I4			X		X
I5			X		X
I6			X	X	X
I7			X		X
I8					X
I9		X			
I10					X
I11					X

Lake and water descriptors: L1 iron taste of water, L2 corrosive water, L3 absence of fish, L4 waves, L5 water spout, L6 red/orange/yellow colors, L7 glutinous aspect, L8 bubbling/boiling, L9 water spillover/inundation, L10 fish kill, L11 whirlpool, L12 waterspout.

Atmosphere descriptors: A1 roar/hiss, A2 sudden change, A3 explosion, A4 thunders, A5 lightning, A6 hail/ cold, A7 sulfur odor, A8 fog, A9 dense cloud, A10 wind storm, A11 serene weather outside crater.

Impacts on populations and living organisms: I1 dizziness, I2 paralysis, I3 loss of sight, I4 commotion, I5 skin damage, I6 death, I7 damage to fetus/babies, I8 crop damage, I9 fish kills, I10 massive livestock mortality, I11 bird absence or death.

Table 1.
Descriptors of degassing in Europe and Cameroon maar lakes: Pavin Lake (Auvergne, France), Monticchio Lakes and Albano Lake (Italy), Monoun and Nyos Lakes (Cameroon).

2.1 Pavin whirlpool, waterspout, and violent storm in 1785: The ignored description of a limnic eruption in Auvergne (France)

In 1803 (12 Vendémiaire, Year II), a “letter addressed by Citizen Cordier to Citizen Devilliers” is published in the *Gazette nationale* (also called *Le Moniteur Universel*), the high-ranking Parisian newspaper [37]. Cordier, a young geologist, reports to Devilliers, another geologist, the account of a geological tour carried out with two friends in Auvergne and Velay in which is found the following witness account about Pavin, one of the crater lakes he visited [all translations provided by the authors]:

“You will not read without interest the following description of a phenomenon that citizens Legrand and Enjelvin observed there [in Pavin] in August 1785; I got it from the latter.

Attracted to these heights by the same motives as those who brought us there, tired by excessive heat, they sat on the steep banks which dominate the lake; their gaze, which at first wandered vaguely over the mountains, was soon drawn towards the lake by a sudden, dull noise. An extremely dense cloud had already formed near the middle of the bubbling water; it moved around, turning quickly on itself. In a short time, the wind became violent, the vapors increased excessively, and a waterspout 6 meters (18 feet) in diameter began to rise perpendicularly in the air. Barely had it exceeded the height of the enclosure when it ceased to rise; but then it began to pour down in abundance a thick fog, which quickly enveloped the mountain and its surroundings. Driven by a rapid movement, and supported by the waterspout, this stormy cloud swirled on the spot for a long time, and ended up spilling completely into the capacity of the crater. About this time, a terrible crash was heard, and continued for a quarter of an hour, accompanied by dazzling flashes of lightning which followed one another in rapid succession. However, the noise of the lightning gradually diminished, the cloud cleared, and eventually dissipated completely. Finally, the calm of the air was restored after two hours of this singular phenomenon. Descending to the bottom of the crater, the travelers found on the narrow banks of the lake a layer of very thin hail, which was 2 decimeters (7 inches) thick.” Signed: Cordier Mines engineer.

This description is fully contextualized, and both witnesses and the author are well educated and highly credible. Legrand is probably an abbot of St André de Clermont, the capital of Auvergne, and Enjelvin (1758–1815) is the director of the Pb-Ag mines of Pongibaud in Auvergne. Pierre-Louis Antoine Cordier (1777–1861) was 26 years old when he collected and wrote this story and already an experienced scientist, as he had been the assistant of the geologist Dolomieu during the scientific expedition in Egypt led by Bonaparte. He will be one of the prominent figures in the earth sciences of the nineteenth century (general inspector of mines, initiator of the mineralogy collection of the National Museum of Natural History in Paris, founder of the *Société Géologique de France*, and elected to the *Academy of Sciences*). What we can call today the limnic eruption of Pavin is not accompanied by any attempt at explanation or any reservation; it is presented in its simplest terms as an actual phenomenon. Cordier is not aware of other identical phenomena, as he would undoubtedly have pushed the comparison. The volcanic origin of Pavin was only known by scientists since the mid-1700s [9, 10] and mapped for the first time as a crater by Nicolas Desmaret (1725–1815), a pioneer of volcanology [47].

This description leads to the following comments: (i) This is the first detailed description by a scientist of a limnic eruption from start to finish. (ii) The eruption is triggered suddenly and lasts only 2 hours in total, with a high-intensity phase (thunder, lightning), which lasts a quarter of an hour. Such a phenomenon therefore had every chance of not occurring during very scarce visits, as Pavin was avoided at that time. (iii) Its fundamental elements are: bubbling, dense cloud, then violent winds, ascending and spiraling waterspout (“trombe lacustre”), succession of thunderclaps and incessant lightning, total invasion of the crater basin by swirling clouds, then overflowing of them, and finally formation of hail, collected on the edges of the lake. (iv) The witnesses were not affected by the cloud; it is likely that they were standing on the rim and that the cloud had dissipated when they came close to the water.

This letter was only recently found [48]. It appears to be the first—and so far, the only one—witness account of a limnic eruption made by scientists. It is also the most precise and detailed description to date as the Nyos eruption occurred in the middle of the night and was only witnessed by a few persons with limited scientific education. This description, published in Paris, had been so far totally ignored from the nineteenth century scientists, then by all Pavin analysts, including historians and volcanologists.

2.2 Monticchio Lakes (Italy) degassing, a matter of interest for Naples’s scientists (1770s–1820s)

The twin lakes of Monticchio (Lago Piccolo di Monticchio, LPM, and Lago Grande di Monticchio, LGM) are in the Mount Vulture Massif (Basilicate, Southern Italy) (**Figure 1**). They are just separated by a narrow piece of land. Both are meromictic, with a lack of oxygen below 15 m today and a marked positive temperature anomaly in deep layers [21, 49, 50]. The first scientific study of Monticchio Lakes has been realized by Domenico Tata, a prominent Naples scientist and pioneer of volcanology. He reports his observations in the noted *Lettera sul Monte Vulture* [38]. He comes to Mount Vulture in 1777, fully equipped (sounding lines, water sampling bottle) to study these lakes renowned for their marvelous nature. In LPM, he sees no water movements, but the water sampled at the lake bottom burst suddenly at 1 m high with a rotten egg odor, probably the first sampling of gaseous lake water ever realized. Such behavior has also been noted after Lake Monoun degassing by Sigurdson [41]. After Tata, several Naples scientists come to Monticchio [39, 49, 51]: Brocchi makes the first lake water analysis of CO₂ and H₂S. Tenore and Gussone describe a “permanent water fountain” that mixes the whole Lago Piccolo. According to local witnesses, as Father Tortonella, a maximum height of 5 m for the lake fountain was reported at LPM in November 1820. The lake activity gradually decreased and was not observed by Paci, the Naples geophysicist who made an in-depth report on the terrible 1851 earthquake in this region [51].

In their pioneer review of Monticchio historical degassing, Caracausi and his colleagues made the following summary [21]: “*we have come to the conclusion that triggering processes totally different from a landslide and /or a seismic shock should also be taken into due consideration. In fact, there have been gas bursts in both the Monticchio lakes up to no later than 200 years ago, which indicates that they have a recurring character, even if the temporal intervals have not been constant. A paroxistic activity occurred on 1 June 1810 when a 6-m-high water column formed in LGM. A new event was observed 2 months later on 31 July, when an intense roar was also heard; the column of water reached a height of about 3 m. Ten years later, a similar paroxistic event occurred in LPM; historical reports*

state that the water-spouts surged upwards out of the lake, reaching a height of 5 m. There were no fatalities, although a lot of dead fish were found on the land, a few meters from the shore, thus bearing witness to the explosive nature and gas toxicity of the event. It is worth noting that during the 10 years leading up to 1820 every so often LPM reached similarly dangerous conditions when all the fish living in LPM were killed.”

2.3 Lake Albano (Italy): A long degassing period in 1829 with impacts on population

Albano Lake is a major maar lake in the Colli Albani (Alban Hills) volcanic district, South of Rome (**Figure 1**). It is 3.5 km long, 2.3 km wide, 168 m deep, and is sometimes anoxic below 50 m. Its annular drainage area is very limited, and there are neither aerial inputs nor natural outlets. Major Latin historians such as Plutarch and Livius reported that, during early Roman times in 398 BC, a 1.45 km long tunnel had been dug out across the lake rim, following an elevation of the lake level by 70 m in 2 months and a subsequent overflow, threatening Rome, an event named the Albano *prodigium*, according to the tradition. The tunnel, a technical feat of Roman engineers, was still functioning in the early 1900s. The exact cause and effect of this event is still debated among geologists and volcanologists [23, 24, 52].

In 1829, a period of 8 months of degassing of Lake Albano is reported with great details by Luigi Bassanelli, a medical doctor in the city of Albano, located on the lake rim [40]. In his scientific letter to Pr Giacomo Folchi in Rome, he mentions the past local earthquakes (1762, 1777, 1778, 1779) and details the physical attributes of atmospheric changes in 1829. His report is also a unique medical testimony of the multiple effects of CO₂ intoxication on the population and the behaviors of animals, and of the social and religious responses. Despite a minimal description of Lake Albano itself, this detailed account includes: suddenness of event during serene weather, atmospheric storm with lightning (“electric atmosphere”), unusual cold in summer and hail, change of lake waters appearance, CO₂ presence, various diseases affecting the nervous system, deaths of babies, activation of traditional protection rituals (statue of the protector saint carried in procession), and population escape (developed in Appendix A and listed in **Table 1**).

2.4 The Laacher See (Germany) sudden and violent event in 1844

The Naples geophysicist Giacomo Maria Paci ([51], p. 79) also made an inter-comparison between the Monticchio Lakes misbehavior and another misbehavior event which occurred in 1844, according to a Naples journal, in the Laacher See, the biggest Eifel maar lake in Germany (**Figure 1**). The original Laacher See event was actually published in Germany [53] by an unknown local witness, most probably a Benedictine monk from the Laach Abbey, established within the crater since the eleventh century:

“Today, early in the morning, around half past four, the following natural phenomenon occurred here: in calm and serene weather, suddenly the lake rose to a remarkable height and, at the same speed, it withdrew, while we perceived with a shudder rocks and abysses never seen. At the same time a dull sound, like thunder, was heard, while almost suffocating smoke swirled high in the air. On the other side of the lake, “there, where the well-known asphyxiating air perpetually rises from the earth”, the earth opened up, and several trees were violently shattered as they fell towards the

cavity. After this apparition, several dead fish were seen floating on the surface, and around the suffocating pit, many dead birds were dragged. It was all the work of a moment. It would therefore be desirable for specialists to take note of this interesting phenomenon and deem it worthy of further investigation."

However, this witness description is invalidated a few days later in the same journal, after a field investigation by a journalist: "most everything said here is false and is essentially limited to the very simple fact of the formation of crevasses and landslides... It is fairy tales." In addition, an unidentified expert interviewed by the journal writes that the phenomenon was linked to a sudden slide of the crater rim generated by on-going clay extraction: "*The sudden growth and fall of the lake, the rocks and abysses that became visible in the lake basin, the thunderous roar, the suffocating smoke swirling high into the air and everything else the*" eyewitness "claims to have seen can only have been the product of an excited imagination. The naturalist should beware of this, even if it may well be fitting and appropriate for the poet."

Such abrupt judgment, typical of the position of academic scientists, has been formulated many times for Pavin, until recently. Today, the suddenness of the lake level rise, then its drop, the thunder-like roar, the suffocating pit and the impact on fish and birds seem to us much more credible and suggest a violent lake degassing. The Laacher See is also the Eifel maar with the greatest number of legends, evoked in Section 6.3.

2.5 Monoun, Cameroon (1984), "a hitherto unknown natural hazard"

This catastrophic event occurred in Cameroon on August 15, 1984, at the Monoun Lake (0.53 km², 96 m deep) and officially claimed 37 victims. Haraldur Sigurdsson, a volcanologist from the University of Rhode Island, made the post-event investigation only a few months later 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 [44]. Sigurdsson eventually had it accepted in the Journal of Volcanic and Geothermal Research and therefore published a year after the Nyos event [42]. He was unaware of the Montichio, Pavin, and Albano historical degassings, unreported in volcanology or limnology textbooks at that time. No early warning was given to the scientific community or to local Cameroon authorities about such type of lakes. The reluctance of the scientific community to conceive this "new natural hazard" is exemplary.

Monoun rescuers, who came a few hours after the catastrophic event, observed "a misty cloud which did not disperse until three to four hours later" [43]. The Monoun eruption also occurred at night, and the gas cloud filled a low-lying area near the lake [42]. 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.

Lake Monoun was then surveyed by scientists from several countries, and one of them, Minoru 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" [44]. This corresponds to a near-saturation state (97%), very sensitive to any perturbation, as throwing a stone.

2.6 The Nyos (Cameroon) catastrophe, which shocked scientific communities (1986)

The catastrophe occurred on Lake Lwi, below the village of Nyos in the Cameroon Grasslands, on August 21, 1986. Today most scientific papers refer to Lake Nyos. The explosion occurred at night, and only a few surviving eyewitnesses gave a detailed account [4, 8, 45, 54]. The main features of the event can be summarized as such:

In the evening, an intermittent jet of water was seen, topped by a white plume. At 10 p.m. a major detonation—a series of rumbling or bubbling sounds lasting 15–20 seconds—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. Soon after, the carbon dioxide invaded the low-lying valleys and intoxicated the population and the animals over 20 km. Although people smelled the odor of rotten eggs or of gunpowder, they lost consciousness owing to the dense, ground-hugging, and toxic cloud of CO₂ mixed with water vapor and droplets, which smelled bitter and acidic. Livestock and other animals, birds, and insects also died in the event. Vegetation was “mechanically damaged,” but no thermal or chemical damage could be identified with certainty. Just after the event, the surface of the lake turned reddish brown. This was eventually attributed to the oxidation of dissolved ferrous iron mixed to the surface from depth. A few months after the event, Rose-Marie Chevrier, a French geochemist, observed a sudden and intense flash of light in the crater and, again, a red spot in the water [46].

The medical symptoms of the Nyos victims and survivors have been analyzed by a specialized team [43]. 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, and dyspnea (5% each). Many of them had a sudden loss of consciousness with a coma lasting a few hours, followed by rapid recovery that could be related to anesthetic concentrations 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 skin damages: erythema, big skin bullae, more than 5 cm, skin changes resembling burns, often developed 2 or 3 days after the degassing. Only five patients—out of 161—attributed their skin lesions to burns. Long-term neurological damages could not be estimated. Surviving victims interviewed by the Cameroon Tribune also reported: “I felt dizzy,” “I vomited blood,” “I felt drunk” [5].

The most salient physical figure of Nyos limnic eruption is the erosion traces on a cliff up to 50–80 m above lake level, suggesting the occurrence of either landslides and/or violent waterspouts. An up to 4 m thick turbidite deposit was sampled at the lake bottom by gravity coring in 1988 and mapped with 3.5 kHz seismic profiles in the deep central basin of Lake Nyos. In 1991, further studies supported that Limnic Eruption Deposits (LEDs) can be recorded in meromictic maar lakes sedimentary infills [55].

There has not been a water overflow but an overflow of the CO₂ cloud, which caused victims over 20 km in downstream valleys. The official number of victims is 1700 and more than 5000 cattle heads [5]. The whole event lasted 4.5 hours.

2.7 Common descriptors of maar lake degassing and its impacts on populations and animals

When the descriptors of these degassing events and their impacts on populations are compared, many similarities are noted (**Table 1**). The differences are due to the

type and/or intensity of degassing and to the position of observers. The actual state of the lakes during these events is not always detailed. The Nyos and the Pavin-1785 events represent what is now called a limnic eruption, a sudden degassing phenomenon, violent and short in both cases, while the Montichio and Albano-1829 descriptions represent more a prolonged state of degassing, suggesting different degassing causes and mechanisms [19, 24].

Toxic effects on humans are well detailed in Cameroon and Albano Lakes, ranging from dizziness, drunkenness, skin lesions, loss of sight, contusion, loss of consciousness, and coma to sudden death. Post-event effects on fetus and breast-fed babies are noted. At Albano Lake, the overall death toll on people is not given.

The early warning of animals is noted at Albano, although it cannot be said if they reacted to the CO₂ cloud or to micro tremors, radon emission, or else. At Nyos, the deaths of all, humans and animals, generated a post-event rumor: the secret experimentation of a neutron bomb supplied by a foreign country [56]. In the Roman Antiquity, the death or absence of birds was a well-known consequence of ground degassing in so-called mephitic places. As this was particularly observed in Lake Averno (a-ornos, i.e., without birds) in the Phlegrean Fields near Naples (**Figure 1**), *avernism* has been used to qualify such places [11, 25, 36].

The mist, fog, or clouds reported over these lakes are thought to be related to CO₂ and water vapor emissions, but only water analysis was realized at Monticchio to confirm this assumption. The gaseous micro particles emitted in the atmosphere can generate electrostatic storms with thunder and lightning. At Nyos, Monticchio, and Albano, a sulfur odor is noted in the atmosphere, although not dominant; for some it is gun powder smell (SO₂), for others rotten eggs (H₂S). In many meromictic lakes, H₂S is present in deep anoxic waters due to the decomposition of organic matter [2, 15].

The fish kills and the sudden change of water color and fluidity are the markers of the mixing of anoxic and iron-rich deep waters with surface water, the so-called rollover which results in the precipitation of orange-red iron oxide Fe(OH)₃, as the one that has been observed in Monticchio Piccolo Lago in January 2017 [48].

Limnic eruptions are characterized by an ascending column of water (Pavin-1785, Monticchio-1810 and 1820, Monoun-1984, Nyos-1986), reaching 5–80 m high. It generates a great emission of micro particles, which are associated with electrical storms. In the Pavin-1785 event, a great amount of hail is found on the shore, possibly due to the gas expansion. A colder atmosphere is also noted in Albano-1829.

3. Past accounts of tempestuous Pavin revealed by historical sources (1549 onwards)

Many historical accounts on Pavin have been found since 2009 [9–11], only the major ones are presented in this paper [57–81]. They represent several hundred pages, which are summarized in Appendix B and re-analyzed in **Table 2** using the grid of maar lakes degassing descriptors established in **Table 1**. The 1785 Pavin event has been fully described in Section 2.1.

3.1 The first pictorial representations of Lake Pavin in a royal land register (1579)

Pavin is figured on a landscape representation, the first ever made in France, hand painted in the royal land register of Besse [57]. In this magnificent illuminated

manuscript, ordered by Catherine de Medicis, the Queen Mother and lord of Besse, Pavin cup shape and position “on top of a mountain” are very accurately represented (**Figure 2**).

The discharge of the lake outlet—the Couze Pavin River—is over-represented as if there were a lake overflow, spreading across the cascade 500 m below the lake.

Events	1551	1566	16th–17th	1750s	1783	1847	1936
Ref.	[59, 60]	[62]	[59, 60]	[66]	[68]	[71]	[72]
L1				X			
L2				X	X		
L3				X			
L4						X	
L5							
L6					X		X
L7					X		X
L8					X		
L9							
L10							
L11							
L12							
A1							
A2	X				(X)	(X)	
A3	X						
A4	X	X					
A5	X						
A6		X					
A7	X	X					X
A8				X			
A9				X		X	
A10	X					(X)	
A11	X						
I1							
I2			X				
I3			X				
I4			X				
I5			X				
I6							
I7							
I8		X					
I9							
I10			X				
I11				X			

Table 2.
Analysis of major witness accounts of Pavin Lake through the degassing descriptors listed in Table 1 (details in Appendix B and Section 2.1 for the 1785 event).



Figure 2.
 Pictorial representation of Pavin Lake area in 1579 in the royal land register of Besse, featuring the lake and the city of Besse [57] (actual size of this partial picture: 20 × 30 cm).

The mountain featured behind the lake is the Montchal, today identified as a volcano with its crater. The Vassivière Mountain is the last one on the upper right side. The area between Vassivière and Besse—the valley of the Couze Pavin River—is the location of many miraculous healings recorded between 1547 and 1750s. This is the first landscape and first lake ever depicted in France. In 1663 the lake is localized for the first time in Joan Blaeu's world atlas published in Amsterdam, an indication of its famous reputation [10].

3.2 Geographic setting of Pavin and its surroundings

Lake Pavin is in the center of the Auvergne lake district, located at mid-altitudes between 800 m and 1200 m, on top of the hydrological divide between the Allier-Loire and the Dordogne-Garonne river basins (**Figure 3**) [9, 14]. The lake altitude is 1196 m above sea level today. The Pavin area is located at the limits between the historical regions of Haute and Basse Auvergne near the city of Besse (4 km east of Pavin) known across Auvergne for its famous Catholic pilgrimage dedicated to Notre Dame located on the Vassivière Mountain at 1.5 km west of the lake at 1300 m asl (**Figure 3**). Before the twenty-first century, all these lakes were frozen during the whole winter, up to 6 months of ice cover for Pavin in the 1700s [58]. The mountainous region of Besse was isolated, and the local road was avoiding the valley below Pavin until the 1820s. The Couze Pavin River, originating from the Southern Mont Dore massif and Lake Pavin, joins the Allier River, some 30 km downstream of Pavin, at the main city of Issoire. Until the 1800s, the population in this mountainous part of Auvergne was largely uneducated and isolated from the main communication routes, particularly during the 6-month snow season.

3.3 Geological setting of Pavin

For volcanologists, the Pavin volcanic zone is located between two ancient volcanic districts of the French Massif Central (**Figure 4**), the Mont-Dore stratovolcano, aged 0.2–1 Ma, and the Cézallier stratovolcano, aged 3–8 Ma, at only 20 km of the northern

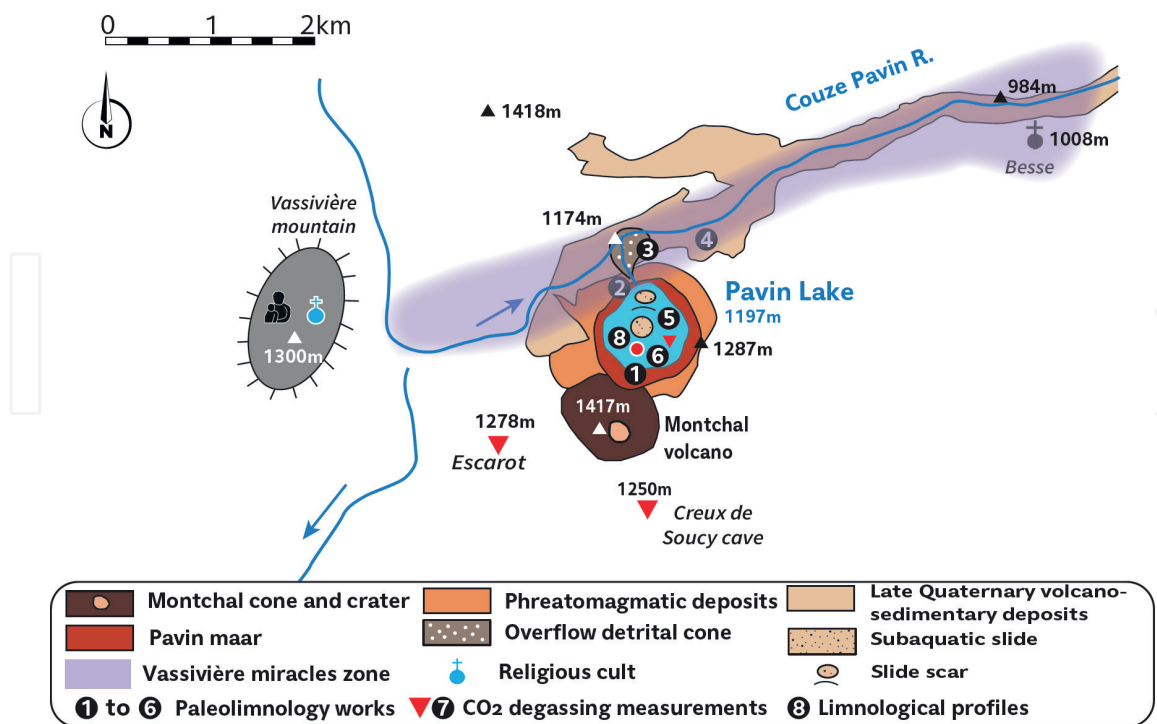


Figure 3. Schematic map of Pavin geosite and its current scientific approaches (see also **Figure 6**). 1. Paleo lake levels revealed by LIDAR and morphological analysis of lake rim. 2. Natural outlet incision analysis. 3. Pavin detrital cone stratigraphy below outlet. 4. Scattered overflow deposits in Couze Pavin River thalweg. 5. Scars and deposits of subaquatic sediment sliding revealed by fine-scale bathymetry, sub-bottom profiling, and radiocarbon dating of long piston sediment cores. 6. Sedimentary archives (7000 BP–Present) from lake core stratigraphy and geochemistry. 7. Present CO₂ measurements in lake and surroundings. 8. Limnological profiles in the lake waters and measurement of CO₂ emission from the lake surface. Besse city and the sacred site of Vassivière are culturally linked to Pavin by the Vassivière cult and its attributed miracles.

side of the Cantal stratovolcano, aged 2–13 Ma. In contrast, Pavin maar results from a very recent phreato-volcanic eruption 6730 years BP, which occurred a few hundred years after three other nearby eruptions, the Montcineyre, the Estivadoux, and the Montchal; this recent volcanic area is almost aligned with the N-S Chaîne des Puys. Pavin maar depression, cut into the Mont Dore basalts and into the northern part of the Montchal volcanic cone, generated the latest cataclysmic phreato-magmatic eruption of Plinian type in the Massif Central; its tephra found in numerous peat bogs are considered to be the last ones emitted in continental France [35].

3.4 Written sources and attempts to solve the mysteries of Pavin

The type of historical descriptions of Pavin and its surroundings have evolved a lot since their first publication in the sixteenth century. They also depend on the geographic position of the witness with regards to the lake and on their social position. As the lake was avoided until the mid-1800s [6, 10] and its violent events can be quite short—two hours for the 1785 waterspout—full descriptions of events by in situ witnesses are rather rare. Therefore, the post-event descriptions are dominant.

Heterogeneous sources on Pavin history were found one by one: an official complaint to the King of France (1566), a pictorial representation in a royal manuscript (1575), a visit by a medical hydrologist (1605), the religious registers of local miracles (1615, etc.), a very detailed manuscript description of the lake written by a local Besse scholar (1750s), publications in local and national newspapers (1783, 1803, 1986),

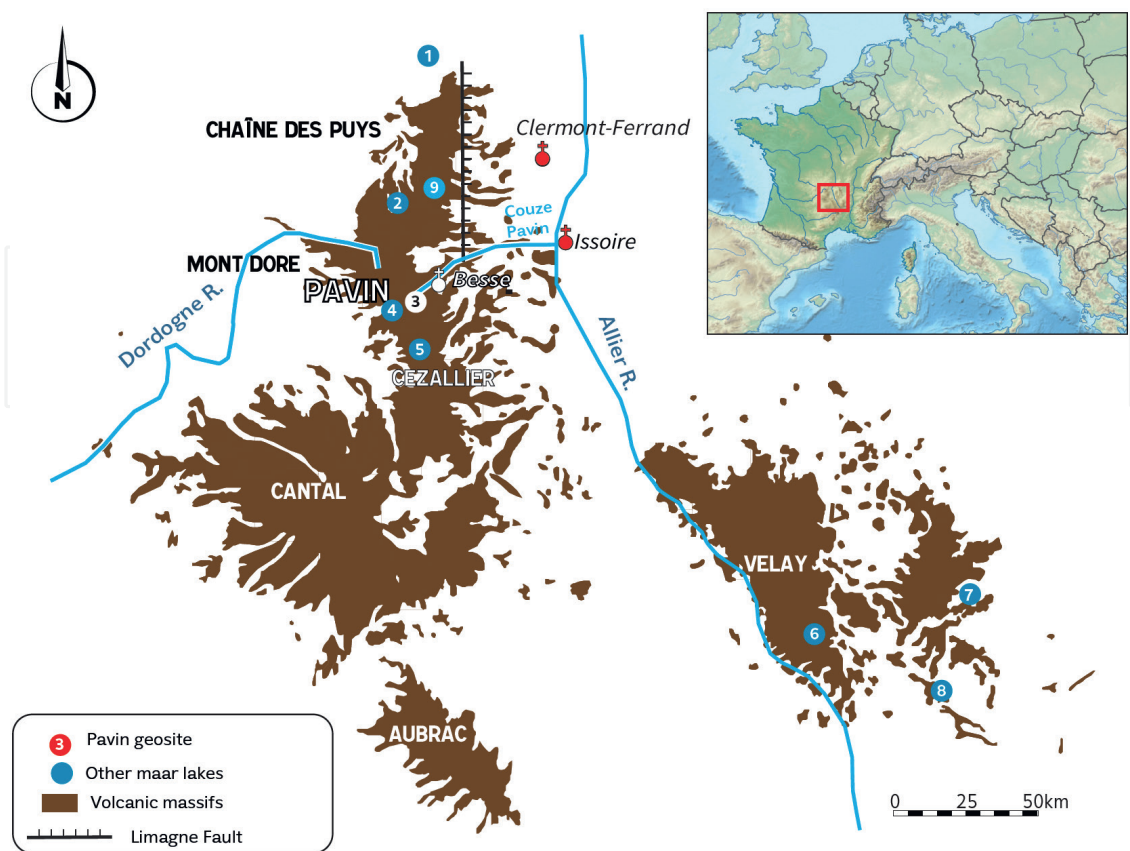


Figure 4.
Pavin Lake in the Central Massif volcanic provinces (France): Cantal, Mont Dore, Cézallier, Chaîne des Puys, Aubrac and Velay. Maar lakes: 1 Tazenat, 2 Servièrès, 3 Pavin, 4 Chauvet, 5 La Godivelle d'en haut, 6 Bouchet, 7 St Front, 8 Issarlès. 9 Aydat Lake (lava flow dam). Only Lake Pavin is presently meromictic and believed to have degassed in the recent past.

maps (since the mid-1600s), multiple travelers' accounts (eighteenth century and after), guide-book (nineteenth century), recent interviews, and contemporary legends collected by the authors. An unexpected and precious source of information on the Pavin area is the register of miracles, attributed to the power of an early medieval wooden statue, the Vassivière Madonna, revered since ages. There, a famous local pilgrimage was re-initiated in 1547. Since then, all miraculous healings occurring in the Vassivière-Pavin-Besse area have been carefully registered by the Catholic Church authorities, including a striking tempestuous event reported in 1551. Numerous Pavin legends have orally been transmitted across centuries and then transcribed between 1820 and 1925; they are discussed in a companion paper [36].

3.5 Analysis of historical accounts and descriptions about Pavin

We have selected here the most detailed and pertinent descriptions, generally made by identified eyewitnesses (**Figure 5**). They are well contextualized, providing dates and positions, and are often reported by local elites with higher educational backgrounds. These sources have been largely or totally ignored by Pavin analysts until now [6].

Pavin misbehavior is reported here through seven events of various intensities. Several violent storm events (1551, 1750s, 1785) combining lake and atmospheric disorders have been described through a triple motif: atmospheric and lake storm + thunders + lightning's, generally associated with the suddenness of the event occurring within a "serene

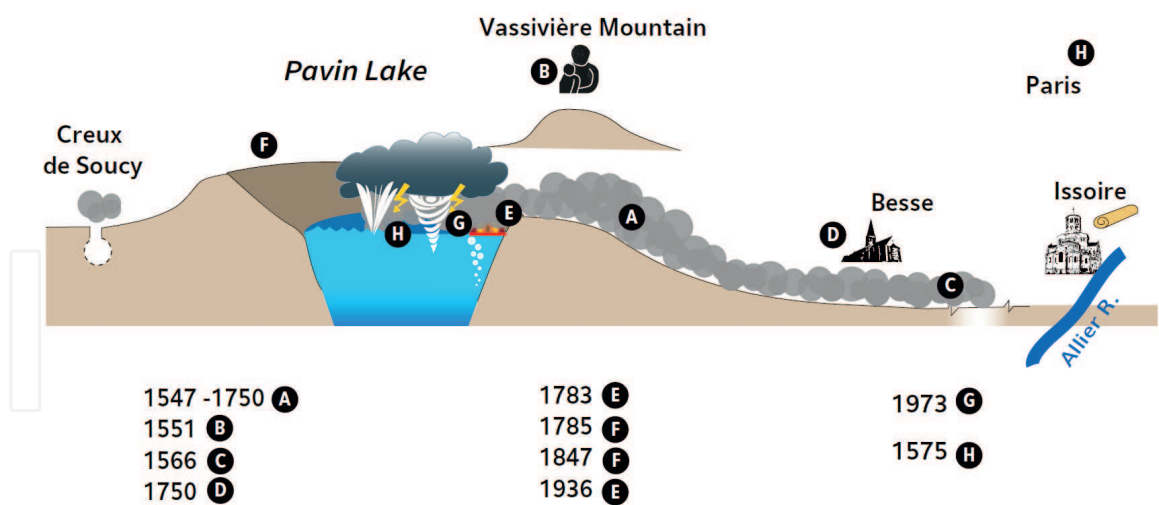


Figure 5. Principal historical observations of Pavin degassing and positions of witnesses (see Annex B for details). A, 1547–1750s: neurological damages in Vassivière-Pavin-Besse area, reported in Vassivière chronicles. B, 1551: violent explosion witnessed from Vassivière. C, 1566: storms with thunder and hail causing damage to crops in the valley. D, 1750s: detailed description of Pavin behavior by Besse observer. E1, 1783: sudden color change (within 4 hours) and whole lake boiling witnessed at outlet. E2, 1936: color change (in less than 12 hours) witnessed at outlet. G, 1785: limnic eruption with whirlpool and waterspout (6 m diameter, 50 m high). F2, 1847: lake storm, observed from rim (?). G, 1972: boiling circle in lake (10 m wide with 20 cm eddies) crossed on boat. H, 1575: Pavin storm generated by a tempestary stone, published by Parisian cosmographer Belleforest. Many historical manuscripts were kept in Issoire monastery, 30 km downstream of the lake, and exposed to its misbehavior.

atmosphere” (clear sky), often with smoke emission, whirlpool, and/or waterspout. They can be understood as limnic eruptions. Medium-intensity degassing events are accompanied by fog and devastating clouds (1566, 1750s). Low-intensity events include rollovers with boiling waters and sudden color and texture changes (1783, 1847, and 1936). The impacts on the local population are inferred from the Vassivière miracle register. The detail of the descriptions depends on the position of the observers (Figure 5).

In 1575, the description of Pavin—not listed here—published by Parisian cosmographer Belleforest [57] attributes the sudden storms of tempestuous Pavin, in association with thunders and lightning, to a stone thrown into the lake (see Appendix B, 1575). A thorough analysis reveals that Belleforest had actually reproduced an earlier description (thirteenth century) of an unlocated and unnamed tempestuous “mountain pit” where demons generated storms when a stone was thrown into it [36].

4. The perception and response of the local population to Pavin disorders (1547–2024)

Historical sources also allow us to reconstruct the perception, the representation, and, in general, the social response to Pavin disorders, which have been officially considered for several centuries and then gradually called into question. While in the nineteenth and twentieth centuries official science erased the past behaviors of Pavin, whose original name, *pavens*, means “the terrifying” (Appendix B, 1605), the memory of the fear he generated and the need for protection remain very present today in an exceptional religious practice, which has been taking place since the mid-1500s, without the connection with the stormy lake ever having been recognized by the church. The chronological summary of Pavin descriptions, perceptions, representations, and analyses is proposed in Table 3.

4.1 The Vassivière register of miracles, an account of degassing impacts on local population (1547–1700s)

The past effects of Pavin degassing on local populations are derived from our re-interpretation of well-known local miracles collected since 1547 by the religious authorities from Besse, then validated by a complex process set up by the Catholic

1551	Sudden violent storm, thunder, and lightning observed from Vassivière [60, 61, 66, 73].
1549–1700s	Healings (contusion, loss of sight, sudden paralysis...) observed between Vassivière and Pavin [60, 61, 66, 73].
1566	Complain to Charles IX about a <i>mountain pit exhaling clouds, thunder, and hail that damage crops in valleys</i> [62].
1575	Belleforest's description of a tempestuous lake on top of a mountain whose storm is triggered by a thrown stone [61].
1579	Pavin is pictured for the first time in the royal Besse manuscript, overlooking the valley of the Couze Pavin [57].
1672*	A stone thrown into Pavin does not trigger any storm [67].
1750s	Tempestuous Pavin detailed description; every day in summer the lake produces misty fog and occasionally few violent storms which threaten the whole region, hence its name: <i>lacus pavens</i> , the terrifying lake [66].
1770*	Pavin is sounded for the first time (96 m) by a royal engineer [58, 77].
1783	Boiling lake (rollover): the watercolor and aspect of the lake outlet changed within a few hours. The whole lake is boiling. Corrosive water generates skin buboes. A sub-lacustrine slide is inferred [68].
1785	Limnic eruption by fair weather: a spiraling ascending column of water, 6 m wide, is seen. When reaching the edge of the crater, a terrible storm breaks out, with thunder and incessant lightning. The storm lasts 2 hours, then the sky is clear again. A hail deposit, 20 cm thick, is observed on the shore [37].
1788*	<i>Pavin is just a simple lake; I would like to dive in its deep waters to unveil its secrets</i> [77].
1829	<i>Often thick clouds and hot exhalations would spread on its shore...; Its name, Pavens, imposed by the Romans, tells well that it was a threat in this area</i> [75].
1835*	<i>Pavin stories are absurd tales and legends invented by fear and transmitted by credulity</i> [70].
1847	Storm developed at the lake surface with shocking waves and whirlpools [71].
1859*	First salmonidae fishes successfully introduced in Lake Pavin by Rico and Lecoq [6, 10].
1892	CO ₂ emission from Creux de Soucy cave is assessed for the first time by a speleologist [82].
1896	CO ₂ presence and impact on visitors near the lake are evoked for the first time [80].
1890–1909*	Development of touristic access to the lake; first limnological studies [9, 10, 14].
1929	Degassing hypothesis: the CO ₂ , stored in Pavin deep waters and generated by volcanism could suddenly burst out and generate lake overflows as those traditionally feared by Issoire people [30 km downstream] [81].
1936	Color change (rollover) overnight, from very transparent waters to yellowish-orange glutinous waters that clogg the lake outlet grid; colloidal sulfur smell is perceived; fish kill [72].
1950s	Limnologists discover Pavin meromicticity by O ₂ profiles, then by water chemistry (Fe, Mn, etc.) [9, 10].
1971*	Pavin stories are <i>tales of maid women</i> ; the Pavin name originates from <i>pallenc</i> , palissade in Occitan [78].

1972	Column of bubbles emitted from the southern part of the lake, 10–15 m wide, 20 cm high (August 1972); no specific smell was observed. Witness never dared to report the event. [Interview in Besse, May 2024].
1993*	First degassing risk assessment at the request of national authorities [26].
2005–2009	Detrital deposits were found in the Couze Pavin thalweg and attributed to violent lake overflow [83]. A confidential commission is set up by regional authorities.
2008*	Limnologists report: “No spontaneous gaseous eruption can take place; The present situation is stable and only important landslides, disturbing bottom sediments could generate a partial degassing.” [84].
2009*	The Pavin and Meromictic Lakes conference held in Besse rejects the hypothesis of Pavin misbehavior.
2010–2024	Paleolimnological, geomorphological, and geological evidence of Pavin Lake events during the last two millennia, coherent with perception and description of past Pavin “misbehavior” [6, 9–11, 29, 30, 36, 48, 85–91].
2016	First synthesis on Lake Pavin [27]; geohistory and paleolimnology cover several chapters [9–11, 35, 91].
2021*	Volcanologists report: <i>The so-called Lake Pavin misbehavior (Meybeck, 2016a, 2016b) has not been well documented or understood</i> [32].
2023	<i>Only three lakes in Europe (i.e., lakes Pavin in France, Albano, and Monticchio in Italy) and one in Africa (i.e., Lake Kivu in the D.R. Congo) evidenced markers of limnic eruptions in their sedimentary archives</i> [87].
2024	First modeling of a sudden release of CO ₂ during a limnic eruption with risk assessment for Pavin visitors and Couze River valley population [34].

Table 3.
Chronological summary of past Pavin misbehaviors, normalizations (), and analyses (detailed accounts in Appendix B).*

bishop of Clermont, including names of witnesses, their locations, and dates [59, 60, 73, 74].

The Vassivière Mountain, located 1.5 km West of Pavin at 1300 m asl (**Figures 2 and 3**), is the location of continuous and major Christian worship for the last 500 years. According to some local historians, it was probably active in the Late Antiquity [73]. There, a wooden statue of a Black Madonna with Child was worshipped since the Early Middle Age in a first church dismantled in 1320 for “profane behavior” of the population. From 1320 to mid-1500s, the statue, put in a depository in an ancient wall, was still worshipped. The devotion to the statue was re-vitalized after 1547, when the miraculous healing of a merchant, suddenly caught blind between Vassivière and Besse, was officially declared by church authorities [59, 60]. A chapel was rebuilt in the 1550s, and a new pilgrimage started at a time when Pavin misbehavior was particularly noted and feared. The original statue was destroyed at the Revolution and quickly replaced by a copy, continuously revered in the 1800s and 1900s [11, 73, 74]. One of the authors, MM, assisted several times as a kid to the ritual masses of August 15 in honor of N.D. de Vassivière in the mountain sanctuary. The most significant ceremonies (1638, 1881) attracted up to 20,000 pilgrims from all over Auvergne to this tiny hamlet, abandoned in winter, where snow was sometimes lasting in August [59]. The Vassivière Guild, composed of all parishes, 20–30 km around, oversaw the rituals, the collection of offerings, and the acquisition of the many relics.

The close relation between the ancestral Vassivière worship and Pavin misbehaviors has been suggested in some local religious sources, although not officially

recognized by the church and the miracles attributed to the Madonna were never contested by the local population. In 1688, Cladière reports in his chronicle: “*The inhabitants of Besse carry the Image [statue] in every danger... the corrupted air was purified in an instant*” [60]. In the early 1800s the “tradition” collected at Besse by Nodier, Taylor and Cailleux [75] clearly connects Pavin disorders to the Vassivière pilgrimage: “*Some would also tell you that if She [the Vassivière Virgin] was not brought back [from Besse to Vassivière], one could see at once a luminous vapor surging from the earth and wrap the church, with gliding cherubs, musicians archangels and all Christian mythology spirits, who bring her back with pomp in her uninhabited land*”. In 1857, a Vassivière poem still evoked the mighty storms generated by demons: “*Satan, on the stormy peak, led his infernal rounds... For eight days, the storm roared, and during this time the devils, unleashed in the neighborhood, damned the inhabitants. ... Lucifer, without being exorcised, flies away...the demons come out of their hideouts, the air regains its serenity*” [69].

The detailed Vassivière “miracle register,” maintained from 1547 until the 1800s, contains 109 miracles, many of them occurring locally in the area between Vassivière and Besse [73, 74]. One of the most remarkable miracles relates a sudden and violent storm in 1551 (Appendix B, 1551).

In 1907, Dr. Noir, a Parisian medical doctor, noted [76]: “*the group of the most numerous and most interesting miraculous cures consists of 33 cases where the illness clearly has the characteristics of hysteria. Most of these patients are unfortunate people who are at once paralyzed, blind, deaf, and mute and who suddenly recover movement and the use of their senses after prayer to the Virgin.*” The doctor could not offer any explanation for these neurological damages. The similarities with the impacts on populations generated by the degassing of lakes Albano and Nyos are striking (**Table 1**). We believe that these diseases were most likely generated by CO₂ emissions from Pavin, invisible, sudden, and sneaky, and, for centuries, their spontaneous healings have been considered miracles by the local population. The Vassivière records rarely mention human life losses since there was no miraculous healing but occasionally report a massive mortality of cattle.

The multi-secular belief in miracles attributed to N.D. de Vassivière is so deeply grounded in traditions and Auvergne culture [74] that no historian has attempted a re-assessment of this unique and long-lasting tradition from a non-religious point of view [6].

4.2 The successful sounding of Pavin in 1770

In the 1700s, the reputation of the unfathomable nature of the marvelous lake seemed unbearable to the authorities. After a failed attempt in 1726 by locals, a successful sounding is carried out in 1770 by Chevalier, a royal engineer of bridges and roads [9]. He is equipped with the latest scientific instruments (navy-sounding instrument, Réaumur thermometer, and leveling instruments) to achieve precise measurements and examine the possible relationships between the Pavin and the Creux de Soucy cavity (**Figures 3** and **5**). Chevalier finds the bottom at 288 feet (96 m), discovers the hidden springs that feed Lake Pavin, identifies the lava cliffs (Mont Dore lava flow), and establishes that the tiny and secret lake found at the bottom of the Creux de Soucy is at a higher elevation than Pavin level, making communication possible, a hypothesis denied today. The normalization of Pavin Lake can begin. Ironically, a few years later, two major descriptions of Pavin misbehaviors are published; both will be ignored by authorities and Pavin analysts [6, 48].

4.3 The normalization of Pavin's tempestuous character by scientists and authorities (1770–1993)

Many attempts to solve Pavin mysteries have been made since 1788, by literary voyagers, a botanist, a naturalist and geologist, authors of scientific guidebooks, local historians, a school professor, folklorists, a renown Auvergne historian, writers, and many others [6, 9, 10, 36]. Generally, they are based on one or two sources only.

In 1770, the sounding by Chevalier puts an end to several Pavin mysteries listed by Belleforest (Appendix B, 1575). Legrand d'Aussy in his *Voyage en Auvergne* (1788) [77] and Abbé Delarbre [58] went further and invalidated the famous devastating clouds and the sudden storms mentioned by the cosmographer, although Legrand raises many questions on Pavin deep waters [6, 10]. Meanwhile, the local and regional authorities pushed for a complete normalization of Pavin. All were ignoring the 1785 limnic eruption, only published in 1803 [6], but reported orally by local guides to a growing number of visitors. Naturalist Henri Lecoq [70] will name them “Pavin stories” (Appendix B, 1835). In the 1820s, a new local road is constructed in the Couze Pavin valley; the previous one avoided passing below the lake. A first boat is built and brought to the lake, allowing the successful introduction of fish (trouts, salmon, chars)—absent until then—by Lecoq and Rico in 1859, an ultimate reason to invalidate all Pavin stories [6].

The first access pathway to the lake and the walkway around the lake (1859–1909) finally allowed the visitor access and the development of tourism. Meanwhile, the city of Besse pushed for the scientific analysis of Pavin by the first limnologists in 1890–1914 [6, 9].

In the twentieth century, all volcanologists and limnologists avoided evoking the tumultuous Lake Pavin history [9], including one author of this paper [15, 26]. It must be recognized that, until recently, the very few known historical descriptions of past Pavin events were often entangled with legendary accounts told by local guides, such as those of Delarbre and Lecoq, particularly the story of the tempestary stone (Appendix B, 1575), still told orally in the Pavin area in the 1960s (MM personal observation). Historians and social scientists had also not much addressed Pavin: most were following the statements of Legrand d'Aussy in 1788, “Pavin is just a simple lake” [77], and the official Pavin descriptions, as the one of Jouan (Appendix B, 1566), were regarded as “legends invented by fear and transmitted by credulity” [71] or as “tales of maid women” [58], an expression endorsed later by renown Auvergne historian Pierre-François Fournier [78], for whom the lake name comes from the Occitan *pallenc*, which means palisade, an allusion to its steep basaltic cliffs (and not from the Latin *pavens*). This judgment made by a well-respected scholar 15 years before the Nyos eruption, has probably limited further investigations by other historians [6].

4.4 Deep-water CO₂ degassing, a hypothesis made by writers ignored by scientists

At the end of the nineteenth century, the hypothesis of lake degassing is made for the first time by Ajalbert, a noted Parisian writer visiting Auvergne [80]: “*suddenly one can no longer breathe, the throat is strangled as at the bottom of caves where, for lack of air, one would suffocate. It is the upper part of a crater which jumps under the force of the underground gases, like the cork of a bottle of champagne.*”

In 1929, this hypothesis was further developed by Jean Larat, a literature teacher at Issoire, 30 km downstream from the lake (**Figures 3 and 5**): “*the volcanic activity has not completely disappeared and it still results in continual releases of carbonic acid. At the bottom of Lake Pavin, these gases remain trapped in the crevices of the volcano under the effect of the*

heavy mass of water which covers them. But if the fall of a stone, reaching the bottom of the lake, releases the gaseous masses it contains, the rise of these gases which explode on the surface of the lake then produces a sort of bubbling of the water and the formation of real waves. It's a storm in miniature, a small storm on the lake. Here, the legend is therefore not entirely devoid of any reality... Nor will we try to dissipate the fear which consists of seeing a geological commotion project, one day, the enormous mass of the lake onto the slope of the ravine of the Couze [Couze Pavin River]. According to legend, it must, in its furious descent from the mountain, after having carried away numerous villages, submerge the town of Issoire" [81]. This striking analysis, published in a local journal at a time when neither the meromictic character of the lake nor the presence of CO₂ in deep waters were yet established, has been ignored by all Pavin analysts and scientists.

4.5 The degassing controversy among scientists (1986–2024)

When the Lake Nyos catastrophe occurred in 1986, Pavin was quickly identified as a maar lake with potential degassing risk [6] for the nearby population and for the 200,000 annual visitors coming to see the beautiful site, most of them standing a few meters above the lake level, at the outlet, and on the circular hiking path.

The first risk assessment of Pavin is carried out in 1987–1992 at the request of national authorities by volcanologists and geochemists, including one of the authors (MM), and led by Guy Camus, a Clermont-Ferrand volcanologist. CO₂ was measured for the first time in its deep waters, and we concluded in 1993 that there was no risk of degassing under current conditions [26]: *"it is considered that poison gas outburst of limnic origin (upset and ebullition of CO₂-rich water from the monimolimnion) is not to be held today as a realistic hazard in the French Massif Central."* Pavin history was totally ignored. A second assessment (2005–2008) was carried out confidentially at the request of the provincial authorities by a committee of experts, including one of us (PL), following his discovery of a patchy detrital recent sedimentary formation deposited downstream the lake in the Couze Pavin thalweg over 10 km when updating the local geological map [48] (see **Figure 3**). For its discoverer, it would have been generated by a recent sudden overflow of the lake [83], hardly dated, a catastrophic hypothesis as soon questioned by local volcanologists and rejected when it was submitted to the Journal of Auvergne natural history. A similar rejection consensus was reached once more at the International meeting on Pavin and other meromictic lakes held in Besse in 2009 and attended by French specialists of Nyos, local volcanologists, and scientists from Pavin [6], including three of the authors (PL, EC, and MM). There, the hypothesis of past violent degassing/overflow presented during a field visit (led by PL) was again ruled out. At the meeting, Pavin history analyses made by Delarbre [58] and Lecoq [70] were still considered references by Pavin scientists.

These three official scientific risk assessments (1993, 2005–2009, 2009) ignored the comparisons with other degassing maar lakes (Monticchio, Albano) and the exceptional geohistory of Pavin. The Besse meeting in 2009 triggered an interest in Pavin history and paleolimnology, while Pavin limnological studies were also developing.

5. Pavin degassing approached by scientists

Since the 1970s, Pavin has been studied using very diverse scientific approaches in limnology, hydrobiology, geochemistry, microbiology, sedimentology, paleolimnology, geology, and geomorphology [27], as schematized in **Figure 6**.

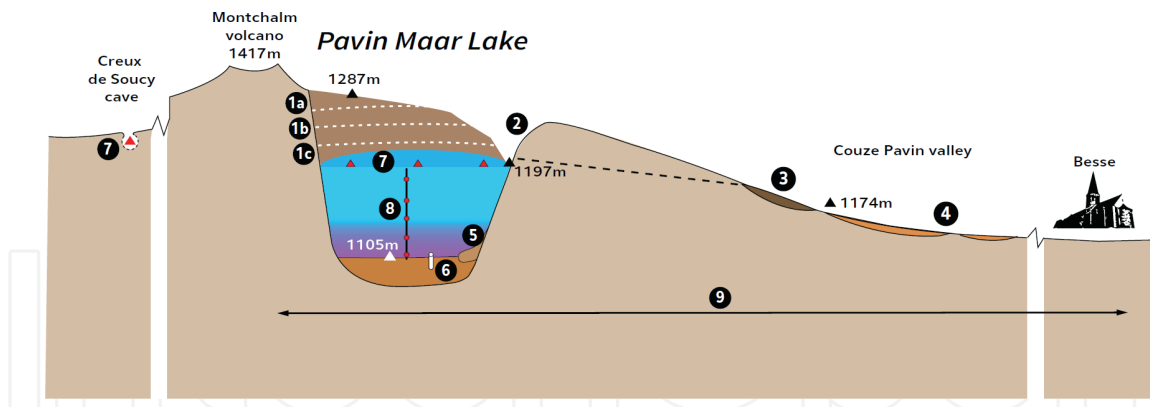


Figure 6.

Scientific approaches used to analyze Pavin functioning, its current degassing risk, and its past behavior, as overflows and rollovers. 1a, 1b, 1c: Paleolevels (+18 m, +8 m, +4 m, respectively) revealed by LIDAR and morphological analysis of lake rim. 2: Outlet incision geomorphological analysis. 3: Pavin detrital cone stratigraphy below outlet. 4: Scattered overflow deposits in Couze Pavin River thalweg. 5: Scars and deposits of subaquatic sediment sliding revealed by fine-scale bathymetry and sub-bottom profiling. 6: radiocarbon dating of long piston sediment cores and sedimentary archives (7000 BP-Present) from stratigraphy and geochemistry. 7: Present CO₂ flux measurements at lake surface and in Pavin surroundings. 8: Profiles of water geochemistry, physics, biodiversity, and microbiology in monimolimnion, chemocline, and mixolimnion. 9. Degassing risk model of the Pavin area covering the crater zone and Couze Pavin valley.

5.1 Pavin for limnologists: A “lake monster,” a window on primitive Earth

Lake Pavin is one of the very few lakes that have been studied continuously by limnologists for more than 100 years [9]. They have gradually discovered its limnological peculiarities, which make the lake attractive for dozens of scientists from many disciplines [27] and so different from all other maar lakes of Auvergne-Velay. Pavin rare peculiarities (origin, morphology, hydrology, chemistry, ecology, algal biodiversity, sedimentology) already found in the late nineteenth century by Delebecque [14] and by local naturalists from Clermont-Ferrand [9, 10], have been confirmed by recent investigations [27, 92].

It took limnologists a hundred years to realize its hybrid nature, due to sub-lacustrine hydrothermal inputs linked to the recent volcanic origin of the lake [27, 93–97]. The well-oxygenated surface layer, the mixolimnion (0–60 m 40 years ago, today 0–50 m) is controlled by photosynthesis, water, and material inputs by atmosphere and lake basin, as in any other lake. The lower part is regulated from the hydrothermal control (heat, water, salts, and CO₂ inputs) and by the constant rain of siliceous diatom algae detritus produced in the euphotic zone (0–15 m). This bottom layer, the monimolimnion (65–92 m formerly, today 55–92 m), is much richer in dissolved salts and totally anoxic. Between these two layers, there is a transition layer of a few meters, the chemocline, also termed the redoxcline, in which gradients of ionic concentrations (e.g., Fe and Mn species) and dissolved gases (CO₂, CH₄) can reach two or three orders of magnitude. Today, the in situ and continuous profiles of O₂, temperature, and electrical conductivity profiles reveal the great complexity and dynamics of the chemocline.

Pavin chemocline and monimolimnion are now a natural laboratory, intensively studied over 50 years [93–102], offering insights on the chemical and microbiological functioning of the Archean Earth, 2.5 billion years ago. Also, its varved diatomite sediments provide precious archives at various time scales, including for the analysis of the Anthropocene, as in a few other lakes [103–105]. Until recently, many limnologists were rather skeptical about the historicity of its past misbehavior: “the current pressure of CO₂ and CH₄ is much lower than the hydrostatic pressure: spontaneous degassing is improbable... however, other events must be taken into consideration such as a large landslide” [84].

5.2 Pavin, a model for paleolimnology of degassing maar lakes

The first obvious morphological feature of Pavin in relation to its past history is its specific outlet. Natural outlets are very rare in maar lakes, whether in Auvergne, Eifel, or Italy, and none of them are as incised as Pavin. Actually, the rim of several European maar lakes has been excavated by tunnels in Antiquity or Middle Age (Albano, Nemi, Laacher See) to generate artificial outlets, probably to limit overflows [11, 23, 24]. These enormous works around 400 BC (Albano, Nemi) or in the eleventh century (Laacher See) can be considered as technical feats. In 1783, the Pavin outlet was described as a terrifying gorge [68], and the original steep outlet notch incised in the lake rim, suggesting intense erosion, is well pictured in Lecoq's watercolors in 1835 [9, 48, 106]. Today the outlet has been completely modified by the construction of an access road and a visitor platform [9, 10].

Detailed geomorphic analysis of the Pavin area also revealed a lake outlet fan, multiple scars of movements on lake slopes, and rockslides [31], which result from the instability of Pavin Maar and Lake. Integration of terrestrial LIDAR data with multi-beam bathymetric data, sub-bottom profiling, and multiproxy study of radiocarbon-dated long sediment cores in the deep central basin of Lake Pavin suggests at least three former periods characterized by higher lake levels (**Figure 6**) [85]. Two abrupt lake level drops around 600 AD and 1300 AD were probably synchronous to crater outburst floods in the Couze Pavin valley and subaquatic sediment slides in Lake Pavin [86].

A team of volcanologists [87], well trained in the study of degassing maar lakes, recently reviewed how "Lake Nyos-type" behavior can be archived in the geological record. They are presenting Pavin as a model for a multidisciplinary paleolimnology approach and list what has been found there by a team led by one of us (EC) for a decade [29, 30, 55, 86–90]. (From [87] with a few additional elements and citation numbers from the authors of this paper):

"Local CO₂ degassing currently occurring in Pavin area: *"It was not until 2005–2006 that CO₂ degassing points were discovered in many places in the region [83].*

Lake overflow deposits: *A long mudflow deposit downstream of the lake outlet has been suggested and attributed to a recent (and undated) violent overflow of the lake [107].*

Multidisciplinary paleolimnological study: *acoustic surveys, sediment cores stratigraphy and geochemistry (spectrophotometry Total organic carbon, Hydrogen index, Si/Ti and Fe/Mn ratios).*

Detrital sediments indicator: *the titanium concentration makes it possible to monitor the evolution of the supply of detrital sediments [30].*

Past lake levels: *A significant drop in lake level since 600 AD is suggested by changes in littoral subaquatic environment and sedimentary organic matter [29, 91].*

Major subaquatic sediment slides: *around 600 AD and 1300 AD reflecting regional seismicity probably favored an intensification of Lake Pavin meromicticity and the development of limnic eruption [88, 90, 91].*

Outlet erosion: *These landslides caused the outlet to erode and the crater rim to rupture, leading to a sudden drop in water level and the release of a debris flow downstream [88].*

Five historical earthquakes: *recorded in the region between 1348 and 1921 AD, they triggered limited sedimentary events characterized by changes in magnetic susceptibility and/or spectro-colorimetry values [107].*

Gas-rich sediments reworking: *it could cause [55, 88, 91]: (i) the release of an enormous amount of gas into the water column and consequently a limnic eruption [28, 108, 109], (ii) the triggering of violent waves and the overflow of the lake which could lead to the formation of a debris flow as well as a sudden drop in the lake level, thus affecting the stability of sediments and gases in the water column and leading to a limnic eruption [28].*

Thunder sounds and orange water color: *documented by Meybeck [10, 48] they are linked to the rollover of 1783 and to the waterspout of 1785 AD, similar to a limnic eruption [48].*

Conclusion: *Signs of limnic eruptions in Pavin include reworked sediments of reversed ages, deposit colors reflecting a mixture of highly gas-laden water in an anoxic environment and water in an oxic environment and/or at the surface, sediments gas-rich, sediments rich in iron hydroxide, strong peaks of Ti and Fe oxidized during events."*

Pavin paleolimnological (sedimentary) records of major events (large subaquatic landslides around 600 AD and 1300 AD) are associated with clusters of regional earthquakes, but also records of minor events (small slides or thin turbidites contemporary to historical earthquakes in 1783 AD, 1844 AD, 1863 AD, and eventually in 1921 AD), overflows (after 1765 \pm 55 cal BP), and eventually of rollovers (in 1783 AD).

A regional lake study [88] highlighted that numerous erosive events are characterizing sedimentary basin fills of the Auvergne volcanic lakes and are thus limiting paleo environmental reconstructions during the Roman period. Only one subaquatic slide has been identified and dated to 170 \pm 40 Cal AD (1770 \pm 60 Cal BP) in Lake Aydat (**Figure 4**), located 30 km north to Lake Pavin near the Limagne active fault (UNESCO world heritage), suggesting that the oldest reports of potential Lake Pavin misbehaviors may as well be a consequence of the active geological setting of this volcanic province rich in maar lakes.

If the mantellic or bacterial origin of CO₂ stored in the deep waters of Pavin has been discussed [26–28], regional investigations of volcanic lakes from Mont Dore and Chaîne des Puys volcanic provinces (**Figure 4**) highlighted the impact of two main active faults in this territory: a first one below the Mont Dore stratovolcano and a second one at the edge of the Chaîne des Puys and Limagne basin [89]. Based on multidisciplinary studies of lacustrine deposits from Tazenat, Chauvet, Pavin, Montcineyre, Aydat, Chambon Lakes, and Limagne palustrine sequence, clusters of paleo-earthquakes are suggested since 2700 Cal BP [88].

5.3 Current CO₂ measurements in Pavin and its area and modeling of sudden lake degassing

In the last two decades, CO₂ measurements have been realized in the Pavin area (**Figure 3**), confirming the CO₂ emission around the lake, particularly at the Escarot Mofette, 1 km southwest of Pavin where deep-seated CO₂ levels may be highly variable) [33, 83]. The nearby Creux de Soucy cavity, located on Montchal lava bed 1.5 km south of Pavin (**Figure 3**), is also a site where CO₂ can be very variable. In 1575, the cosmograph Belleforest mentioned that it was emitting “vapor,” as observed in Pavin [61]. In 1860, the mayor of Besse made a first attempt to explore the cavity; it failed because of “lack of air.” In June 1892, the famous speleology pioneer, Alfred Martel, came fully equipped to explore the Creux de

Soucy but failed to reach the bottom: a 6 m layer of gas was resting in the cave. Six months later, the CO₂ had vanished, allowing the cavity exploration for the first time by Clermont-Ferrand biologists [82]. During the second half of the twentieth century, other occurrences of CO₂ have been noted in this cavity, a sign of the great variability of CO₂ emission in the Pavin area. Today, speleologists and scientists check its occurrence before working there, and they believe that the cave water is not discharging underground to Pavin.

Rafflin and Boudoire from the Clermont-Ferrand Volcanology Laboratory (LMV) and several Italian teams from the Istituto Nazionale de Geofisica e Vulcanologia (INVG) have carried out the first comprehensive assessment of the degassing risks of Lake Pavin [34]. They acknowledge that *“past degassing events can be inferred from historical records describing activity in 1551, 1783 and 1936 according to Meybeck”* [9, 10], a statement in contrast to other LMV volcanologists who are denying the historicity of Pavin misbehavior and doubting its violent overflow events (**Table 3**, 2021) [32]. Their risk analysis starts with seasonal CO₂ profiles inferred from water chemistry that lead to the quantification of CO₂ stocks in deep water, then by measurement of CO₂ flux escaping from the lake surface. The potential degassing is simulated according to three scenarios, including a sudden limnic eruption emitting 450 t of CO₂, contained in the lower layer from 80 m to 92 m, out of a total of 1750 t, triggered by an external event (slide, earthquake, etc.). The dispersion of the CO₂ cloud in the entire Pavin-Couze Pavin area is then simulated by the INVG model, taking into account the topography established by LIDAR and the local distribution of winds. For the first time, the effects of degassing are quantified. Concentrations encountered at 1.5 m above ground are simulated, particularly those at the outlet platform. Impact on the 2000 daily summer visitors is finally assessed using the reference toxicity scale developed by the American Department of Industry. The risk is greatest for visitors standing on the lake outlet platform and for those hiking around the lake. In the sudden degassing scenario, the toxic cloud would reach the platform in 15 minutes and would be fatal during 1 hour (CO₂ > 15%). People in the Couze River valley at Besse, 4 km downstream (**Figure 3**) would be affected by the CO₂ cloud after 30 minutes but exposed to much lower concentrations, generating breathing difficulties (0.5% < CO₂ < 1.9%). Impacts would also be more severe for people with respiratory problems. Several risk management measures are proposed [34]: *“Areas around the lake would experience lethal CO₂ contents in the air less than 15 min after the beginning of a limnic eruption... The spatio-temporal evolution of the potential CO₂ cloud raises issues regarding the impacts of such a hypothetical event in the close vicinity of the lake and, given the area is populated and highly visited, needs to be considered in future risk mitigation strategies by (i) continuous monitoring of CO₂ in the Pavin area, (ii) rapid emergency response in the event of a limnic eruption, (iii) installation of gas detectors, sirens and information panels, (iv) an evacuation route and signage to identified safety points.”*

5.4 A new look at Pavin is now needed

The debate on Pavin misbehavior, initiated after Pavin sounding in 1770, closed by Lecoq in the nineteenth century, forgotten by the twentieth century limnologists, has been reactivated after 2005, *i.e.*, two decades after the Nyos catastrophe. In the last

20 years the parallel analyses of Pavin geohistory and paleolimnology have proven to be consistent. Furthermore, they are similar to historical descriptions of past degassing in other lakes. At Pavin several levels of degassing intensity are reported; most of them do not leave geological traces, such as bubbling, little waterspouts, fog, emission of vapors and clouds, effects on animals, and even limnic eruptions (**Tables 1 and 2**; Appendix B). The impacts on populations related to numerous Vassivière miracles include many neurologic damages and skin diseases [76], also mentioned at Nyos and at Albano.

Our on-going geomythological analysis of Pavin before the 1500s is suggesting that in Late Antiquity and Early Middle Age, Pavin was probably also very active [36]. The impacts on populations, evoked in some ancient lives of Auvergne saints (*Vita Sanctorum*, seventh-tenth century) and in some legends transcribed during the 1800s [11, 36], may thus be rooted in cascading natural hazards documented in and around Lake Pavin (earthquakes, landslides, tsunamis, crater outburst floods, lake level drops, limnic eruptions). Archeological and further historical investigations are now required to precise their possible origin since the Roman period.

We also believe that Pavin threats and damages on local populations are expressed in the unusual and rich iconography found in the local church of Besse: the medieval capitals, the 16th misericords (wooden sculptures), and the 17th chapel dedicated to S^{ta} Martha, a famous dragon slayer [11]. Other social and religious responses concern the Vassivière cult and the protective ritual, initiated in the mid-1500s and continuously practiced until today: the statue of the miraculous Black Madonna with Child is brought each summer from Besse church to the mountain sanctuary across Pavin zone by a devout assistance convinced of its power of protection and healing (**Figure 3**). End of September, the statue is brought back to Besse, waited by thousands with great joy and gunshots, a ritual famous across Auvergne (La Dévalade). One striking result of our study is this intimate connection between lake degassing and religion, a point which could be investigated in many similar lakes.

The famous French geographer Elysée Reclus knew about Pavin and continued to refer to its “enchantments” in 1885 without being able to understand their origin [110]. A new, multidisciplinary, and open-minded look at the lake must now be taken by scientists (Limnologists, geochemists, volcanologists, etc.) but also by social scientists (Auvergne historians, historians of religions, human geographers, anthropologists, etc.).

Until now, Pavin visitors are still largely unaware of its past history, but this could change now that a scientific consensus on its past degassing is being reached. An appropriate reaction of local Auvergne authorities (city of Besse, Puy de Dôme département, Parc Naturel Régional des Volcans d’Auvergne) to the re-assessment of degassing risk [34] is now expected. According to the local press (La Montagne, September 29, 2024), the lake CO₂ and the Escarot Mofette (**Figure 3**) are now surveyed since spring 2024, nearly two decades after the early warning by one of the authors (PL), and historical degassing is now mentioned, replacing “Pavin stories.” The social response at the local scale will probably diffuse gradually, although slowed down for several reasons [6]: (i) authorities have been so far denying any risk on the basis of scientific reports and very reluctant to admit the historicity of Pavin misbehavior, e.g., on information panels presented to the visitors; (ii) admitting any potential risk may probably lead to a revision of tourism management at Pavin and may concern properties in the down lake area potentially exposed to the modeled CO₂ cloud. However, these changes would probably be balanced by the increased attraction of Pavin if it is developed as an exceptional geosite with great geoheritage value.

The diversity of historical sources and the variety of scientific approaches that have been used here for the reconstruction of Pavin past were unsuspected when this

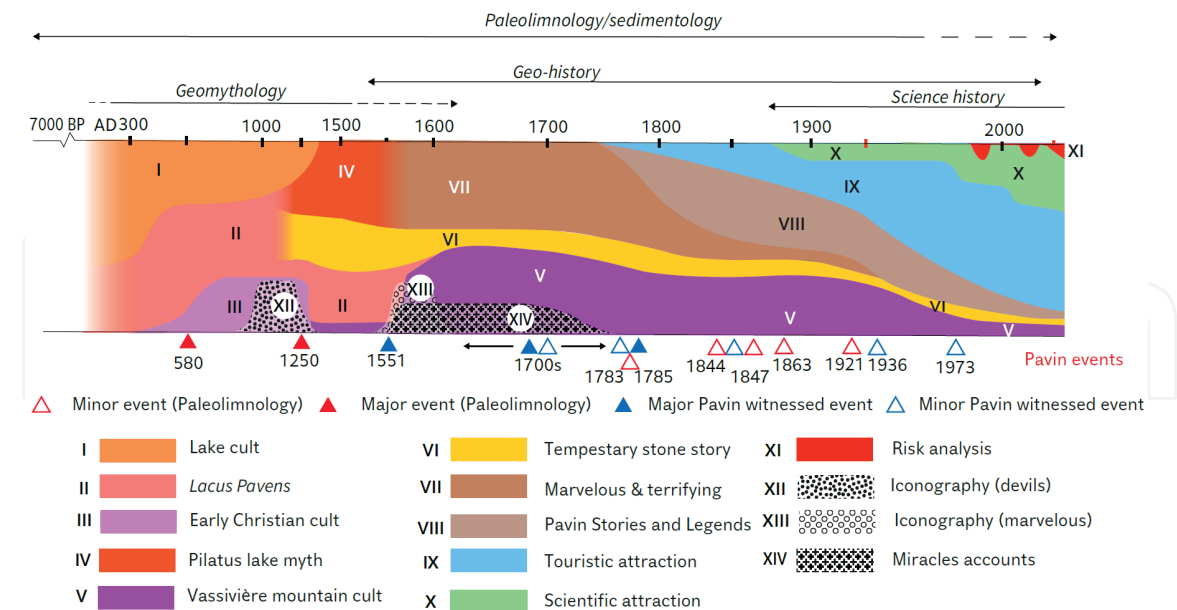


Figure 7. Reconstruction of Pavin past misbehaviors and graphical summary of the evolution of Pavin perception, representation, and memorialization from antiquity to the present. The analysis of Pavin geomythology—before 1550—and legends is not detailed here [36]. (Key dates of major Pavin events, normalization attempts, and degassing hypothesis: see text, **Tables 1 and 2**; Appendix B).

analysis started in 2009. This was made possible because we shifted the traditional points of view previously used by scientists (including one of us, MM) and by historians of Auvergne [78] or of Pilatus lakes at the Middle Age [111], and we did not rule out the hypothesis of its degassing as in Nyos.

Our current understanding of the complex and evolving social, religious, and scientific relationships between Pavin and society is presented through a temporal fresco (**Figure 7**).

6. Degassing maar lakes, from “new hazard” to global geoheritage

6.1 Past misbehavior in other European maar lakes, a growing evidence

Descriptors of maar lakes degassing (**Table 1**) can now be tested at Pavin before 1550, and in other maar lakes, where archives, archeological artifacts, literary and legendary sources, or traditional rituals are abundant. Preliminary assessments show that perception and representation of the degassing risk in antiquity, the Middle Age and the Renaissance can be quite different. The re-analyses of ancient sources at Lake Albano [23–25, 112], Lake Montichio [21, 22, 113, 114] and Lake Averno [25] are promising and reveal that degassing perception can be quite old, related to many Greek and Roman myths [25], to Christian myths and associated with religious cults of these periods.

The Eifel maars in Germany have a great potential for such reconstruction. A first analysis of local legends has revealed that at least four of them could be linked to lake misbehavior events [11, 115]: (i) Ulmener Maar where “giant fishes” (probably waterspouts) were described by Rhenan cosmographer Sebastian Münster (1550s), who reports their association with the death of new-born babies [116], and where legends of witches living by the lake and possibly intoxicated by it are still locally celebrated, (ii) in Weinfelder Maar (or Toten Maar) where the population of a whole

village suddenly disappeared between two censuses in the 1500s and in which a “Pilatus rock” is still shown on the lake cliff, (iii) Pulver Maar, famous for its legend of a shepherd making circumambulation around the lake to prevent its eruption [11], (iv) Laacher See which has the richest set of legendary accounts: legends of Early Middle Age sudden storms with thunder and lightning—as reported in the 1844 event (see Section 2.4), legend of a violent lake overflow, prior to the construction on the lakeshore of the Maria Laach Abbey in the eleventh century, where the sudden death of livestock led to the execution of local witches in the sixteenth century [117], finally where an historical sudden rise of lake waters led to the construction of a tunnel in the twelfth century to stabilize the lake level (as for Albano and Nemi Lakes).

Other legends of the Rhine Valley, analyzed by Scottish author Lewis Spence, mention two stories, according to Christian tradition [118]: (i) a pit-dragon with pestilential breath terrifying the whole country, then defeated during the evangelization of this area, and (ii) a sudden atmospheric storm with big waves and thick clouds encountered in the 800s³³ on the Rhine River by Emperor Charlemagne. Unlike for Italian lakes, the re-analysis of these sources has not yet been attempted, and the possibility of past violent degassing events has not been explored in paleolimnology works.

The preliminary analysis of the legends and beliefs of maar lakes (or other lakes which can be assimilated to them as Guatavita Lake) in other continents revealed many similarities with Pavin: tempestary stone stories, pit dragons, lake cults, lake fear, sudden lake storms associated with lake spirits, etc., in Ethiopia (Shetan Lake, *i.e.*, Satan Lake), Columbia (Guatavita Lake), and Northern Japan (Ainu people lake legends) [36]. The presence of Mamy Wata, a famous water myth in West Africa, has also been invoked after the Nyos catastrophe [5, 56]. Italy undoubtedly has the most important set of written archives, from the pre-Roman to Christian periods. Potential sources of historical archives exist on all continents, such as the missionary archives that were regularly sent to the Vatican and the General Archive of the Indies in Sevilla—for Latin America. The re-analysis of the Motif-Index of Folk Literature of Stith-Thompson can also be considered.

6.2 Lake degassing, a new risk, still underrated

We recognize here how much the human community owes to the people of Nyos and Monoun, who have unfortunately attracted attention on “degassing maar lakes” (DML). Before these catastrophes, some DML were already known, feared, or revered, but modern sciences and humanities failed to recognize them.

Even if the degassing of DML, observed by some scientists at Monticchio (1770–1820), Pavin (1785), and Albano (1829), had been recognized by scientists of the last century and integrated into academic courses, it is unlikely that the attention of scientists and authorities could have avoided the disasters of Monoun (1984) and Nyos (1986). The Cameroonian authorities made little attempt to attract the attention of scientists after Monoun. Also, Sigurdsson’s paper on Monoun, first rejected by Science, was still in press when the Nyos disaster occurred [6]. A similar reluctance of academic science to admit the reality of degassing occurred for the Laacher See in 1844, for Pavin at the end of the eighteenth century, and it still does today.

In addition, each of DML constitutes a potential risk toward local populations and their visitors, which remains to be addressed in all its dimensions. In Cameroon, the issues of people resettlements, of their information and warnings, of their grief

and mourning have been barely addressed, four decades after the catastrophe, but an efficient lake degassing device has been installed at Nyos.

Recent calls to better take this risk into account [21, 34, 87] must be supported. Our current knowledge on DMLs covers only a very small part of active volcanoes in the world (**Figure 2**). The inventory of maars initiated in Africa [18] should be extended to other continents. Meromictic lakes should be particularly targeted: Cameroonian and European maar lakes convinced or suspected of degassing are presently meromictic. These inventories should combine paleolimnological, geohistorical, and geomorphological approaches.

6.3 Degassing maar lakes: A world heritage

Degassing maar lakes are extremely rare natural objects that have multiple patrimonial values: scientific, cultural, literary, folkloric, anthropologic, sociological, etc., as demonstrated for Lake Pavin and outlined here for a few others. The interest in DML seems to have no limits. The famous Messel Pit in Germany, 47Ma old formation, and now classified as a world heritage by UNESCO, holds one of the richest fossil deposits ever found. Recently, geologists understood that it was an ancient maar lake, the Lake Messel, which became permanently meromictic with anoxic bottom waters. Sudden or sneaking degassing could have killed instantly animals on the shore or in the lake itself. Their remains are now extremely well preserved in anoxic sediments with their soft parts, feathers, colors, copulation figures, etc.

The global inventory of the DML could lead to a global network of selected maar lakes geosites of world heritage value [36]. The first on the list are, of course, Nyos and Monoun, Albano, Nemi, Averno and Monticchio, Pavin, Laacher See, Ulmener Maar and a few other Eifel maars, Ainu lakes, and Lake Guatavita, from which the El Dorado legend is derived, although its maar origin is still debated. So far only the Eifel maars are recognized as a geopark by UNESCO, but their legends remain to be studied and valorized. This first set could be followed by a larger set of DML from all continents.

Appendix

A. Lake Abano degassing in 1829

Summary of Bassanelli's description [40] (*made by the authors.*)

“Start of event: *on May 22nd, 1829 around 4 a.m., suddenly, in a serene sky, at 5:45 a.m. a furious wind rose accompanied by heavy rain. Shortly after 1:30 p.m., downpours of water coming from the south-southwest side of the lake fell accompanied by a smell of sulfur. A few days after these tremors, we began to hear loud and terrible detonations, in the atmosphere and in the ground, like distant cannon fire. [Bassanelli counted the detonations each month].*

Population response: *At 6 p.m. on May 23 a big shock which put everyone in anguish, fearing for the destruction of the city. It is said that this volcano is waking up., the families were afraid and left for Rome; 300 leave. On the night of the 23rd,*

a memorable procession was held. The relics of St. Pancrace (local protector)) are carried out and brought to safety. The following days people sleep outside. On May 31, another shock and on June 1, an even bigger one: it cracked houses, caused stones to fall, broke windows, accompanied by a terrible atmospheric rumbling.

Vapors and electric atmosphere: *Most of the time the air was dusty, especially in June and July, filled with nocturnal electric clouds. At the end of July, just before the tremors, we could observe small white clouds, similar to the Milky Way, and strong winds. They were stretched in bands, often colored, dark blue or white. From July 8 to 12, electric clouds produced lightning on the south / southwest side. Sometimes these phenomena developed in a line, like an aurora borealis, with columns of fire and flying dragons, almost always from the south side, without connection with tremors... The lightning, whether generated by ambient electricity or not, predicted nothing. On some days, most people have smelled sulfur in the atmosphere... The wind almost always came from the south/southwest and on certain days was very strong, impetuous, overflowing. It was instantaneous changes from serenity to rain with thick, dense fog, even on the most beautiful summer day. This happened all day on June 28 and on the evening of the 29th there was a terrible storm with hailstones (chabili), a confirmation of a complete atmospheric imbalance. Very dirty rain (poiggie) occurred on October 21, 22, 27 and on November 4, 16, 23 ...Some days the continuous shaking was accompanied by specific gases and an unusual cold in summer.*

Animal behavior: *The inhabitants were well warned by prior animal warning signs of the tremors: braying of donkeys, barking of dogs, meowing of cats, and crowing of roosters.*

Lake waters: *The edges of the lake, at the port, from the beginning of May (before the tremors) were always turbid, flaky. During these and even after, they remained opaque, and never presented their magnificent blue color of the previous year. Until December, the waters remained cloudy and turbid.*

CO₂ presence: *In many cavities under the city there was a spontaneous formation of carbon dioxide, making breathing impossible, killing animals and putting out the lights; in others, this non-respirable gas developed during the tremors and persisted for a certain time.*

Effects on people: *People suffered from profuse sweating and nervous system disorders. Some had a feeling of warming in their legs, accompanied by intense nervousness, tightness in the chest. I felt it, particularly on the first morning of the earthquake, May 22. Others, at the first emission of gas, had an intense inner emotion, felt a few minutes before the shock. Others, during and after the shocks, began to cry or experienced severe tremors. The most common diseases affected the nervous system, the joints and catharsis affecting the throat and lungs, sometimes cured, and sometimes leading to death. Also mild to severe ophthalmia. There were many intermittent fevers especially in summer and fall. Hive was very pronounced, with unbearable skin burning. There were a large number of abortions at 6, 7, and 8 months, even among robust women, and fetal growth delays of 2 to 3 months, attributed to delayed fetal nutrition. Most deliveries were difficult and most babies came with skin diseases (herpes and tumors). I observed that many of the babies breastfed during the tremors died of stomach problems, vermin*

and feces, others died of convulsions. The other children were tormented by diarrhea, by dental conditions with cough, by ophthalmia... Nervous conditions affected all individuals, even more so women, producing strong convulsive movements, vomiting, heart pain and more, and even a loss of the senses."

B. Main historical sources concerning Pavin and its area

B.1 1551: The terrible storm was witnessed at 1.5 km from Pavin

This first recorded Pavin event, witnessed by six persons of high social positions from Besse, is fully contextualized, with an exact date (28 August 1551). It has been carefully recorded by the church authorities, kept in their church, and published for the first time by a Jesuit born in Besse, Father Michel Coyssard (1615) [59] then by a Benedictine also originating from Besse (1688) [60], reproduced in many others Vassivière pilgrimage histories [9, 10]. Witnesses were standing on the Vassivière Mountain (**Figure 3**) when a mentally sick child was brought for healing by the miraculous statue, a new chapel being under construction:

"The air, which was at this moment very calm and tranquil, changed so suddenly that all attendants were astonished: an impetuous wind rose all of a sudden with such violence that they were almost all knocked on the ground, scattering their hats and coats. What put them most in fright and fear is that at the same time the whole air was like ignited by the length of terrible lightning, that occurred without stopping, and by terrible thunder that could be heard around them...this was just the effects of the furiousness of the demon who was being exorcized, as one could smell for a long time after an awful sulfur smell. The weather went back to clear state as it was before, lightning and thunder stopped and the atmosphere went tranquil again".

The very sudden, brief and violent change occurring in a serene atmosphere is much similar to the 1785 limnic eruption (Section 2.1, **Table 1**), although it is not reported that it originates from the nearby Pavin, masked by the crater rim. The sulfur smell is noted, as in the 1936 Pavin event; see further.

B.2 1566: A hazardous abyss, generating storm, thunder, and hail presented to Charles IX

On March 31, 1566, King Charles IX, touring his kingdom of France, and his mother Catherine de Medicis are informed in Clermont, the capital of Auvergne province (**Figure 4**) about "*a mountain, called Puy de Dome, on which there is a big abyss from which escapes ordinarily a big storm of thunder and hail, which damages grains in the valleys.*" [62].

Although this description made by the royal chronicler Abel Jouan wrongly places the terrible abyss (a lake is not mentioned) on top of the Puy de Dôme, the famous mountain near Clermont, the attribution is most likely at the Mont Dore mountain and concerns Lake Pavin. According to this official complaint, Pavin misbehavior is permanent; damaging grains in the downstream valleys, which could correspond to at least 20–30 km downstream, may be as far as the city of Issoire (**Figure 4**). The triplet wind storm, thunder, lightning, and the occurrence of hail are very close to the 1785 (Section 2.1).

B.3 1575: The sudden lake storm in “a lake on top of a mountain,” triggered by a tempestary stone

In the *Cosmographia Universalis*, an impressive work realized by the royal cosmographer François de Belleforest [61], there is no direct mention of Pavin, nor of Paven, its common spelling, until 1800:

“...Near this Mont D’or [Now Mont Dore] stands the city of Besse, at a half quarter league from which one can see a great lake located nearly on top of a mountain, without a measurable depth and without any water inlet. Actually, it is both admirable and terrible to see as, if a stone is thrown into it, it is ascertained that soon thunder, lightning, rainstorm and hail would occur. Not far from this lake there is an abyss named Creux des Soulcis...from which gas is emitted”.

This universal geography is very well organized with a final index of topics and locations featuring about 10,000 entries, where Pavin is found as a “marvelous lake located on top of an Auvergne mountain.” This topographic position is a recurrent marker of Pavin, which probably dates from the Late Antiquity [36]. It is striking to find small natural objects as Pavin (44 ha) and Creux de Soucy (a few feet wide cavity) described with details that could only be known by a local scholar. In this work, there are only fifteen lakes named and described; all of them are very peculiar, such as the Asphalt Lake (Dead Sea). The Auvergne description in this work is the most complete one at the time. At that period, no one knows that the Auvergne Mountains are volcanoes and that Pavin is a volcanic crater; their origins will be discovered two centuries later.

Pavin Lake storm is triggered, according to this description, by a “tempestary stone.” This story is one of the best-known motifs of Pavin, constantly replicated over the following centuries by many geographers [9–11]. It was still reported locally in oral tradition in 1969 (MM, personal observation). We first put forward two hypotheses [10]: (i) it could describe a lake close to saturation state and ready to degas at any time, as was described at Lake Monoun after its explosion in 1986 [42], or (ii) it is the metaphor of a landslide or a rockfall which would have triggered the eruption as suggested at Nyos. Additional investigations show that in fact this motif was already existing, word per word, in the thirteenth century and diffused by religious scholars in Vienne, 160 km east of Pavin, in the Rhône River valley. They were mentioning “a tempestuous lake in mountains where demons were producing major disorders in air and in water” [36]. For this reason, these scholars were also linking this demonic place to the final resting place of Pontius Pilate, the Roman magistrate who chaired the trial of Jesus of Nazareth: according to a religious tradition, his body was attached to a big stone, thrown into the Tiber River, where it provoked a violent rejection! This story, made famous in the Christian world near 1300 AD by Jacques de Voragine in his *Golden Legend* [63], has been very popular in Christianity for centuries. Religious scholars and profane authors have attributed many locations to this maleficent and tempestuous lake: in the Pilatus Mountain (Central Switzerland), in Mont Canigou (Catalonia) and in Monte Sibillini (Abruzzo, Italy). Also, a Pilatus rock is found in the Weinfelder Maar (Eifel), famous for its legend. Medieval Pavin behavior could have generated this myth of Pilatus Lake, famous across Western Europe, a hypothesis difficult to support due to the scarcity of medieval sources [36].

B.4 1605: *Lacus pavens*, the terrifying lake, is mentioned by a hydrologist

In his book on thermal resources of Auvergne Jean Banc, a medical hydrologist visiting Besse, he mentions the term *lacus pavens*, in Latin the terrifying lake, and reports its storms generated by the tempestary stone, a story told by a local peasant [65]. It is the earliest citation of the lake with its original name. “Paven” will be replaced by “Pavin” in the early 1800s in maps and written accounts. Until the twentieth century, the proponents of a normal lake have always doubted this origin, preferring the Occitan “pallenc,” meaning palisade, a hypothesis evoked since the 1700s, then abandoned in the following manuscript source.

B.5 1750s: The Godivel Manuscript details permanent degassing and occasional storms of “Pavent”

This manuscript, written in the 1700s by a member of the notorious Godivel family from Besse, found and transcribed in 1884 [66], contains Pavin’s three-page-long detailed description, which is summarized as such:

“The lake is one of the most beautiful to be found in Europe. Its depth is thought to be unlimited: some courageous and curious [men] went with a craft in the middle of the lake and let run 313 fathoms of ropes [without reaching the bottom]. The outlet discharge is important, even during summer drought. The water is clear, a little bitter and smells like ferruginous springs in the Pyrenees. Fish has never been seen [in the lake] nor any water grass. Birds are rare in the surrounding woods: the reason is that the frequent fog, which is seen escaping from the lake at any time, keeps them out and makes this place uninhabitable...This place is feared because in summer several exhalations and vapours are emitted and eventually result in clouds and storms that threaten the whole area. The lake has always been called the Pavent Lake. This paving stone that can be seen all around it could have given rise to this name, which originally comes from the verb paveo which was used in the past and means to pave in French. ... It seems more likely that it is called the Pavent Lake because of the fear and fright that it causes in all those who look at it, even if they had seen it every day of their lives. Pavent would therefore come from these two patois words Par-ven or from the verb paveo which means I am afraid, either because this fear is excited by the mere sight and consideration of the lake, or because several exhalations and vapors rise from this lake during the summer which shortly after degenerate into clouds and finally into storms which hold the whole country in fear.”

Several lake descriptors are mentioned here: the taste of water, the absence of fish and the rarity of birds in the woods, the permanent fog. The occasional exhalations and vapors, which shortly after degenerate into clouds and storms, also reported in 1566, terrorize the whole country. Several possibilities to explain the origins of the “Pavent” toponym are proposed here, but the terrifying lake—*lacus pavens*—is clearly privileged.

It must be noted that no reference is made here to a tempestary stone. Actually, this motif, reported until the 19th and still present today, has never been mentioned by an identified witness of Pavin misbehavior! For instance, in 1672 de Fretat [67], a Jesuit cartographer of Auvergne who qualifies Pavin as the 11th wonder of Auvergne

clearly asserts that “a stone thrown into the lake does not trigger any storm, as reported by Belleforest,” then by its many followers in France and in Western Europe [10]. He also reports that he has sounded the lake at 60 fathoms, about 110 m, although without mentioning how he proceeded. His work remained ignored so far [9, 10].

B.6 1783: Paven is suddenly boiling, orange, and glutinous in summer 1783

This detailed account of this sudden Pavin event is published only a week after the event in a two-page “letter to the editor” sent to the *Feuille Hebdomadaire de la Haute et Basse Auvergne*, a pre-revolutionary weekly magazine [68]. The author is Chatelain Godivel, another member of the notorious Besse family and magistrate of this city. It is abridged as such:

“Paven Lake, at half league from Besse, is one of Auvergne marvels. It represents a terrible gorge in a mountain...Its water has always been very clear, never clouded by rains nor by storms or inlets, which are invisible. The outlet discharge is very stable and could work a watermill. On August 21 [1783], on a very clear day, I have crossed this stream at eight in the morning to go to Vassivière [Location on figure 3]. When going back at four in the evening..., I found the outlet water very turbid and yellowish...My son climbed to the lake, some 150 fathoms [180 m] from there, and found the lake surface completely troubled, carrying a sort of yellow-orange and glutinous silt. He took the water in his hand and when this substance dried it produced on his hand some pimples with a slight pain that lasted some time. The same day the land keeper came to tell me: “Sir, there is something extraordinary in Paven which I have never seen, the water is boiling everywhere but there is no wind, it is yellowish and even rusty in some places”. The day after, I called my farmer Gelac who stays close to the lake. He told me that the water had been dirty two or three times this summer, in the evening...I suppose that there has been inside the lake some slide, so important that such volume of water was clouded and infected by some venomous material.”

This journal, the first news magazine in Auvergne, has a section devoted to “Arts and science,” and aims to be read by nobles, bourgeois, and ecclesiastics. When the lake change occurred, the witnesses were only 1.5 km away and did not remark any thunder or lightning; it was probably a moderate lake mixing (boiling waters) and non-violent degassing. For the first time, a scientific hypothesis, a sediment slide, is put forward. This Pavin event is probably a limited mixing of deep anoxic and iron-rich waters with surface waters, leading to oxidation of ferrous iron and ferric hydroxide precipitation, as observed in Nyos Lake, in Monticchio Piccolo Lake and in Albano Lake, in 1829 (Section 2).

In 1877, one finds a veiled reference to this event in a manuscript, where the 1783 event is evoked in relation to the 1783 Calabria earthquakes [68].

B.7 1835–1847: Contrasted Pavin descriptions made by Henri Lecoq

In 1835, this prominent Auvergne scientist—he is also a botanist, a hydrologist, and a noted businessman—makes his first visit to the lake and collects “Pavin stories” told by his local guides [70]. They can be understood as a mixture of secular

traditional beliefs dating from Belleforest, as the tempestary stone, with allusions to the Pavin event of 1785, featuring a whirlpool:

“No boat crosses its deep waters. No inhabitant of the surroundings would dare to linger on this liquid plain. A whirlpool exists in the middle, and would swallow up the imprudent person who wanted to drive his boat there. A stone thrown far enough to reach this chasm, boils the waters and produces a storm. The lead of the probes melts in the middle of the lake and its depth reaches no limits. Such are the absurdities we heard told.”

This description will be popularized throughout the nineteenth century and picked up by most authors of guidebooks [10]; it is still found today in some of them [6]. During his many visits to Pavin, Lecoq has not attempted to use the latest scientific instruments, unlike lake study pioneers such as Tata at Monticchio (Section 2.2). In 1871, he sums up 35 years of visits to Pavin in a book on Massif Central hydrology, much descriptive [71]. He mentions once more the Pavin stories as “legends invented by fear and transmitted by credulity.” However, he also describes, without further analysis, a strange lake storm as he was sounding the lake with the first boat ever brought to Pavin, thus giving credit to some Pavin stories:

[September 13, 1847, great storm] “We noticed from time to time a phenomenon that could have led one to believe in whirlpools and smoke from the lake that rises during stormy weather. We could indeed see the wind driving the water in various directions, pushing the waves in different directions and from their shock real whirlpools and white dust were born that rose while turning and gave rise to large smoke.” Lecoq invokes the wind effect, actually due to its high rims, Lake Pavin crater is actually very well protected from external wind.

B.8 1936: The sudden color change of Pavin

This summer 1936 event has been only revealed by its witness in 1987 [72], while press journalists were investigating Pavin past (Section 4.5). The witness, Paul Joanny, a pharmacist at Clermont, had not dared to report the event for 50 years [6]! In 1936 he was a young fisherman from Besse; he has also been interviewed in 2012 by one of the authors (MM):

“My father had a boat on the lake. On Sundays, I go and get the crayfish by putting down a basket. I had left the lake spotless, smell and consistency. The next day, I went back with my father: the whole lake was coloured, I saw a big yellowish foam floating in certain parts of the lake, from yellow to orange, with streaks of blue. A fisherman named Bocard, arrived in turn; he told me he had already seen that once or twice. The cap of the basket was caught in this gelatinous mass that smelled a lot of sulphur. (In pharmacy, when I was studying, we prepared colloidal sulphur for the preparation of the arsenic poisoning test: the same smell floated in Pavin). I took a bottle of water: the teacher thought it was algae. The foam floated on half of the lake. It was forming before my eyes: the wind was gathering the deposit towards the spillway of the lake. The river was no longer flowing. We unblocked the spillway; the fishermen reported dead trout. It was not the water that had changed colour, it was the yellow-orange deposit, as in the pharmacy studies program.”

In 1987, this witness account has not been considered by scientists despite the striking comparison with the 1783 event, rediscovered in 1986 and well noted by the journalist.

A similar reluctance to report past Pavin misbehaviors is still found today: during our investigations in Besse (PL and MM, May 2024), an eyewitness from Besse (J-L V.) also reported another event that occurred in summer 1972 while he was asked to take back to the lake outlet a rented rowing boat left near the south shore of the lake:

"I choose to go across the lake straight to the outlet. At one moment, I suddenly crossed a boiling area 10 to 15 m wide with eddies about twenty cm high. I expected to see a monster emerge and I rowed harder to get past this dangerous area."

Fifty years later, this witness still does not want to disclose publicly his name, fearing ridicule. These two delayed testimonies illustrate the difficulties of assembling contemporary accounts of Pavin misbehaviors. The major reason is the lack of official recognition of the turbulent past of Pavin, which has been developed over more than two centuries by scientists, historians, and local authorities [6].

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References

- [1] Sigvaldason GE. International conference on Lake Nyos disaster, Yaoundé, Cameroon 16-20 March, 1987: Conclusions and recommendations. *Journal of Volcanology and Geothermal Research*. 1989;**39**(2):97-107
- [2] Wetzel RG. *Limnology*. 1st ed. Philadelphia: Saunders College Pub.; 1975. 743 p
- [3] Blong RJ. *Volcanic Hazards. A Sourcebook of the Effects of Eruptions*. Academic Press; 2013
- [4] Kling GW, Clark MA, Wagner GN, Compton HR, Humphrey AM, Devine JD, et al. The 1986 lake Nyos gas disaster in Cameroon, West Africa. *Science*. 1987;**236**(4798):169-175
- [5] Molo B. Cameroun : de l'assistance internationale en situation de crise à la politique étrangère de gestion des risques et catastrophes. 1986-2012. In: Esseba C, Bidias R, editors. *Comprendre les relations internationales contemporaines*. Paris: L'Harmattan; 2020. pp. 59-91
- [6] Molo B, Meybeck M. Faire face à l'inconnu. Des Hommes face au dégazage des lacs tueurs : la naissance d'un risque. In: Alary V et al., editors. *Percevoir, représenter, communiquer les risques naturels*. PUBP: Clermont; 2024. pp. 149-184
- [7] Thienemann A. *Physikalische und chemische Untersuchungen in der Maaren der Eifel. Verhandlungen des Naturhistorisch Vereines der preussischen Rheinlande und Westphalens*. 1914-1915;**70**:249-302 and **71**:273-389
- [8] Shanklin E. Exploding Lakes and maleficent water in grassfields legends and myth. *Journal of Volcanology and Geothermal Research*. 1989;**39**:233-246
- [9] Meybeck M. Pavin, the birthplace of French limnology (1770-2012), and its degassing controversy (1986-2016). In: Sime-Ngando T, Boivin P, Chapron E, Jézéquel D, Meybeck M, editors. *Lake Pavin: History, Geology, Biogeochemistry, and Sedimentology of a Deep Meromictic Maar Lake*. Springer; 2016. pp. 3-27
- [10] Meybeck M. A rich but fragmented history (200 AD-2016). In: Sime-Ngando T, Boivin P, Chapron E, Jézéquel D, Meybeck M, editors. *Lake Pavin History, Geology, Biogeochemistry and Sedimentology of a Deep Meromictic Maar Lake*. Springer; 2016. pp. 29-52
- [11] Meybeck M. Dragons, fairies, miracles and worship at Pavin and other European Maar-Lakes. In: Sime-Ngando T, Boivin P, Chapron E, Jézéquel D, Meybeck M, editors. *Lake Pavin History, Geology, Biogeochemistry and Sedimentology of a Deep Meromictic Maar Lake*. Springer; 2016. pp. 53-79
- [12] Scharf BW, Björk S, editors. *Limnology of Eifel Maar Lakes. Advances in Limnology (Archiv. für Hydrobiol.)*. Vol. 38. 1992. 348 p
- [13] Margaritora FG. *Limnology in Latium: The volcan lakes. Memorie dell'Istituto Italiano di Idrobiologia*. 1992;**50**:319-336
- [14] Delbecq A. *Les Lacs français*. Paris: Chamerot et Renonaire; 1898. 436 pp
- [15] Pourriot R, Meybeck M. *Limnologie générale*. Paris: Masson; 1995. 976 pp
- [16] Rouwet D, Christenson B, Tassi F. In: Vandemeulebrouck J, editor. *Volcanic Lakes*. Heidelberg: Springer; 2015

- [17] Christenson B, Németh K, Rouwet D, Tassi F, Vandemeulebrouck J, Varekamp JC. Volcanic lakes. In: Rouwet D, Christenson B, Tassi F, Vandemeulebrouck J, editors. *Volcanic Lakes*. Springer; 2015. pp. 1-20
- [18] Rouwet D, Németh K, Tamburello G, Calabrese S, Issa. Volcanic lakes in Africa: The VOLADA_Africa 2.0 database, and implications for volcanic hazard. *Frontiers in Earth Science*. 2021;**9**:717798
- [19] Tassi F, Rouwet D. An overview of the structure, hazards, and methods of investigation of Nyos-type lakes from the geochemical perspective. *Journal of Limnology*. 2014;**73**(1):55-70
- [20] Negendank JFW, Zolitschka B. *Paleolimnology of European Maar Lakes*. Berlin: Springer Verlag; 1993
- [21] Caracausi A, Nuccio PM, Favara R, Nicolosi M, Paternoster M. Gas hazard assessment at the Monticchio crater lakes of Mount Vulture, a volcano in southern Italy. *Terra Nova*. 2009;**21**(2):83-87
- [22] Cabassi J, Tassi F, Vaselli O, Fiebig J, Nocentini M, Capecchiacci F, et al. Biogeochemical processes involving dissolved CO₂ and CH₄ at Albano, Averno, Monticchio meromictic volcanic lakes (Central-Southern Italy). *Bulletin of Volcanology*. 2013;**75**:1-19
- [23] De Benedetti AA, Funicello R, Giordano G, Diano G, Caprilli E, Paterne M. Volcanology, history and myths of the lake Albano maar (Colli Albani volcano, Italy). *Journal of Volcanology and Geothermal Research*. 2008;**176**:387-406
- [24] Rouwet D, Chiodini G, Ciuccarelli C, Comastri A. Costa A Lago Albano, the “anti-Nyos-type” lake: The past as a key for the future. *Journal of African Earth Sciences*. 2019;**150**:425-440
- [25] Lancini L. Un terrible et affreux combat. L'apport de l'approche géomythologique à la compréhension ancienne du volcanisme. *Travaux du Comité français d'Histoire de la Géologie*. 2020;**3**:7-23
- [26] Camus G, Michard G, Olive P, Boivin P, Desgranges P, Jézéquel D, et al. Risques d'éruption gazeuse en Auvergne. *Bulletin de la Societe Geologique de France*. 1993;**164**:767-778
- [27] Sime-Ngando T, Boivin P, Chapron E, Jézéquel D, Meybeck M, editors. *Lake Pavin, History, Geology, Biogeochemistry, and Sedimentology of a Deep Meromictic Maar Lake*. Berlin: Springer; 2016. 421 p
- [28] Aeschbach-Hertig W, Hofer M, Kipfer R, Imboden DM, Wieler R. Accumulation of mantle gases in a permanently stratified volcanic lake (Lac Pavin, France). *Geochimica et Cosmochimica Acta*. 1999;**63**(19-20):3357-3337
- [29] Chassiot L, Chapron E, Di Giovanni C, Albéric P, Lajeunesse P, Lehours AC, et al. Extreme events in the sedimentary record of maar Lake Pavin: Implications for natural hazards assessment in the French Massif Central. *Quaternary Science Reviews*. 2016;**141**:9-25
- [30] Chassiot L, Miras Y, Chapron E, Develle AL, Arnaud F, Motelica-Heino M, et al. A 7,000-year environmental history and soil erosion record inferred from the deep sediments of Lake Pavin (Massif Central, France). *Palaeogeography, Palaeoclimatology, Palaeoecology*. 2018;**497**:218-233
- [31] Thouret JC, Boivin P, Labazuy P, Leclerc A. Geology, geomorphology and slope instability of the maar lake Pavin (Auvergne, French Massif

- Central). In: Sime-Ngando T, Boivin P, Chapron E, Jézéquel D, Meybeck M, editors. *Lake Pavin: History, Geology, Biogeochemistry, and Sedimentology of a Deep Meromictic Maar Lake*. Springer; 2016. pp. 155-174
- [32] Thouret JC, Boivin P, Miallier D, Donnadiou F, Dumoulin JP, Labazuy. Post-eruption evolution of Maar Lakes and potential instability: The Lake Pavin case study, French Massif Central. *Geomorphology*. 2021;**382**:107663
- [33] Gal F, Leconte S, Gadalia A. The “Escarot” gas seep, French Massif Central: CO₂ discharge from a quiescent volcanic system-characterization and quantification of gas emissions. *Journal of Volcanology and Geothermal Research*. 2018;**2018**(353):68-82
- [34] Rafflin V, Boudoire G, Massaro S, Stocchi M, Costa A, Grassa F, et al. Modelling CO₂ dispersion in the air during potential limnic eruption at the lake Pavin (France). *Journal of Volcanology and Geothermal Research*. 2024;**447**:108024
- [35] Juvigné E, Miallier D. Distribution, tephrostratigraphy and chrono-stratigraphy of the widespread eruptive products of Pavin volcano. In: Sime-Ngando T, Boivin P, Chapron E, Jézéquel D, Meybeck M, editors. *Lake Pavin: History, Geology, Biogeochemistry, and Sedimentology of a Deep Meromictic Maar Lake*. Springer; 2016. pp. 143-154
- [36] Meybeck, Chapron E. Geocultural and geomythological values of degassing maar lakes. The Pavin example (France). *Geoheritage* 2025. Submitted
- [37] du Citoyen Cordier L. Ingénieur des mines, au Citoyen Devilliers. *Gazette Nationale (Le Moniteur Universel)*. 1803;**102**:410-411. (15 Vendémiaire An II)
- [38] Tata D. Lettera sul Monte Vulture a sua eccellenza il signor D. Guglielmo Hamilton. Napoli: Stamperia Simoniana; 1778. 62 p
- [39] Tenore, Gussone. Peregrinazioni effettuate nelle state del 1838 dai Signore Tenore e Gussone (1838). In: Ciarallo A, Capaldo L, editors. *Principitato Citeriore e di Basilica. Viaggio al Vulture*, Edition Osanna; Venosa; 1995. 157 p
- [40] Bassanelli L. Sopra il tremuoto che ha sofferto la città di Albano con le sue vicinanze dal giorno 21 di maggio a tutto il dì 6 di dicembre 1829. Lettera del dottor fisico Luigi Bassanelli all’ecc. mo sig. dottor Giacomo Folchi pubblico professore di medicina nell’archiginnasio romano. *Giornale Arcadico di Scienze, Lettere, ed Arti*. 1829;**44**:37-74
- [41] Sigurdsson H. Gas bursts from Cameroon crater lakes: A new natural hazard. *Disasters*. 1988;**12**(2):131-146
- [42] Sigurdsson H, Devine JD, Tchua FM, Presser FM, Pringle MKW, Evans WC. Origin of the lethal gas burst from Lake Monoun, Cameroon. *Journal of Volcanology and Geothermal Research*. 1987;**31**(1-2):1-16
- [43] Baxter P, Kapila M, Mfonfu D. Lake Nyos disaster, Cameroon, 1986: The medical effects of large scale emission of carbon dioxide? *British Medical Journal*. 1989;**298**:1437-1441
- [44] Krajick K. Efforts to tame second African “Killer Lake” begin. *Science*. 2093;**299**:805
- [45] Westerman F. *La vallée tueuse*. Paris: Christian Bourgeois Éditeur; 2015. 390 p
- [46] Tazieff MH, Faivre-Pierret RX, Le Guern F, La. *Catastrophe de Nyos*, République du Cameroun. Vol. 811.

Gif sur Yvette: Centre des Faibles Radioactivités, CNRS Contrib; 1987. 76 p

[47] Desmarest N. Lacs volcaniques. In: Dictionnaire de géographie physique, Lacs Volcaniques. Vol. 5. Paeis: Agasse; 1798-1828. pp. 687-688

[48] Meybeck M. Les dégazages ignorés du Pavin, le terrifiant lac-maar d'Auvergne. *Géochroniques*. 2019;**150**:18-36

[49] Ciarollo A, Capaldo D. Viaggio al vulture. Venose: Edizioni Osanna; 1995

[50] Chiodini G, Cioni R, Marini L, Principe C, Braco B. Water and gas chemistry of the Lake Piccolo of Monticchio (Mt Vulture, Italy). *Current Research on Volcanic Lakes, IAVEI Newsletter*. 1997;**10**:3-9

[51] Paci GM. Relazione dei tremuoti di Basilicata del 1851, Stabilimento Tip. Vol. 2, 1853. Naples: del Real ministero dell'interno. pp. 113-299

[52] Funicello R, Heiken G, De Benedetti AA, Giordano G. Volcanic activity of the Lake Albano maar in Roman history and mythology. In: Funicello R, Giordano G, editors. *The Colli Albano Volcano*. Special Publications, Geological Society: London; 2010. pp. 331-338

[53] Koblenzer Anzeiger (The Journal of Coblenz). Koblenz, July 3 and July 10, 1844

[54] Le Guern F, Shanklin E, Tebo S. Witness accounts of the catastrophic event of August 1986 at Lake Nyos (Cameroon). *Journal of volcanology and Geothermal Research*. 1992;**51**(1-2):171-184

[55] Chapron E, Albéric P, Jézéquel D, Versteeg W, Bourdier JL, Sitbon J.

Multidisciplinary characterization of sedimentary processes in a recent maar Lake (Lake Pavin, French Massif Central) and implication for natural hazards. *Natural Hazards and Earth System Sciences*. 2010;**10**:1815-1827

[56] Molo B. Une géohistoire des catastrophes rumorogènes au Cameroun : les éruptions limniques de Njindoun et Nyos, 1984-1986. *Géocarrefour*. 2019;**93**(1). Available from: <https://journals.openedition.org/geocarrefour/12993>

[57] Godivel A. Terrier pour la Roynne mère du Roy, de sa terre, ville et mandement de Besse, fait par Antoine Godivel, notaire royal en la-dite ville. Chantilly: Manuscrit Bibliothèque du Musée Condé; 1579

[58] Delarbre A, (abbé). Notice sur l'Auvergne et en particulier sur la ville de Clermont. Landrier: Clermont-Ferrand; 1805. 256 p

[59] Coyssard M. Abrégé de l'histoire et miracles très-bien avez de Notre-Dame de Vassivière. Près du Mont d'Ore en Auvergne, à une lieue de Besse; Lyon; 1615

[60] Cladière J-J. L'histoire de la Sainte-Chapelle de Vassivière près du Mont-d'Or en Auvergne, célèbre par les miracles que Dieu y fait continuellement par l'intercession de sa très pure et glorieuse Mère. Par un religieux Bénédictin de la congrégation de St Maur. Damien Boujon, Clermont (1688 or 1687). Re-impressed in 1837, Clermont-Ferrand

[61] Belleforest (de) F. *Cosmographie Universelle*, 3 volumes, Nicolas Chesneau, imprimeur-libraire, Paris. Vol. 2. 1575. 1127 p. (Bibliothèque Sainte-Geneviève-Sorbonne, Paris, réserve, cote RXVIB 3=321-1)

- [62] Jouan A. Recueil et discours du voyage du Roy Charles IX, Charles Etienne, imprimeur du Roy. Paris; 1566
- [63] Voragine J. The Golden Legend. Medieval Sourcebook: The Golden Legend (Aurea Legenda). Compiled by Jacobus de Voragine, 1275. Englished by William Caxton, 1483. Available from: <http://www.fordham.edu/halsall/basis/goldenlegend/>
- [64] Meybeck M, André MF. Histoire du Creux de Soucy. Revue des Sciences Naturelles d'Auvergne. 2015;**79**:1575
- [65] Banc J. La Mémoire retrouvée des merveilles des eaux naturelles en faveur de nos Nymphes Françaises et des maladies qui ont recours à leurs emplois salutaires. Paris: L. Pierre Sevestre; 1605
- [66] Jaloustre E. Le Beffroi de Besse. Clermont-Ferrand: Mémoires de l'Académie Royale des Sciences, Belles-Lettres et Arts de Lyon; 1884
- [67] Frêtat (de) Aimable. Carte de la Haute et Basse Auvergne (1672) (map)
- [68] Godivel (chatelain). Lettre ouverte au Rédacteur de la feuille. Feuille Hebdomadaire de la Haute et Basse Auvergne, contenant ce qui peut intéresser cette province. In: Chabrit M, editor. Antoine Delcros imprimeur. Clermont-Ferrand; 1783. p. 152
- [69] Bouillet J-B. Description historique de Besse. Clermont-Ferrand: University Library (BCIU), Manuscrit, 40 f, Ms 977-fo; 1875. pp. 39-40
- [70] Lecoq H. Description de l'Auvergne. Paris: Le Mont d'Or et ses environs. Paris: J-B Baillère; 1835. 437 p
- [71] Lecoq H. L'Eau sur le Plateau Central de la France. Paris: J-B Baillère; 1871. 394 p
- [72] Joanny P. Un Pharmacien clermontois raconte un souvenir de jeunesse. Interview by J Gandebeuf. Le Républicain Lorrain. 1987
- [73] Jaloustre E. Histoire du pèlerinage de Notre-Dame de Vassivière. Impr. Dumont, Clermont-Ferrand; 1910. 150 p
- [74] Mosnier SM(A). Les Saints d'Auvergne. Paris: Le Thielleux; 1899
- [75] Nodier C, Taylor JD, De Cailleux J. Voyages pittoresques et romantiques dans l'ancienne France; 1829. (Re-edited 1987, Presse du Languedoc, Montpellier Tome 1, 110 p)
- [76] Noir J. Besse en Chandesse et ses environs. Folklore médical : La Foi qui guérit au sanctuaire de Vassivière. In: Histoire et géographie médicale d'une vieille commune d'Auvergne. Paris: Le Progrès Médical; 1907. pp. 33-44
- [77] Legrand d'Aussy JB. Voyage en Auvergne. Paris: E. Onfroy; 1788. 555 pp
- [78] Fournier PF. Le Nom du lac Pavin, Essai d'étymologie. Bulletin Historique et Scientifique de l'Auvergne. 1971;**85**(631):159-164
- [79] Sebillot P. Les Eaux douces, Folklore de France, (1904-1906), (Re-edited in 1983). Paris: Imago. 304 p
- [80] Ajalbert J. L'Auvergne. Paris: Ancienne maison Quentin; 1896. 362 pp
- [81] Larat J. Les peurs du lac Pavin. Le Soleil du Centre. 1929 (Bibliothèque Henri Pourrat, Clermont-Ferrand)
- [82] Martel E-A. Les Abymes. Chap. XXII Le Creux de Souci (Puy-de-Dôme); 1894. pp. 387-393
- [83] Lavina P, Del Rosso T. New geological findings in Pavin area. In:

Oral Communication, Symposium Pavin and Other Meromictic Lakes, Besse-en-Chandesse. 2009

[84] Jezequel D, Sarazin G, Fonty G, Tassin B. Le lac Pavin, le volcan, l'eau et la vie. Pour la Science, L'eau Attention Fragile. 2008;Feb:52-59

[85] Serieyssol K, Beauger A, Miras Y, Chassiot L, Arricau V, Chapron E. Diatoms-based paleolimnology of Lake Pavin over the past 7000 year. Journal of Paleolimnology. 72(3):99-315. DOI: 10.1007/s10933-024-00330-2

[86] Chapron E, Ledoux G, Simonneau A, Albéric P, St-Onge G, Lajeunesse P, et al. New evidence of holocene mass wasting events in recent volcanic lakes from the French Massif Central (Lakes Pavin, Montcineyre and Chauvet) and Implications for Natural Hazards. In: Yasuhiro Y, Kiichiro K, Ken I, Yujiro O, Urgeles R, Mosher D, Chaytor J, Strasser M, editors. Submarine Mass Movements and Their Consequences. Dordrecht: Springer Netherlands; 2012. p. 25564. DOI: 10.1007/978-94-007-2162-3_23

[87] Mouhamed AN, Rouwet D, Tassi F, Fantong WY, Mouncherou OF, Ekomané E, et al. Evidence of "Lake Nyos-type" behavior in the geological record: A review. Earth-Science Reviews. 2023;247:104603

[88] Chapron E, Foucher A, Chassiot L, Fleurdeus W, Arricau V, Perdereaux L, et al. Evaluating Holocene natural hazards in the French Massif Central from a regional lake sediment approach. Quaternary International. 2022;636:134-153

[89] Chassiot L, Chapron E, Di Giovanni C, Lajeunesse P, Tachikawa K, Garcia M, et al. Historical seismicity of the Mont-Dore volcanic province

(Auvergne, France) unraveled by a regional lacustrine investigation: New insights about lake sensitivity to earthquakes. Sedimentary Geology. 2016;339:134-150

[90] Chassiot L, Chapron E, Miras Y, Schwab MJ, Albéric P, Beauger A, et al. In: Sime-Ngando T, Boivin P, Chapron E, Jézéquel D, Meybeck M, editors. Lake Pavin Paleolimnology and Event Stratigraphy. Lake Pavin: History, Geology, Biogeochemistry, and Sedimentology of a Deep Meromictic Maar Lake. 2016. pp. 381-406

[91] Chapron E, Chassiot L, Lajeunesse P, Ledoux G, Albéric P. Lake Pavin sedimentary environments. In: Sime-Ngando T, Boivin P, Chapron E, Jézéquel D, Meybeck M, editors. Lake Pavin: History, Geology, Biogeochemistry, and Sedimentology of a Deep Meromictic Maar Lake. Springer; 2016. pp. 365-379

[92] Rioual P. Limnological characteristics of 25 lakes of the French Massif Central. Annales de Limnologie-International Journal of Limnology. 2002;38(4):311-327

[93] Michard G, Viollier E, Jézéquel D, Sarazin G. Geochemical study of a crater Lake: Lake Pavin, France. Identification, location and quantification of the chemical reactions in the lake. Chemical Geology. 1994;115:103-115

[94] Viollier E, Jézéquel D, Michard G, Pèpe M, Sarazin G, Albéric P. Geochemical study of a crater Lake (Lake Pavin, France): Trace elements behavior in the monimolimnion. Chemical Geology. 1995;125:61-72

[95] Viollier E, Michard G, Jézéquel D, Pèpe M, Sarazin G. Geochemical study of a crater Lake: Lake Pavin, Puy-de-Dôme, France. Constrains afforded by

the particulate matter distribution in the element cycling within the lake. *Chemical Geology*. 1997;**142**:225-241

[96] Busigny V, Planavsky NJ, Jézéquel D, Crowe S, Louvat P, Moureau J, et al. Iron isotopes in an Archean Ocean analogue. *Geochimica et Cosmochimica Acta*. 2014;**133**:443-462

[97] Lehours AC, Bardot C, Thenot A, Debros D, Fonty G. Anaerobic microbial communities in Lake Pavin, a unique meromictic lake in France. *Applied and Environmental Microbiology*. 2005;**71**:7389-7400

[98] Lehours AC, Evans P, Bardot C, Joblin K, Fonty G. Phylogenetic diversity of Archaea and Bacteria in the anoxic layer of a meromictic Lake (lake Pavin, France). *Applied and Environmental Microbiology*. 2007;**73**:2016-2019

[99] Cosmidis J, Benzerara K, Morin G, Busigny V, Lebeau O, Jézéquel D, et al. Biomineralization of iron-phosphates in the water column of Lake Pavin (Massif Central, France). *Geochimica et Cosmochimica Acta*. 2014;**126**(2):78-96

[100] Busigny V, Mathon FP, Jézéquel D, Bidaud CC, Viollier E, Bardoux G, et al. Mass collection of magnetotactic bacteria from the permanently stratified ferruginous Lake Pavin, France. *Environmental Microbiology*. 2022;**24**(2):721-736

[101] Bidaud CC, Monteil CL, Menguy N, Busigny V, Jézéquel D, Viollier E, et al. Biogeochemical niche of magnetotactic cocci capable of sequestering large polyphosphate inclusions in the anoxic layer of the Lake Pavin water column. *Frontiers in Microbiology*. 2022;**12**:789134

[102] Stebich M, Brückmann C, Kulbe T, Negendank JF. Vegetation history, human

impact and climate change during the last 700 years recorded in annually laminated sediments of Lac Pavin, France. Review of Palaeobotany and Palynology. 2005;**133**(1-2):115-133

[103] Krishnaswami S, Lal D, Martin JM, Meybeck M. Geochronology of lake sediments. *Earth and Planetary Science Letters*. 1971;**11**:407-414

[104] Martin JM. The Pavin Crater Lake. In: Stumm W, editor. *Chemical Processes in Lakes*. New-York: John Wiley; 1985. pp. 169-188

[105] McCarthy FM, Patterson RT, Head MJ, Riddick NL, Cumming BF, Hamilton PB, et al. The varved succession of Crawford Lake, Milton, Ontario, Canada as a candidate global boundary Stratotype section and point for the Anthropocene series. *The Anthropocene Review*. 2023;**10**(1):146-176

[106] Lecoq H. *L'Auvergne pittoresque. Atlas colorié. Le Mont-Dore et ses environs. Seize vues coloriées*. Paris: Chaillon; 1835

[107] Del Rosso-d'Hers T. Montchal-Pavin, mise au point sur les travaux récents (2004-2010). *Eruption*. 2010;**23**:41-43

[108] Ewans WC, White LD, Tuttle ML, Kling GW, Tanyileke G, Michel RL. Six years of change in lake Nyos, Cameroon, yield clues to the past and cautions for the future. *Geochemical Journal*. 1994;**28**:139-162

[109] Mott RW, Woods AW. A model of overturn of CO₂ laden lakes triggered by bottom mixing. *Journal of Volcanology and Geothermal Research*. 2010;**192**(3-4):151-158

[110] Recluz E. *Géographie Universelle*. Vol. II. Paeis, France: Hachette; 1885

[111] Berlioz J. Crochet de fer et puits à tempête. La légende de Ponce Pilate à Vienne (Isère) et au mont Pilât au XIII^e siècle. Le Monde alpin et rhodanien. Revue Régionale d'ethnologie. 1990;**18**(1):85-104

[112] Grandazzi A. Une nouvelle hypothèse sur le miracle du lac Albain. Bulletin de l'Association Guillaume Budé. 2003;**1**(1):96-106

[113] Pietrafesa F. *La badia di Monticchio*. Laurenziana: Napoli; 1980

[114] Spicciarelli R, Marchetto A. The contrasting evolution of twin volcanic lakes (Monticchio, Mt. Vulture, Italy) inferred from literature records: Literature record of Monticchio lakes. Advances in Oceanography and Limnology. 2019;**10**(1):44-56

[115] Meybeck M. La longue et terrible histoire des lacs maars. Relief. 2019;**10**(3):58-63

[116] Münster S. Cosmographie Universelle. Paris: Michel Sonnius; 1565-1566. 1430 pp

[117] Voltmer R. Jagd auf "böse Leute". Hexenverfolgungen in der Region um den Laacher See (16.–17.Jahrh.). Plaidter Blätter. Jahrbuch des Plaidter Geschichtsvereins. Available from: historicum.net

[118] Spence L. Hero Tales and Legends of the Rhine. North Chalmersfort: Courier Corporation; 1995