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Review Article

Evidence of “Lake Nyos-type” behavior in the geological record: A review

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ABSTRACT

In this article, volcanic lakes that have shown sedimentological evidence of limnic eruptions (i.e., Nyos-type gas bursts) are reviewed. Indeed, to better assess “Nyos-type lakes” related hazards, paleolimnology offers a promising tool to trace the evidence of potential ancient Nyos-type gas explosions. After gas bursts from Lakes Monoun and Nyos in 1984 and 1986, respectively, multiple paleolimnological approaches have been applied to several lakes assumed to be Nyos-type Around the world,. Only 3 lakes in Europe (i.e. lakes Pavin in France, Albano and Monticchio in Italy and one in Africa (i.e. Lake Kivu in D.R. Congo) evidenced markers of limnic eruptions in their sedimentary archives. These features include reworked sediments with reversed ages, brown colors of sedimentary deposits, gas-rich sediments, iron hydroxide-rich sediments, strong Ti and Fe enrichments, sedimentary hiatuses, absence of seismic evidence in the sedimentary record, and significant change in geochemical signature. The dating of these sedimentary deposits has made it possible to determine the ages of the events and their recurrence. This has led to associating these markers with evidence of limnic eruptions, even though some lakes are in temperate climates that favor seasonal overturning of lake waters and thus gradual release of accumulated gas. There is still no agreement on the dynamics and causes, and the scientific debate remains open since there is no concrete reference event in historical time. Lakes Monoun and Nyos, the first and only lakes exploded in recent history, could therefore be considered as natural laboratories to better understand limnic eruptions in lakes around the world. Unfortunately, the well-studied aspects of these Cameroonian “killer lakes” are based more on the dynamics of the explosions, hazard assessment based on water chemistry, and gas releases, rather than on the possible similar behavior in the recent geologic past by applying a combination of old and new limnological approaches. In addition, as the first natural laboratory, Lake Monoun features several advantages, including smaller surface area, shallower depth favorable for coring, easy access, and negligible gas content after artificial degassing since the early 2000s.

1. Introduction

Volcanic lakes provide a view into the aquifers hosted in a volcanic edifice. Depending on the origin and the activity of the underlying volcano, the physical and chemical properties of the water in lake basins –generally craters– change (Pasternack and Varekamp, 1997). Volcanic lakes can be hyperacid and hypersaline, evaporating and degassing crater lakes topping the most active volcanoes as well as meteoric water bodies similar to “normal” lakes in non-active crater structures. The latter fit the “Nyos-type” lakes (Varekamp et al., 2000), which fill diatreme-maar craters, generally in monogenetic volcanic fields and do not manifest active magmatic degassing of SO_2, H_2S, HCl, and HF. In a deep and permanently stratified lake, however, dissolved CO_2 can be present in the bottom waters, due to the hydrostatic loading of the lake water column, for decades or even centuries. Such permanently stratified lakes with a monolimnion (i.e. unmixed deep layer with a clear chemical gradient) at depth are called meromictic lakes (Boehrer and Schultze, 2008). If the recharge of CO_2 continues up to supersaturation levels, the gas can be released violently from the lake when the dissolved gas pressure exceeds the hydrostatic pressure. As CO2 is denser than air,

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an asphyxiating cloud will flow into low laying areas (Sigurdsson et al., 1987).

The combination of required conditions to create a Nyos-type gas burst is rather unique. The phenomenon is hence only observed in a few lakes, at least during historical times. In the eighties such a lethal gas burst occurred twice along the Cameroon Volcanic Line (CVL hereafter, see location on Fig. 1), first from Lake Monoun on 15 August 1984, and afterwards from Lake Nyos on 21 August 1986. The former event killed 37 persons (Sigurdsson et al., 1987) whereas the major Lake Nyos burst killed ~1800 persons (Tanyileke et al., 2019 and references therein). The limnic eruption mechanism was understood by Sigurdsson et al. (1987) for Lake Monoun and further applied for Lake Nyos. After 1986, many monitoring efforts revealed the ongoing CO_2-recharge at both Lakes Nyos and Monoun (Kusakabe et al., 1989, 2000; Evans et al., 1993). Such observation confirmed the spontaneous gas release as the most plausible eruption mechanism and suggested a highly probable future recurrence of these events (Kusakabe, 2015, 2017). This awareness gave rise to the unique disaster risk reduction intervention through artificial degassing of both “killer lakes” in Cameroon (Halbwachs et al., 2020 and references therein).

Previous research, monitoring operations and mitigation strategies on Lakes Nyos and Monoun dealt with the present state and possible future recurrence of such limnic gas bursts, but did not integrate the past behavior of both lakes. Monitoring studies of some of the volcanic lakes in the world reveal characteristics somewhat similar to those of Nyos-type lakes. Thanks to paleolimnological methods based on sedimentary archives, some of these lakes show signatures of limnic eruptions in the past. Given that lake overturn is sensitive to atmospheric conditions,

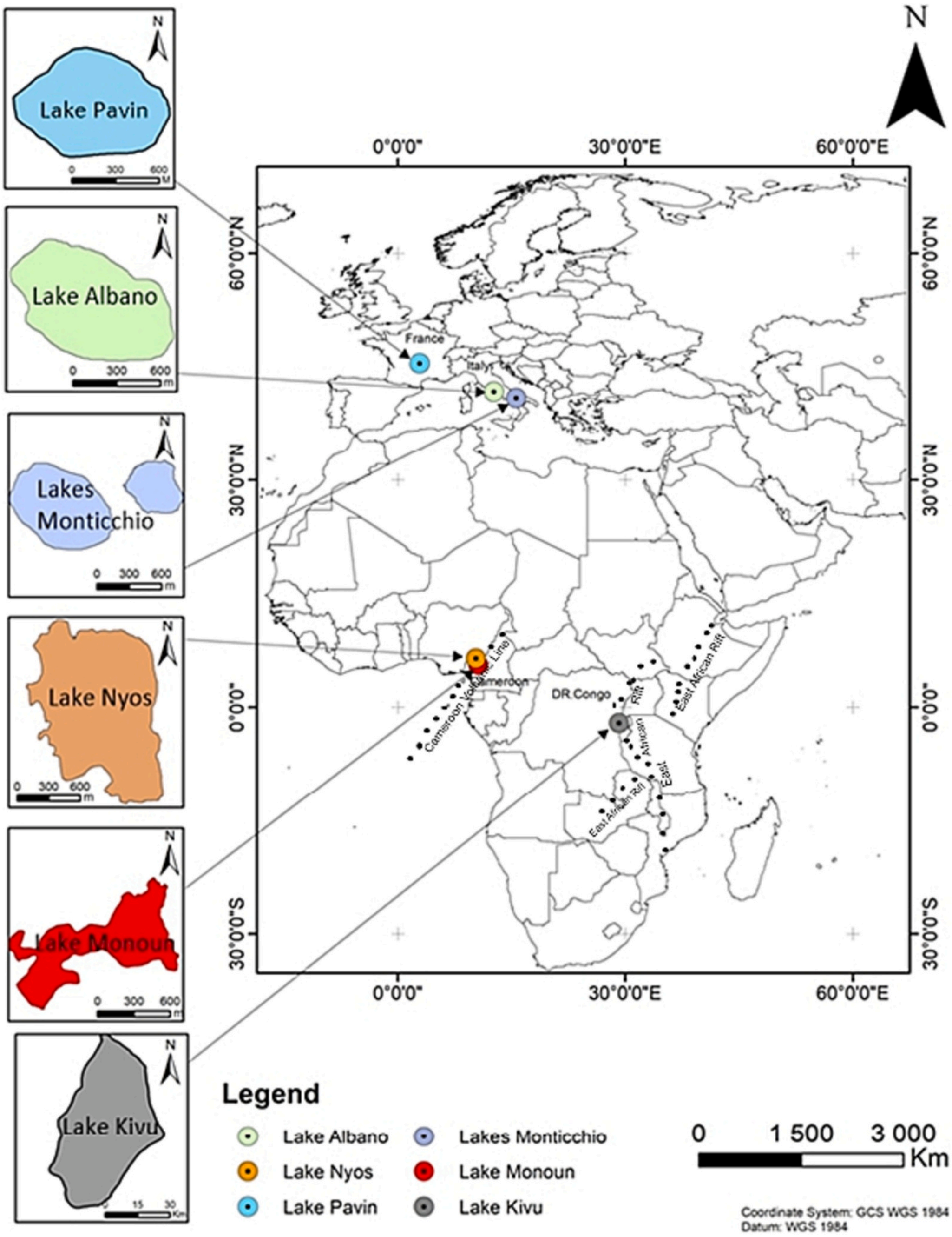

Fig. 1. Location of limnic eruption and suspected limnic eruption lakes in the world. The dashed lines underline the Cameroon Volcanic line and the East African Rift described in the text. Made from ArcglobeData 2019 In ArcGis version 10.7.1.

climate change will probably modify the physical stability of any lake. This effect could jeopardise safety as CO2 release from “Nyos-type” lakes depends on overturn dynamics.

This study reviews the use of lake stratigraphy from sediment cores and seismic reflection surveys on volcanic lakes worldwide to prove its usefulness to evidence any recurrence intervals of degassing events and to line out future research strategies for Lakes Nyos and Monoun, Pavin (France), Albano, Monticchio (both in Italy), Kivu (D.R. Congo) (Fig. 1). First, the main geographical and morphological characteristics and basic limnological parameters of those lakes classified, at least at first sight, to the Nyos-type class (Rouwet et al., 2014) are presented in Table 1. Second, A brief overwiew of the physical limnology of volcanic lakes will be presented. Third, the palaeolimnology of Nyos-type lakes and “suspected Nyos -type lakes” will be described and the various case studies will be compared in order to identify the Characteristics of events and limitations of the applied methods. Finally,some ideas to enhance the research related to limnic eruptions will be proposed.

2. Limnology of Volcanic lakes

Limnology is the study of lake systems, including its ecosystem, the physical and chemical characteristics of its water body, the host rocks, and the past climatic and environmental context deduced from sediments (Boehrer and Schultze, 2008). Paleolimnology, aims at revealing the origin, morphological history of lake basins, variation of biocenes in relation to changing nutrients, temperature and water level, wind conditions and dissolved substances through time (Meyers, 2003; Brauer et al., 2008; Giraudi et al., 2011). During the last two decades, research in the field of limnology has been successful in monitoring lake systems based on lake sediments, which are natural archives that provide details on the evolution of the geochemical, physical and biological characteristics of the watersheds as well as of the climatic regimes (Oldfield, 2005).

Volcanic lakes provide a suitable environment for paleolimnology, because they have (1) generally, an endorheic and deep basin defined by the explosive eruptive activity that emplaced them, and (2) small watersheds that are usually not subjected to intensive erosion. In order to reconstruct the paleoenvironment and paleoclimate, several methods were applied, including seismic stratigraphy, sediment core dating, palynology, magnetism, microfacies analysis, non-terrestrial biological archives and subsurface biosphere (Marchetto et al., 2015). All these methods were successfully used to unravel the paleo-environmental dynamics of volcanic lakes in Europe, Asia, Latin America and Africa, and can be used to recontruct the paleoenvironment of the “ Nyos-type lakes” and “ suspected Nyos-type lakes”. Here, the limnology of some volcanic lakes, “Nyos-type lakes” and “suspected Nyos-type lakes from different continents will be reviewed, with the scope to highlight the possible hazards related to sudden degassing that occurred in the past, and hence could occur in the future. Nevertheless, the lakes that do show gas accumulation at bottom waters (e.g. Laguna Hule and Río Cuarto in Costa Rica, Cabassi et al., 2014; Lakes Chanmico, Coatepeque and Ilopango in El Salvador, Cabassi et al., 2019) but turn over regularly or do not reported any evidence in the paleolimnological record are excluded from this review.

3. Limnic eruption in lake worldwide

3.1. Africa

The African continent, its minor islands and Madagascar hosts approximately 220 volcanic lakes (Rouwet et al., 2021a), largely distributed over two major geological structures, i.e. the Cameroon Volcanic Line and the East African Rift (Fig. 1), containing lakes with a “limnic eruption history”.

Lake Nyos, Cameroon: “Nyos-type lake”

Lake Nyos Maar was formed about 8000 years ago (Aka and Yokoyama, 2013). The 1986 limnic gas burst was characterized by the change in the color of the lake (dark red, Fig. 2), suffocation by CO_2 of magmatic origin causing nearly 1800 deaths, and the overflow of the lake. During the years after the gas catastrophe, the dissolved CO_2 content in deep lake layers increased due to the continuous supply of magmatic CO_2 (Kusakabe, 2015, 2017). To prevent another explosion in the future, artificial degassing was launched (Halbwachs et al., 1993, 2004; Tanyileke et al., 2019). Degassing pipes were installed in 2001, 2011 and 2012 to drain deep lake water, rich in Fe2+, to the surface. Due to this operation the lake surface turned red by Fe(OH)3 precipitates, which eventually sank to the bottom (Kusakabe et al., 2019). Lake Nyos is meromictic with a strong stratification distinguished by four layers: a bottom layer, a transitional and intermediate layer and a shallow layer. In the bottom layer between 205.5 and 209.5 m depth, Fe2+ and HCO3- are highly enriched. The artificial degassing hence mimics what happened after the 1986 limnic gas burst.

The first sediment cores were sampled six months after the Lake Nyos disaster (Bernard and Symonds, 1989). A short sediment core of 1 m was taken from the centre of the lake (Fig. 2) at 210 m to obtain information on the process that led to the gas explosion. The lithology is mainly composed of organic-rich black silts; X-ray diffraction (XRD) analysis indicates the presence of clays as well as gibbsite, $Al(OH)_3$, and a high proportion of amorphous silica. Light microscopic analyses and SEM-EDS analyses of four sediment samples evidence a small amount of siderite ($FeCO_3$) with a morphology typical of minerals precipitated from water under low supersaturation conditions (Bernard and Symonds, 1989).

Chemical analysis indicates the aluminous nature of the sediment. Based on K/Al-Na and (Fe + Mg)/(Al—Na) diagrams (Piboule, 1979), the clayey sediment is a mixture of kaolinite, illite and montmorillonite, as supported by the XRD results for the first two components. The mineralogical and geochemical signatures suggest that the sediment is derived from weathering of the regional granitic bedrock (Piboule et al., 1990). Moreover, the high contents of Ni, Cr and TiO_2 and the absence of

Table 1
Geographical and morphological characteristics, age of the last magmatic eruptions and oxidation state of the lakes reviewed in this study.

Lake parameters	Nyos	Monoun	Kivu	Pavin	Albano	Monticchio (Grande and Picollo)
Location	06°26′N 10°17E	05°35′N 10°35′E	2°03′44”S 29°07′24″E	45°29′46”N 002°53′12″E	41°45′N 12°41′E	40°56’40 N 15°36′30E
Altitude (m)	1091	1080	1463	1197	293	656
Depth (m)	210	100	485	92	167	35 and 38
Volume (m^3)	$1.6\ 10^8$	$1.57\ 10^7$	$549\ 10^9$	$130\ 10^5$	$450\ 10^5$	$3.25\ 10^6$ $3.9\ 10^6$
Ages	9 kyr (1)	?	Miocene (2)	6 kyr (3)	30 kyr (4)	140 kyr (5)
Area (km^2)	1.58	0.53	2400	0.44	6	0.16 and 0.41
Anoxic Zone (m)	90	60	50 (2)	60 (6)	50 (7)	15 (8)

References: (1) Aka and Yokoyama (2013), (2) Schmid et al. (2004), (3) Juvigné and Miallier (2016), (4) Boni et al. (1995), (5) Caracausi et al. (2009), (6) Renault (2009), (7) Cabassi et al. (2013), (8) Zolitschka et al. (1996).

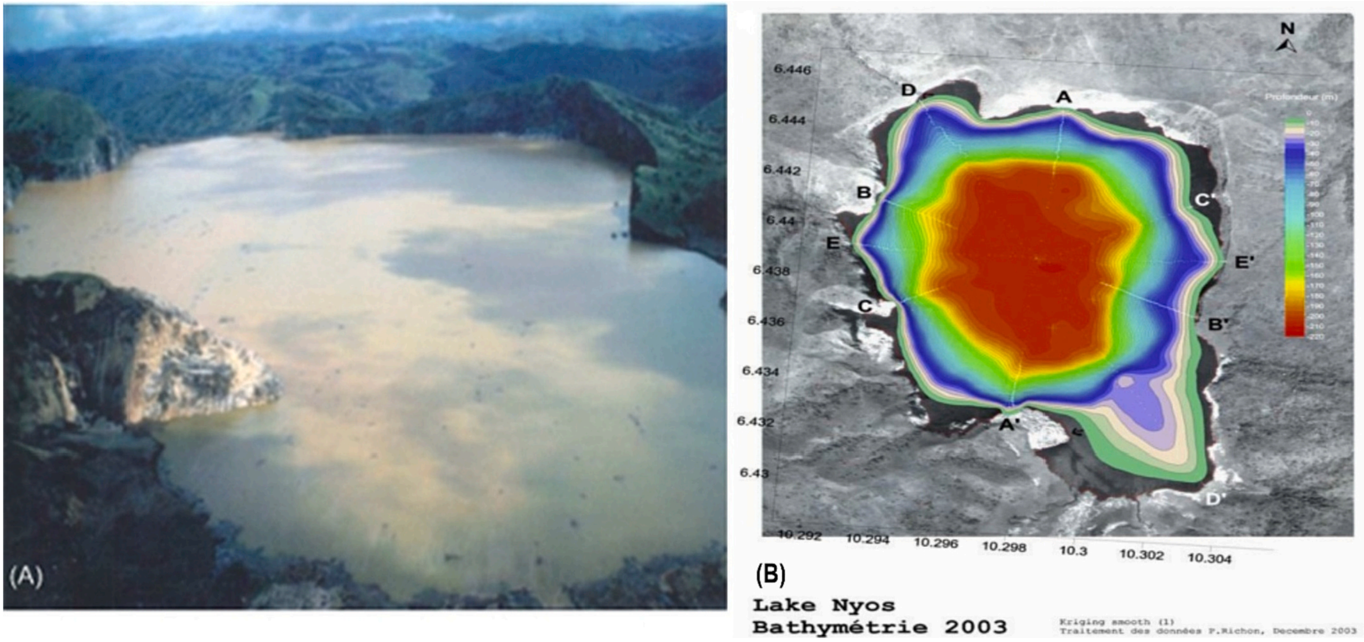

Fig. 2. Lake Nyos: (A) image credit by Kusakabé 10 days after the limnic eruption and (B) Bathymetry of 2003 by P. Richon, (modified after Halbwachs et al., 2020).

carbonates shows that the host rock was leached by acidic waters (Piboule et al., 1990).

The radioisotopes ^{137}Cs and ^{210}Pb (Piboule et al., 1990) provide evidence of sediment mixing.The uniform distribution of ^{137}Cs and ^{210}Pb activity over the 1 m long core indicates complete mixing of the upper layers. A high-resolution seismic profile acquired in 1991 at maximum lake water depth reveals a 4 m-thick turbidite deposit formed after the 1986 limnic eruption (Leenhardt, 1991). The thickness of these acoustically transparent facies suggests the occurrence of significant mass wasting processes (Chapron et al., 2006) accompanied by sedimentary mixing during this event, in agreement with previous ^{210}Pb—^{137}Cs data.

Lake Monoun,Cameroon: " Nyos-type lake"

After the catastrophic event of Lake Monoun (Fig. 3) in August 1984, several hypotheses were put forward about its origin, with the limnic eruption model by Sigurdsson et al. (1987) as the most plausible. Six months later, an attempt at a seismic survey was made by K. Kelts (Sigurdsson et al., 1987). Unfortunately, the bottom sediments were not penetrated by seismic waves and the first coring campaign was also unsuccessful. Indeed, both the seismic survey and coring was strongly affected by the presence of gas bubbles in the sediments. Nevertheless, the bottom lake sediments recovered by dredging were sampled and analyzed. These sediments consist of 87% fine-grained reddish brown silts with organic matter, plant debris and rock fragments (Sigurdsson et al., 1987). The XRD analysis of the silts reveals siderite, quartz, kaolinite, with some muscovite, biotite, pyrite and gibbsite. Only siderite is endogenous. The progressive influx of lateritic sediment and aeolian goethite loess led to the sedimentation of iron hydroxide in the organic-rich sediments. The gradual influx of magmatic CO2 led to an increase in the bicarbonate concentration in deep water, which, together with the sedimentation of iron hydroxide, contributed to the high concentrations of dissolved iron, and hence the precipitation of siderite. The concentrations of Fe2+ and HCO3- were higher in 1993 (Fig. 4) reaching ≥1385 and 1976 mg/l, respectively (Sigurdsson et al., 1987; Kusakabe, 2017). This confirms the increase in CO2 at the bottom of the lake as a funtion of time. Sigurdsson et al. (1987) proposed that the 15 August 1984 limnic eruption was caused by a landslide that deposited a mass at the bottom of the lake, stirring up the lake water. This limnic eruption model is supported by the absence (1) of alteration minerals such as sulphates (e,g, anhydrite, gypsum, alunite) that are markers of a phreatic eruption; (2) of traces of anthropogenic chemicals, or even less (3) of a large fraction of organic carbon in the lake. Nevertheless, the trigger of the limnic eruption has recently been put into discussion based on a high resolution bathymetry (Fig. 3) survey of the Lake Monoun basin (Tanyileke et al., 2019; Ohba et al., 2022). The discovery of a deeper vent, non-coincidentally adjacent to the relicts of the landslide and venting slightly warmer and CO$_2$-rich water on the northeastern sector of the ~100 m deep main basin, stresses the role of this sub-lacustrine spring as the dragger of deep CO$_2$-rich waters to trigger the limnic eruption, (Ohba et al., 2022). At least two other circular depressions, often accompanied by landslide fans, are recognized in the lake bathymetry, although currently not discharging CO$_2$-rich waters, suggesting that limnic eruptions might have been triggered in the same manner in the past. The model by Ohba et al. (2022) implies that supersaturation conditions of dissolved CO$_2$ in deep waters are not necessary for the lake to explode. Hence, a limnic eruption at Lake Monoun may be independent of the CO$_2$-recharge rate, which shows a fairly constant increase with an estimated 8.4 Mmol/year (Kusakabe, 2015, 2017), and recurrence can be more frequent than previously thought. In fact, based on oral traditions, Shanklin (1989) reports on "maleficent" lake behavior in the Monoun area, arguably pointing to limnic gas burst in the past in recent history. Further studies should improve the hazard assessment in Lake Monoun and strengthen the chemical model of the waters already studied.

Post-event measurements of bottom water temperature and conductivity indicate a higher rate of CO$_2$ increase in the lake (Kusakabe, 2015). For instance, between 1989 and 1992, the CO$_2$ recharge rate is estimate at 17 Mmol/year (Kling et al., 1994). Profiles of dissolved CO$_2$ and CH$_4$ show high concentrations below the chemocline confirming the limnic eruption hypothesis, regardless of the trigger mechanism (Kling et al., 2005; Ohba et al., 2022). As for Lake Nyos, this permanent recharge of CO$_2$ in the lake has led to the set up of a degassing system composed of several pipes at different depths. In 2003 and 2006, pipes were installed for artificial and permanent degassing. In 2009 it was found that a large amount of gas was removed by this operation (Hell, 2015; Tanyileke et al., 2019), essential to keep the lake safe despite a steady increase in the CO$_2$ content in the lake after 2011 (Kusakabe, 2015, 2017), which presages a potential danger if nothing is done.

Lake Kivu, D.R. Congo: "suspected Nyos-type lake"

The East African Rift hosts a series of rift-related lakes such as

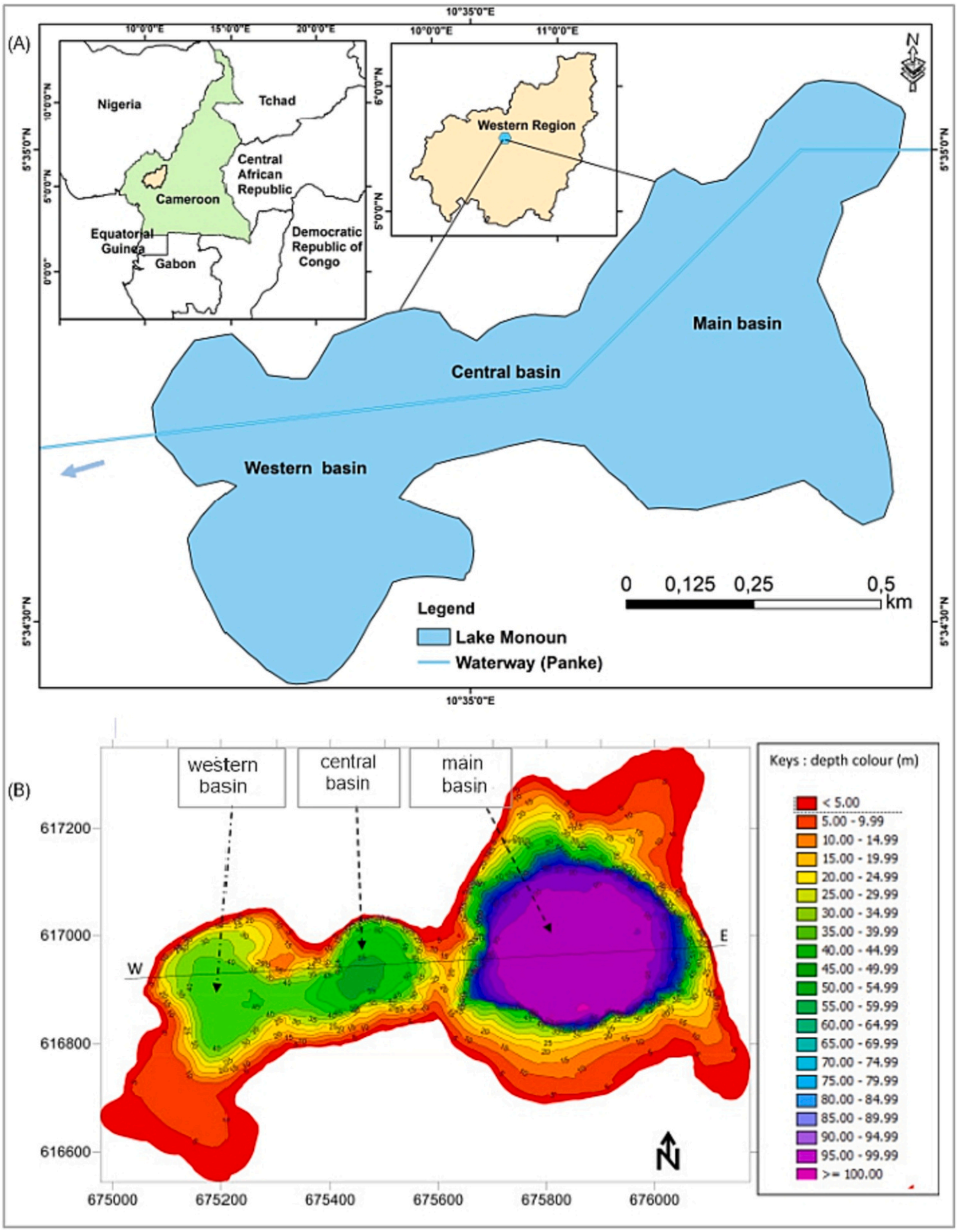

Fig. 3. General location of lake Monoun A) Location map, morphology (extract from the topographic map of Bafoussam, scale 1/200000) and B) bathymetry (modified after Tanyileke et al., 2019).

Tanganyika, Edward, Victoria, Malawi, the maar lakes in western Uganda (Karologo, Maturo, Kaitabarago) and Kivu (Fig. 5). Some of these lakes are monomictic, i.e. characterized by an annual episode of deep mixing, whereas some of the Ugandan maars have daily overturns, for which it would be difficult for a gas eruption to occur. This is justified by the fact that in the tropics, air amplitude, wind speed and direction influence deep mixing (De Crop and Verschuren, 2019). In other words, the day-night temperature range of the lake surface water is larger than the annual range which favors daily overturnings (Rouwet et al., 2021b).

An exception is Lake Kivu which is a large rift lake (Ross et al., 2015). Lake Kivu, formed in the Miocene, was subject to recurrent volcanic activity during the Holocene (Poppe et al., 2016). The northern littoral zone bordered by phreato-magmatic cones bears witness to the presence of Virunga Volcanic Province (VVP) lavas. At the end of the Pleistocene, these lavas blocked the outflow of northern Lake Kivu (Haberyan and Hecky, 1987). This dam closed the basin and induced the possibility for the lake level to rise by 400 m. As a result, thermohaline stratification began due to hydrothermal activity at the bottom of the lake. During the last 10,000 years BP, two periods were described by Haberyan and Hecky (1987) based on evidence of diatoms, chemistry and sedimentology showing the breakdown of this stratification supposedly due to the intensification of hydrothermal activity and volcanism. This rupture, which could only cause a degassing of the deep waters of the lake, is not far from being associated with a limnic eruption. Previously, Degens and Kulbicki (1973) had suggested that the lake was mixed at the onset of intense hydrothermal activity around 5000 cal years BP and then perhaps around 1000 cal years BP. The youngest mixing event in the lake correlates well with the estimated minimum age of the monimolimnion calculated by Schmid et al. (2005). However, these early studies provide little evidence that a limnic eruption of the lake effectively occurred in the past. Over the past 5000 years, Haberyan and Hecky (1987) found that carbonate precipitation abruptly ceased while organic carbon and nitrogen increased sharply, and diatom assemblages completely changed in a short time. The anomalously organic-rich sediment layers are dated to about 2000 cal years BP. Oxygen

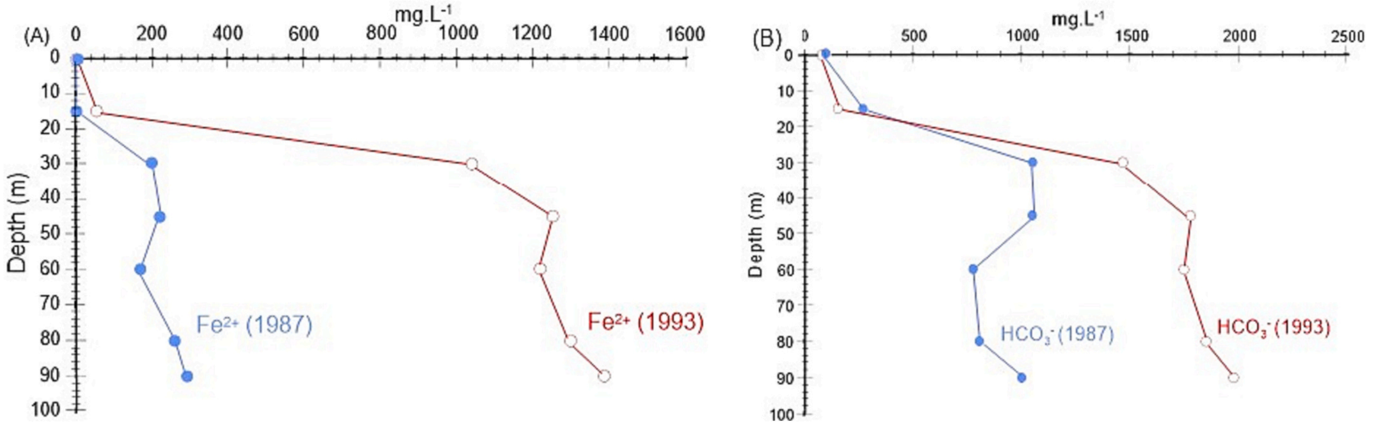

Fig. 4. Comparaison of the concentration profiles for A) Fe2+ in Lake Monoun water in 1987 and 1993 and B) HCO3- in Lake Monoun water with the data of 1987 and 1993 (modified after Sigurdsson et al., 1987; Kusakabe, 2017).

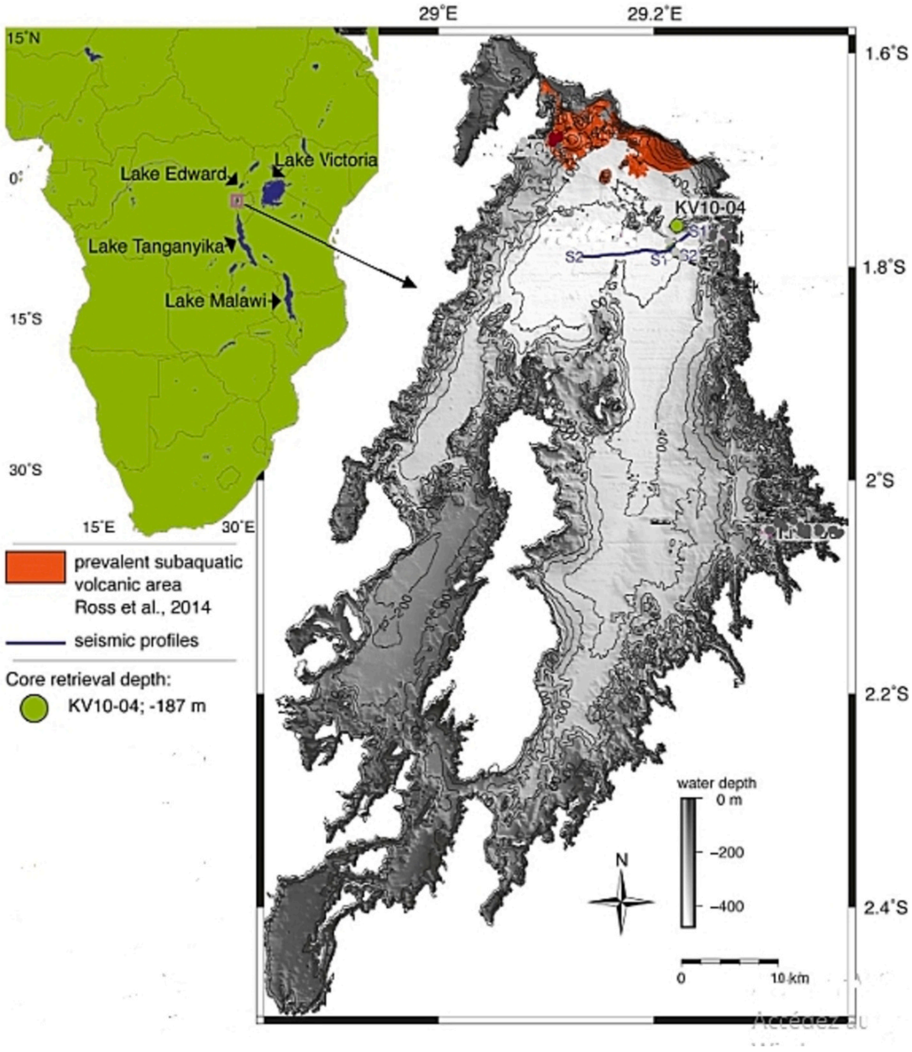

Fig. 5. Overview map of Lake Kivu. The inset shows the location of the Kivu basin within Africa, and reveals its proximity to other lakes within the western rift. Gray scale bathymetric map is overlain by contour lines. Core used for analysis is marked directly on to the map.

depletion during such an event would have killed most of the fish; this explains the present depletion of the lake's fish fauna. Al-Mutlaq et al. (2008) found a sapropelic sediment layer containing algal organic matter. This facies change provides information on the different environmental conditions in the lake which could be caused by lake water turnover and the release of dissolved CO_2 and CH_4, or by hydrothermal activities that contributed to the sapropelic sedimentation for about ~500 years BP from 2000 years.

Work by Ross et al. (2015) on the stratigraphy, lithology, and geochemistry of Lake Kivu sediments provided detail on the paleoenvironment of the lake. From the core KV10–04 taken in the monimolimnion at 187 m water depth southeast of the area of subaquatic volcanic cones, the sedimentological history of the lake was revealed since the rise of its level at the end of the Pleistocene. With seismic stratigraphy, the R3 and R2 tephra layers were deposited at 1000 cal years BP and 5000 cal years BP, respectively (Hecky and Degens, 1973). It is assumed that a gas eruption or lacustrine mixing event occurred at this time. These layers correspond to the bottom of a transparent seismic facies of variable thickness. Lithofacies C1, D (D1, D2, D3), E1, and F1 of KV10–04 show geochemical changes in the mixolimnion (Fig. 6). Punctuations of high productivity are observed and peak in lithofacies C1 and D; this characterizes a downward and upward mixolimnion, respectively. Lithofacies D corresponds to the event-driven layers observed by Hecky and Degens (1973). They present a high content of autochthonous organic matter, poor in diatoms and enriched in 15 N. These layers probably result from intense hydrothermal activity. Furthermore, the lithofacies D of core KV10 covers layers of tephra and could therefore correspond to significant inputs of nutrients into the mixolimnion following subaqueous volcanic activity. The latter probably resulted in a gas eruption accompanied by mixing of the lake. The last mixing events occurred between 1200 cal years BP and 765 cal years BP where a large peak of Ti and Fe is observed in core KV10–04. Fe and Mn would be oxidized during a lake mixing event and the concave Mn/Fe peak at F1 is probably a consequence of the greater solubility of Mn at low pH. The large influx of nutrients into the monimolimnion during lake mixing results in the deposition of the organic carbon-rich layer at D3. The presence of terrestrial macrofossils dated to 10,000 cal years BP at <50 cm depth suggests that this anomalous date is due to terrestrial macrofossils remaining floating in the water column after mobilization of sediments concomitant with seismic events or lake eruptions. Cores collected in parts of the central basin of the lake in 1971 and 1973 by Degens and his team provided paleolimnological information about the lake over a time span that began 13,500 years BP. Several papers (Degens et al., 1971a, b, 1973; Hecky and Degens, 1973; Stoffers and Hecky, 1978; Haberyan and Hecky, 1987) made mention of brown layers and periods of calcite precipitation.

Hirslund (2020) describes these brown layers of the last ~2000 years as the result of magmatic CO2 plumes that transported nutrient-laden bottom waters into the mixolimnion. The presumed relatively low gas pressures during the events underlying the recent brown layers identified at 2200 and 1200 cal years BP are probably the reason why a limnic eruption did not occur. Meromixis and gas accumulation under haloclines are observed from 10,000 years BP when the lake began to overflow due to the limnic eruption (Hirslund, 2020). A limnic eruption triggered by drought (arid climate) around 4000 cal years BP, as it caused the lake level to drop and the dissolved gas pressure under the rising halocline to exceed the hydrostatic pressure. The five mixed zones that currently exist in the lake show that the limnic eruption is responsible for the development of the present salinity profile of Lake Kivu. The work of Tietze (1978), Schmid et al. (2004) and Boehrer et al. (2019) shows that there is an increase in CO_2 in Lake Kivu. Occasional gas discharges in shallow depressions form asphyxiating pockets, known locally as *mazuku* (i.e. "bad wind", Smets et al., 2010), caused death to sleeping people (Hirslund and Morkel, 2020). The considerable volume

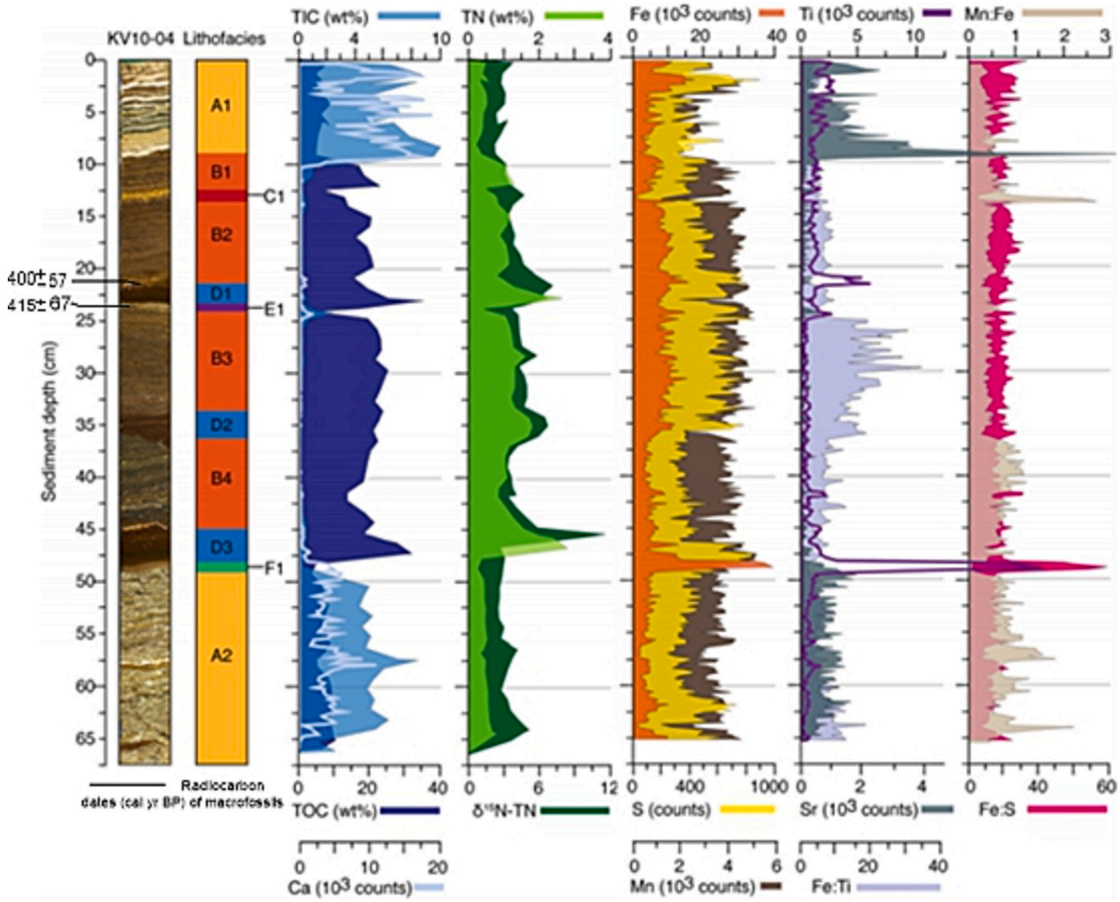

Fig. 6. Geochemical data from KV10–04 (Lake Kivu). XRF data for Fe, S, Mn, Ti and Sr in counts. Geochemical proxy data versus allochthonous input (Fe/Ti), abrupt change in seasonal mixing depth (Mn/Fe) and authigenic pyrite formation. A (A1 and A2) laminated aragonite and diatoms/organic matter + traces of mineral; B (B1, B2, B3 and B4) laminated diatoms and organic matter + traces of mineral; C1) diatom assemblages; D (D1, D2 and D3) amorphic organic matter and diatoms; E1) mixed diatoms and carbonates + trace of mineral; F1) mixed tephra and diatoms (modiffed after Ross et al., 2015).

of gas poses a great threat to the surrounding population. Measurements of gas concentrations in 1975 and 2003 by Schmid et al. (2004) extrapolated to predict a probable limnic eruption by 2090 if these trends persist and no human intervention is made.

The latest fissure eruption of Nyiragongo (May 22, 2021), accompanied by seismic activity in the Goma-Northern region of Lake Kivu, raised concerns about a possible sublacustrine eruption that could have disrupted the stratification of the lake to cause a limnic eruption. Fortunately, this dangerous scenario receded. A possibility to mitigate this limic eruption hazard is commercial CH_4 extraction (Boyle et al., 2009). Many studies are being undertaken in this direction to analyze the pros and cons of sustainable management of Lake Kivu (Hirslund and Morkel, 2020).

3.2. Europe

Lake Pavin, France: "suspected Nyos-type lake"

The idea of developing the recent paleolimnological studies in Lake Pavin was instigated by the famous volcanologist Haroun Tazieff. After his mission in Cameroon where the limnic eruptions had just occurred (although Tazieff categorized them as phreatic eruptions), the first studies on Lake Pavin were initiated. In the summer of 1987, Guy Camus gathered a team to carry out a multidisciplinary geochemical diagnosis of the lake. They came to the conclusion that endogenous gas content was low and mainly derived from the decomposition of organic matter (Camus et al., 1993). It was not until 2005–2006 that CO_2 outgassing points were found in many places in the region (Lavina and Del Rosso, 2009). A 9 km long mudflow deposit in downstream of the outflow of the lake, was attributed to a violent lake spillover around 1300 AD (Del Rosso-d'Hers, 2010). This information, coupled with some historical accounts of the region, rekindled the curiosity of the scientists' assess the hazard of a limnic eruption at Lake Pavin, with evidence of past eruptions (Table 2), despite the claims of other scientists.

In Lake Pavin, a multi-disciplinary paleolimnological study allowed to track the evolution of the lake since its formation about 7000 cal years BP, shortly after the Montchal eruption that formed a cinder cone that was partially preserved by the Pavin eruption (Gourgeaud, 2016). The study of Lake Pavin integrates acoustic soundings, sediment cores and available historical information on climate, human activities and natural hazards (Chassiot et al., 2016). The seismic reflection profiles and the sedimentary record in cores corroborate in the recognition of two facies: (1) the nearshore environments, composed of transparent acoustic facies, and (2) a brownish sedimentary facies. On the sublacustrine shelf, in situ diatom deposits composed of weakly stratified acoustic facies and finely laminated, diatom-rich, greenish and brownish sedimentary facies are recognized. Chapron et al. (2010) characterized these different sedimentary units based on magnetic susceptibility and diffuse spectral reflection (DSR hereafter). The result provide information on sediment composition (Debret et al., 2010) to quantify total organic carbon (TOC) and hydrogen index (HI) that represents the amount of hydrogen relative to the amount of organic carbon. This made it possible to determine the lacustrine or terrestrial origin of the organic matter (Simonneau et al., 2014).

As for Lakes Nyos and Kivu, the titanium concentration is used to monitor the evolution of detrital sediment supply in the basin (Arnaud et al., 2012). This characterization method allowed to track the evolution of the lake level with, for example, the progressive remobilization and incorporation of littoral organic matter into the diatoms. This method revealed that an observed large slump deposit was contemporaneous with a major drop in lake level of about 13 m around 600 AD. Spectrometry and variations in Si/Ti ratios, determined by XRF to indicate diatom productivity, TOC and HI show a complex evolution of organic sedimentation. These findings suggest that the lake underwent several stages of major changes in its productivity and preservation of organic matter. Radiocarbon reservoir effect (either in ^{14}C age scale or Δ14C scale) plotted versus calibrated ages model of Lake Pavin

Table 2
Table of events, ages and characteristics.

Lakes(types)	Hypotheses of events	Ages	Characteristics of events
Nyos "Nyos-type"	Limnic eruption (1)	21 August 1986	Gas explosion, suffocation by CO_2 of magmatic origin, high content of CO_2, change of color of the lake, absence of seismic evidence, evidence of water mixing in the radioisotope (2)
Monoun "Nyos-type"	Limnic eruption (1)	21 August 1984	CO_2 boiling and gas explosion, lake water overflow, water color, whitish cloud, gas rich sediment, rich in iron hydroxide and goetithe. No seismic forecast
Kivu "suspected Nyos-type"	Limnic eruption (3) Magmatic plumes of CO2 (4)	~1000 and ~ 5000 cal years BP	Break in thermohaline stratification and water mixing (5); Change in environmental conditions including water level and gas evacuation (6) (7). Mixed sediments, rich in OM, poor in diatoms and enriched in N, a strong peak of Ti and Fe whose oxidized iron during the mixing event, volcanic activities (3) Woods Hole publications (8) (6) that mention the brown layers in period of calcite precipitation
Pavin "suspected Nyos-type"	Limnic eruption (4)	4000 cal years BP	meromixis and gas accumulation, lowering of the lake level due to the arid climate and dissolved gas pressure exceeding the hydrostatic pressure (4)
	Limnic eruption (9)	600 and 1300 years AD	Age inversion, reworking and destabilization of gas-rich sediment, lake overflow (9) (10)
	Limnic eruption (11)	1785 and 1929 years AD	Thundering sound and orange color of the water, Color and dating of lake deposits (11) (12); high concentration of iron oxide, goethite high magnetic susceptibility and high water content (13) (4)
Albano "suspected Nyos-type"	Limnic eruption (19) (15) Winter snowmelt with degassing typical of seismically active temperate zones (16)	From 4100 to 6800 cal years BP	Sedimentary hiatus, lahar deposit, lake overflow, lake overturning with degassing (21) (19)
	Limnic eruption (14) (15) Winter snowmelt with degassing typical of seismically active temperate zones (16)	2350 cal years BP	Dramatic and sudden increase of the lake level with overflow and release of gas (14)
	Limnic eruption (17) (15) Winter snowmelt with degassing typical of seismically active temperate zones (16)	1829 and 1873 AD	Boiling of water with release of CO2, chemical and color change of water, change of vegetation and human health, increase of lake level due to temperature change caused by

(continued on next page)

Table 2 (*continued*)

Lakes(types)	Hypotheses of events	Ages	Characteristics of events
			hydrothermalism of water (17) (18) (19) (20)
Monctichio "suspected Nyos-type"	Limnic Eruption (22) (15) Abnormal degassing of the Vautour area that cannot cause flooding (23)	From 1810 to 1820 AD	Flooding, rise of the lake level accompanied by degassing, death of fishes during the decade (22)

References: (1) Sigurdsson et al. (1987), Kusakabe et al. (1989, 2000), Evans et al. (1993),(2) Piboule et al. (1990), (3) Ross et al. (2015), (4) Hirslund (2020), (5) Degens and Kulbicki (1973),(6) Haberyan and Hecky (1987), (7) Al-Mutlaq et al. (2008), Schmid et al. (2005), (8) Degens et al. (1971a, b, 1973), Hecky and Degens (1973), Stoffers and Hecky (1978), (9) Chapron et al. (2010), Chapron et al. (2012), (10) Evans et al. (1994), Mott and Woods (2010), Aeschbach-Hertig et al. (1999), Zimmer et al. (2017), (11) Chassiot et al. (2016), Meybeck (2019), (12) Meybeck (2016), (13) Debret et al. (2011), (14) Grandazzi (2008), (15) Sime-Ngando et al. (2016) (16) Galeazzi et al. (2015), Rouwet et al. (2019), (17) Martini et al. (1994), (18) Funiciello et al. (2002), (19) Funiciello et al. (2003), (20) De Benedetti et al. (2008, 2014), (21) Oldfield (1996), Giordano et al. (2006) (22) Ciarollo and Capaldo (1995), (23) Caracausi et al. (2009)

sediments, the Fe/Mn ratio and the presence of goethite provided information on the meromicity of the lake. For example, the increase in the Fe/Mn ratio in a core would partly reflect an intensification of meromicity in a certain period of the lake history (Chapron et al., 2010). These various multidisciplinary studies can help to understand the dynamics of phenomena related to natural hazards in Lake Pavin.

A study on the sensitivity of lake sediments to earthquakes (Nomade et al., 2005) evidenced two historical earthquakes recorded in the region between 1863 and 1892 AD. Sedimentary events dated 1863 and 1840 ± 80 AD by Chassiot et al. (2016), marked by high magnetic susceptibility values, are potentially contemporaneous with these earthquakes. To investigate the triggers of gravity reworking and associated hazards in Lake Pavin, multibeam bathymetry map, high-resolution reflection seismic surveys, lithology and chronology of sedimentary filling were performed on a sediment core with radiocarbon dating. Acoustic data present transparent facies, chaotic facies and an acoustically recognized bedrock with a lake bottom morphology that presents gas-rich sediments in the deep basin and slopes affected by gravity reworking phenomena (Fig. 7). As for the sediment cores, they present four facies with different depths, compositions and densities of sediments. Nine Accelerator Mass Spectrometry-dated radiocarbon samples indicate Holocene ages and are in chronological order except for the age inversion at one depth level (Fig. 8). These reversals indicate that the B-facies sediments are reworked (Chapron et al., 2010). This reworking of the gas-rich sediments could cause: (1) the release of a huge amount of gas into the water column and consequently a limnic eruption (Evans et al., 1994; Aeschbach-Hertig et al., 1999; Mott and Woods, 2010); (2) the triggering of violent waves and the overflow of the lake which can lead to the formation of a debris flow as well as an abrupt drop in the lake level thus affecting the stability of the sediments and gas in the water column and consequently leading to a limnic eruption (Aeschbach-Hertig et al., 1999; Zimmer et al., 2017).

The anomalies recorded in the sedimentary record led to the highlighting of two major landslide disasters around 600 and 1300 AD (Chapron et al., 2010, 2012). These landslides caused the outlet to erode and the crater rim to break, resulting in a sudden drop in water level and the release of a debris flow downstream. Such violent waves can possibly only be associated with a limnic eruption. Moreover, the thunderous sounds and orange water color documented by Meybeck (2016) are related to the waterspout of 1785 AD and would be similar to a limnic eruption (Meybeck, 2019). On the sediment core Pav08-P1, Chassiot et al. (2016) identified two historical limnic eruption deposits in 1929 and 1785 AD from the color of the lake deposits and ^{14}C datings. These colors are marks of high concentrations of iron oxide (Hirslund, 2020) and goethite (Debret et al., 2011), high magnetic susceptibility, and high water content. The latter would result from a capture of water by the sediments during the landslide which led to the sediments being loaded with goethite.

Volcanic lakes in Italy: "suspected Nyos-type lake"

Italian scientists initiated research on maar lakes after their return from Cameroon to seek for evidence of limnic eruptions in the past. This evidence of limnic eruptions was discovered for the early 19th century in the Albano and Monticchio lakes (Chiodini et al., 1997; Funiciello et al., 2002, 2003, 2010; Caracausi et al., 2009; De Benedetti et al., 2014) (Table 1). The Italians compared their results with legends from Roman authors who reported stories about a sudden rise of lake level with catastrophic consequences. In addition, several Italian volcanic lakes were subjected to paleolimnological studies which allowed a reconstruction of the paleoenvironment. From the formation of the lake to the present state, all the variations of the lake levels, the near-lake vegetation, the climatic conditions, the anthropic activities and of the internal processes of the lake, like the mixing and degassing, bioturbation, subsidence or internal reorganization were revealed. Here, the cases of the Lakes Albano and Nemi (Colli Albani volcano, near Rome) and the two Monticchio lakes (Vulture volcano, Basilicata, southern Italy) are examined.

Lake Albano, Colli Albani volcano, Roma

On the basis of the biological records, the history of Lake Albano (Fig. 9) was reconstructed from the period of full glaciation to the Holocene, to date. The first period is subdivided in four stages characterized by lake level fluctuations (Ryves et al., 1996). The transition from this phase to the Holocene, called late glaciation, is marked by the onset of stable meromictic conditions (i.e. stably stratified with chemically distinguished bottom layer), increased water temperature, reduced erosion and the abundance of biological remains. During the Holocene, four major stages are marked by variation in aquatic productivity, a sedimentary hiatus (Oldfield et al., 1996), and forest clearing events (Lowe et al., 1996), besides the evidence of anthropic activity in the area. These results are consistent with those of lithology, paleomagnetism (Chondrogianni et al., 1996; Rolph et al., 1996), biological remains (Belis et al., 1999; Guilizzoni et al., 2002), pollen data (Lowe et al., 1996), as well as chemostratigraphy (Lucchini et al., 2003). Six main stages were recognized in the chemostratigraphy (Fig. 10). The chemical evolution of the lake can be traced by the variations of the ratio between organic and inorganic matter (OM/IM). For example, in zone 1, the OM/IM ratio is very low and the biota encountered and the assemblage of ostracods are typical of the environment that marks the formation of the lake (Manca et al., 1996; Ryves et al., 1996). Moreover, the variation of the lake level and primary productivity in the other zones was observed in combinations of oscillations in biological and lithological data. These oscillations, observed in two cores taken from different locations and at different depths, revealed the absence of sedimentation at ~24.000 years BP suggesting that before this period the lake level was above the depositional site (~30 m; Lucchini et al., 2003). The marked changes in lithology between the massive and laminated sediment units were interpreted by Rolph et al. (1996) and Lowe et al. (1996) as reflecting a periodic geothermal heating of the lake with increased productivity and the formation of stratified sediments alternating with episodes of lower geothermal activity and seismic instability resulting in the influx of detrital material. Guilizzoni and Oldfield (1996) and Guilizzoni et al. (2000) do not share this hypothesis. For them, the phases of increased productivity were probably responses to changes in the warmer, wetter climate and deeper water, whereas the low productivity reflects cooler, drier periods with shallower water.

The study of biota and sedimentary processes is sensitive to paleoenvironmental changes in Lake Albano and the neighboring smaller volcanic Lake Nemi (Guilizzoni and Oldfield, 1996). The results focus on the analysis of stratigraphic variations of pigments derived from anaerobic photosynthetic algae and bacteria, diatom assemblages and

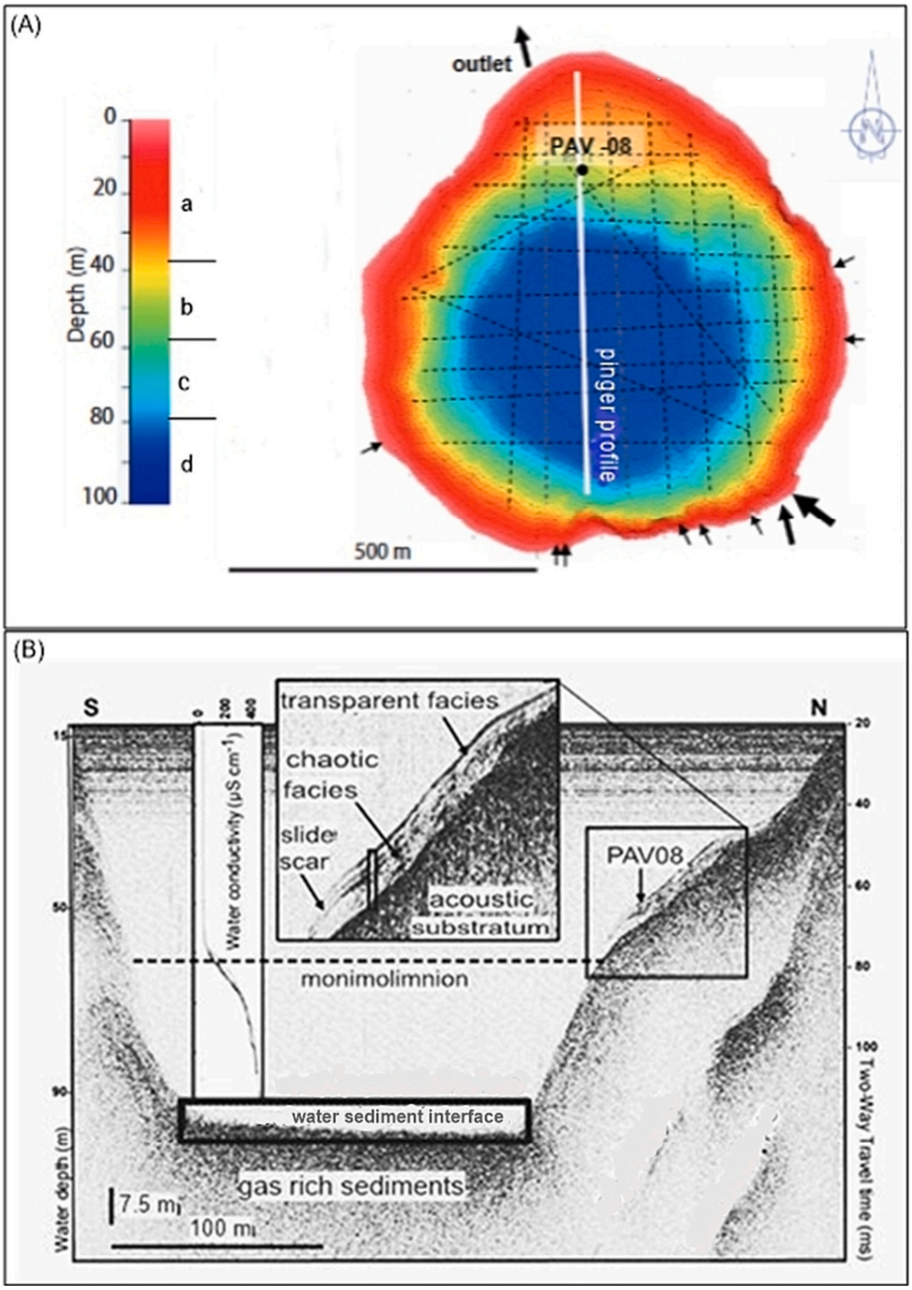

Fig. 7. Geometry of Lake Pavin based on A) multibeam bathymetry map (a: plateau, b: subaquatic plateau, c: steep slopes d: central basin) with the 3.5 kHz seismic grid (dashed lines) PAV08 coring sites and the location of the pinger profile shown in (B) which is the high resolution seismic profile (3.5 kHz) showing the different acoustic facies identified in Lake Pavin and the seismic stratigraphy of core PAV08. The monimolimnion of the lake at 60 m is determined from conductivity measurements of the lake water (modified afterChapron et al., 2010).

fossil remains of invertebrates (ostracods, cladocerans, chironomids) from the sediments on the time scale from 28.000 to 17.000 years BP. The paleoecological indicators studied in these lakes are known to be sensitive to variations in productivity and pH (Guilizzoni et al., 1992). The physical and chemical environment of Lake Albano underwent several variations consequent to lake level oscillations (Chondrogianni et al., 1996. A sedimentary hiatus identified between 4.100 and 6.800 cal years BP was probably due to the variation in lake level and the process of resuspension of sediments within the lake (Oldfield, 1996). A lahar deposit found in the Ciampino plain (NW of Lake Albano) corresponds to the age range of the hiatus; a lahar is interpreted to be associated with the overflow of the lake (Giordano et al., 2006). Nevertheless, the trigger mechanism of this lahar – and lahars that occurred at Lake Albano – is only hypothesized by several generic mechanisms.

This lake overflow was sometimes assimilated to a water overturning with degassing, to be interpreted as a limnic eruption (Funiciello et al., 2003). The sudden and dramatic rise in the lake level is a consequence of the natural outgassing in approximately 2350 years BP (Grandazzi, 2008). Recent studies on the age and isotopic composition of calcite precipitates of the last 2000 years in the Albano area indicate cycles of CO_2 release on average every 100 years with a coincidence with the most violent earthquakes (Tuccimei et al., 2006), or earthquake swarms (Amato et al., 1994; Chiarabba et al., 1997; Chiodini et al., 2012; Rouwet et al., 2021b). The recent historical literature shows two similar abnormal degassing episodes produced during the last five seismic events between 1829 and 1927 (Rouwet et al., 2019). The May 1829 and 1873 seismic events are well described for Lake Albano and reveal

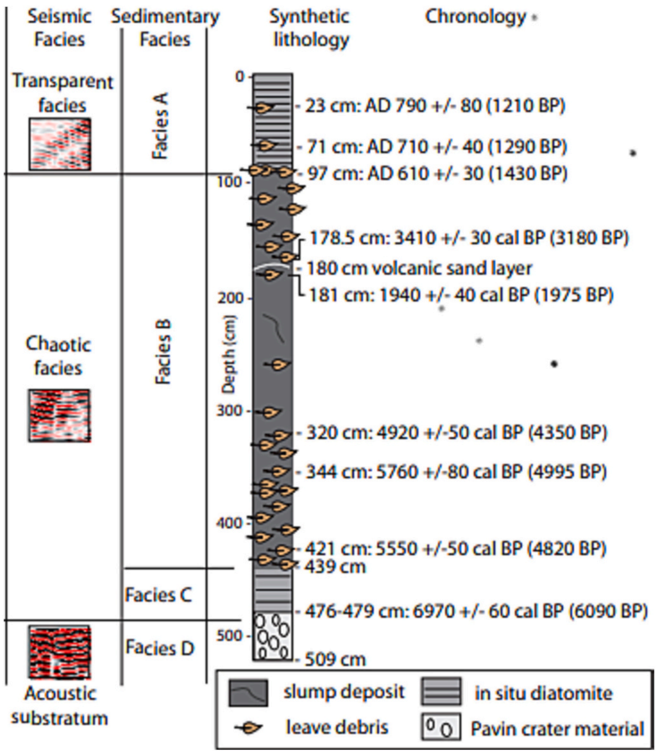

Fig. 8. Lithology of core PAV08 (Lake Pavin) illustrating the chronology of the different sedimentary facies A, B, C and D and the seismic facies (transparent, chaotic and acoustic bedrock). The occurrence of numerous leaf debris and a coarse sand layer in facies B is interpreted as reworked deposits (modiffed afterChapron et al., 2010).

similar characteristics to those of the Lake Nyos disaster, such as the "boiling" of the water with release of CO_2, changes in water chemistry and color, and changes in vegetation and human health. Martini et al. (1994) likened it to a limnic eruption based on the water chemistry similar to that of Lakes Nyos and Monoun. Funiciello et al. (2002, 2003) and De Benedetti et al. (2008, 2014) suggest an increase in lake level due to a change in water temperature that had a volcanic origin (i.e. hydrothermal fluid input).

In contrast, the work of Rouwet et al. (2019), which consists of revising available historical literature dating back 2800 years on the past of Lake Albano, does not always agree with these interpretations of anomalous events in the volcanological literature. Rouwet et al. (2019) support the hypothesis of D'Ambrosio et al. (2010), Galeazzi et al. (2015) on the winter snowmelt around 2350 cal years BP to have caused the necessary rise in lake level for overflow, and for not showing clear evidence of a similar gas release as described for Lakes Nyos and Monoun. They introduced the term "anti-Nyos-type lake" to classify degassing lakes in seismically active, temperate regions, of which Lake Albano is probably a good example. For Lakes Nyos and Monoun, instead, the release of gas is sudden, whereas in Lake Albano it is periodic during winter overturn. As such, other maar lakes in Europe or in other temperate climate regions could also be "anti-Nyos-type" lakes.

The Monticchio Lakes, Basilicata

The basins of the two Monticchio maar lakes (Piccolo and Grande) situated in the volcanic crater in the southwest part of Monte Vulture in Basilicata, southern Italy were formed 140,000 years BP during the last activity of Mt. Vulture volcano (Fig. 11), and were the object of multiple geochemical and paleolimnological studies. At the beginning of this research in the framework of the detailed reconstruction of the European Quaternary archives, radiocarbon dating of organic matter in sediment layers was less reliable, which might have introduced large uncertainties in the first dating of sediment cores. This problem was encountered in 1985, and was probably due to the emission of exogenic CO_2, as recognized later by Chiodini et al. (1997) and Cabassi et al. (2013). In fact, the CO_2 entering into both the Monticchio lakes has an inorganic, magmatic origin, as stated by the $\delta^{13}C\text{-}CO_2$ (between −0.27 and − 3.91 ‰ vs PDB), the high CO_2/CH_4 ratios in dissolved gases, and the accompanying high $^3He/^4He$ isotopic ratios (up to 6.1 Ra where Ra is the $^3He/^4He$ ratio in air of 1.39×10^{-6}) (Caracausi et al., 2009). Methane, instead, has an organic origin ($\delta^{13}C\text{-}CH_4$ (between −61.7 and − 65.7 ‰ vs PDB) (Caracausi et al., 2009). According to Paolino Tortorella reported by Ciarollo and Capaldo (1995), these gases arrived at the surface of Lake Monticchio Piccolo in 1810 AD probably as a result of a flood (Palmiera and Schacchi, 1852). Tenore and Gussone (in Ciarollo and Capaldo, 1995) also reported gas emissions in 1820 AD in combination with a rise in the lake level and several fish kill events during the decade preceding the gas burst and so the limnic eruption (Sime-Ngando et al. (2016). However, Caracausi et al. (2009) hypothesized that an external trigger, such as a flood or an earthquake, is not necessary for the gas to be released, given anomalous degassing in the Vulture area. As such, given that an anomalous degassing event was described for the past, a similar event could happen in the future.

Varve counting, AMS 14C dating, and tephrostratigraphy (Newton and Dugmore, 1993; Huntley et al., 1999; Wulf et al., 2004) provided a reliable chronology of sediment layers. Robinson (1994) illustrated an environmental change in the lake based on sedimentary geochemistry. The sedimentary record submitted to this study covered the glacial cycles up to date (Allen et al., 1999). The indicators of paleoproductivity are organic carbon and biogenic silica. The most striking change occurred at the lower Holocene boundary with an increase in productivity due to high nutrient availability (Tissot and Welte, 1984; Birks, 1986), also affected by light infiltration or temperature. The study by Truze (1990) on Lake Bouchet provided a useful model to explain the increase in organic carbon during the Holocene. This model states that terrestrial vegetation in response to wet or warm climate stabilizes watershed slopes, leading to a consequent decrease in erosion and hence a decrease in nutrient influx, meanwhile organic matter becomes autochthonous.

Evidence of Holocene environmental changes based on pollen records at the Monticchio lakes (Fig. 12) revealed the following observations: (1) Abies(fir) was present at 9.500 cal years BP and became extinct by 3.000 cal years BP, and (2) Taxus was also recorded although for a short period. Both pollens were present in numerous interglacial pollen records in northwestern Europe (Watts, 1988). Their extinction is possibly due to human intervention, a sign of forest exploitation (burning), or even the start of climate change. Alnus appears for the first time at 10.000 cal years BP, and gains in importance at about 7.900 cal years BP. The absence of Alnus may be due to a decrease in lake level, which would lead to its death by drought. The last 2000 years of the sedimentary record are distinguished by evidence of forest clearing and agricultural activity (olea or olive trees, cereals, juglans). There are also traces of Costanae and pistaccia dating back to the Middle Holocene, suggesting the presence of small populations. Correspondingly, evidence of clear human activities are also reported from 4000 cal years BP at Lake Albano (Lowe et al., 1996, see previous section), and 2.600 cal years BP at Lake Vico (Magri and Sadori, 1999) in northern Lazio, Italy. No clear evidence of a limnic gas burst are recognized in the sedimentary record, however, the local populations were probably put at risk by the lakes which could have affected agricultural activity, and hence pollen record, in the Vulture area.

4. Discussion

The characteristics of the limnic eruptions of the Nyos-type lakes prompted researchers to search for the lakes that might correspond to the Nyos-type. In this research, 4 lakes were found with characteristics close to those the Nyos-type lakes. This was made possible by oral traditions, geochemical and limnological methods of lake water and physical paleolimnology. In this study, emphasis was placed on

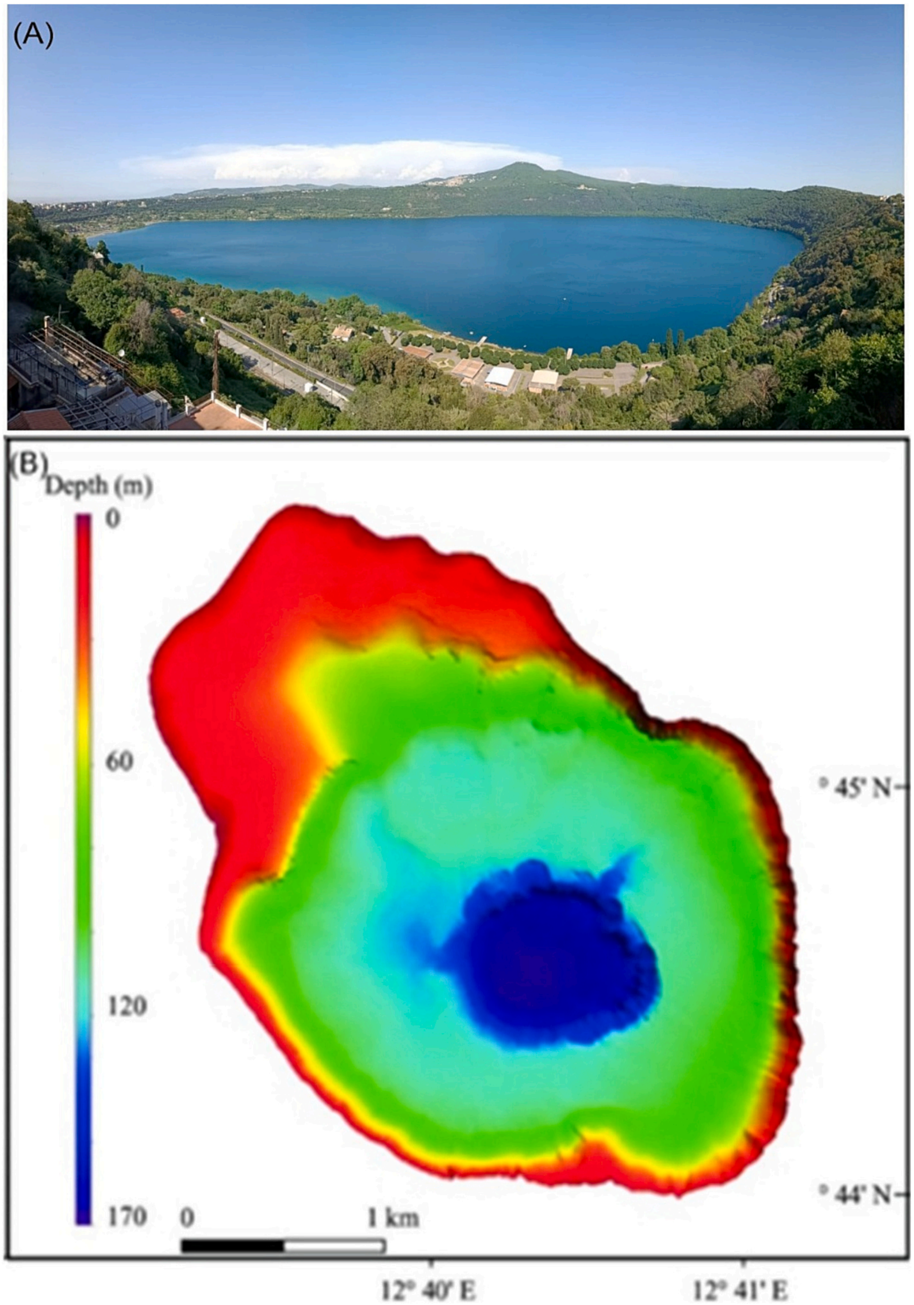

Fig. 9. Lake Albano (A) (Picture by D.R.), and (B) bathymetry modified after Anzidei et al. (2008).

paleolimnological methods based on lake sediment archives. These methods have made it possible to illustrate the characteristics of these events in the past and their recurrence in comparison with those of the Nyos type. The study of lakes in Africa, Asia, America and Europe that are likely to be Nyos-type shows that only a few lakes in Africa and Europe display sedimentological features that can be associated with limnic eruption. These include Lake Kivu in Congo, Lake Pavin in France, Lake Albano and Monticchio in Italy. Sings of limnic eruptions in these lakes include reworked sediments of reversed ages, colors of deposits reflecting mixing of highly gas-laden water in an anoxic environment and water in an oxic environment and/or at the surface, gas-rich sediments, sediments rich in iron hydroxide, strong peaks of Ti and oxidized Fe during mixing events, sedimentary hiatus, turbidites and signifiant changes in geochimical signature.

The occurrence of a limnic eruption is precluded in some lakes located in temperate zones where the water is renewed at least once a year. Therefore, subaqueous landslides or mass deposits and abnormal degassing in volcanic or seismically active areas typical of temperate zones cannot produce limnic eruptions.

Similarly the “woods hole” publications describing the brown layers in Lake Kivu cannot be said to be precrousers of limnic eruptions since relatively low gas pressure was found in these layers; proving that no limnic eruption occured. Instead, they are considered by Hirslund (2020) to be magmatic plumes of CO2. As far as the ages of the events are concerned, the most interesting have been achieved by radiocarbon dating. This is the case for Lake Kivu and Lake Pavin, where studies have been more detailed in the search for evidence of limnic eruptions. Its ages were calibrated, terrestrial macrofossils have been selected for dating and the radiocarbon reservoir effect has been take into account. This would obviously make the dating reliable. The choice of samples for analysis is crucial. For example, old dates could be the result of juvenile volcanic CO2 from sublacustrine springs being assimilated by

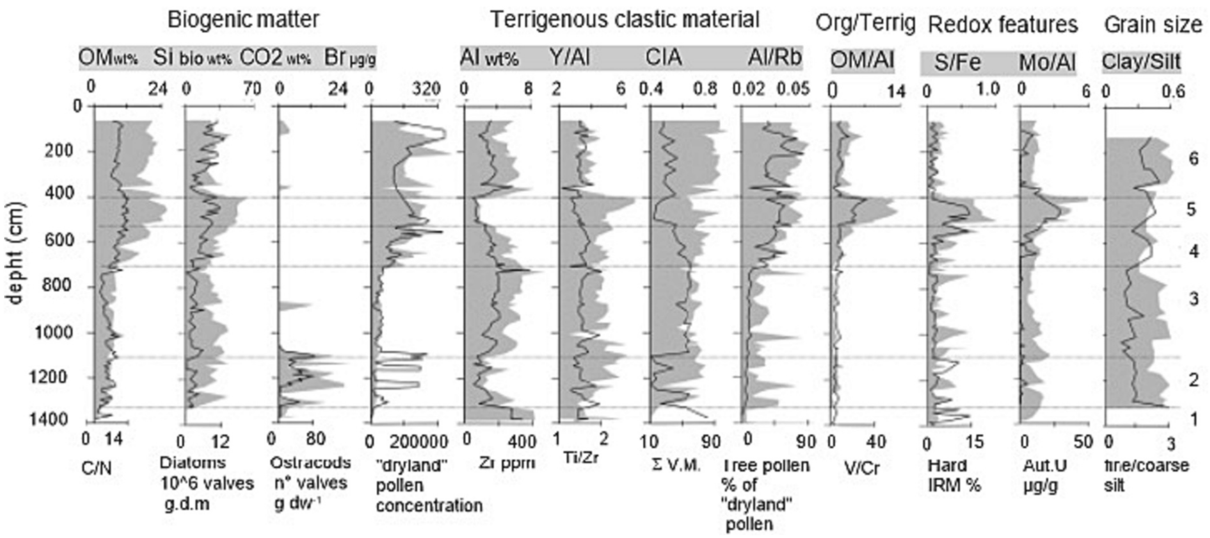

Fig. 10. Depth profiles of selected geochemical indices representative of the main sedimentary components of PALB 94/1E in lake Albano. Dotted lines separate six areas of particular geochemistry and shaded profiles correspond to the upper scales (modified after Lucchini et al., 2003).

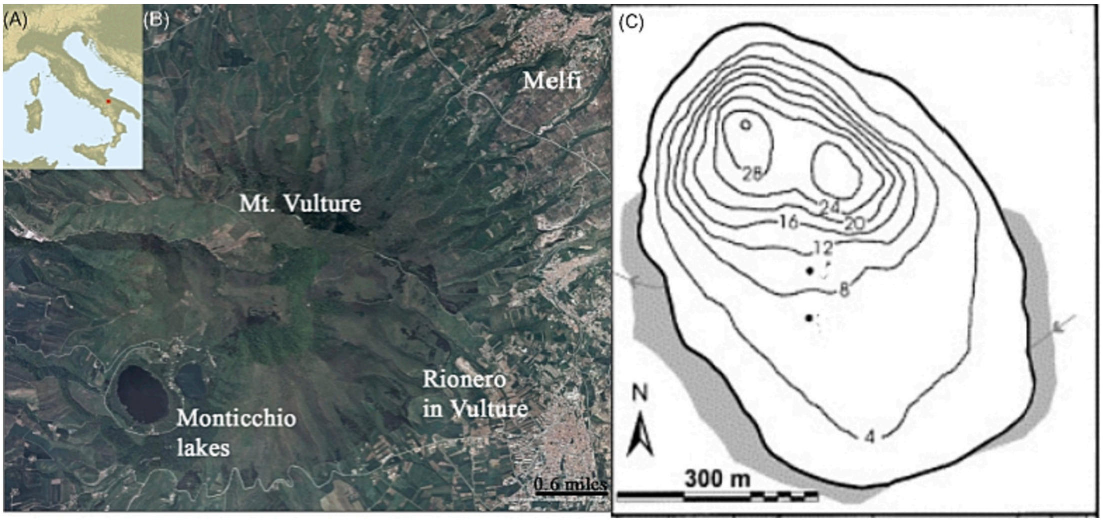

Fig. 11. General location of lakes Monticchio (A) in Italy. (B) Satellite image of Mt. vulture retrieved from google maps by Marco Nicolosi. (C) Bathymetry of Monticchio crater lakes in southwest portion of Mt.vulture volcano.

submerged macrophytes. This problem could be avoided by dating terrestrial macrofossils. The chronological uncertainty of sediments is generally subject to variable effects depending on the age of the reservoir. Local radiocarbon reservoir effects must be take into account to avoid dating errors.

In all these attempts to relate sedimentary archives features to Nyos-type events, it is prudent to note that no Nyos-type lake, namely Lake Monoun and Lake Nyos, has been the subject of an analysis of their sedimentary archives. This suggests that they are sediments from limnic eruptions that occurred around 40 years ago. Further investigation using paleolimnological methods based on sedimentary and seismic stratigraphy in these reference lakes will improve knowledge of the evidence for limnic eruptions and their recurrence in the past and consequently in the future.

5. Future studies: proxies for limnic eruptions

The paleolimnological methods reviewed in the studies aims at evaluating the recurrence intervals of catastrophic events (e.g. limnic overturns, flooding, landslides, earthquakes) to hence better evaluate the long-term risk. In addition to the traditional methods of studying sediment cores, such as geochemistry, physics and biology, several additional methods were encountered to recognize limnic gas burst. Lake Monoun will be considered as a “miniature Nyos-type lake”, a natural prototype with the advantages of an easier access for sediment coring. Clear geochemical markers of limnic lake turnover events are forseen in lake sediments (e.g. Fe-rich oxidized layers). Given that lake overturn is sensitive to atmospheric conditions, climate change will probably modify the physical stability of any lake. This effect could jeopardise safety as CO2 release from “Nyos-type” lakes depends on overturn dynamics.

5.1. Seismic stratigraphy

Seismic profiling provides valuable information on the lithology and geometry of lakes (Ariztegui et al., 2001). This information contributes to the identification and mapping of sedimentary deposits. This limnological approach to lake systems adopted by Kelts (1987) is modelled on

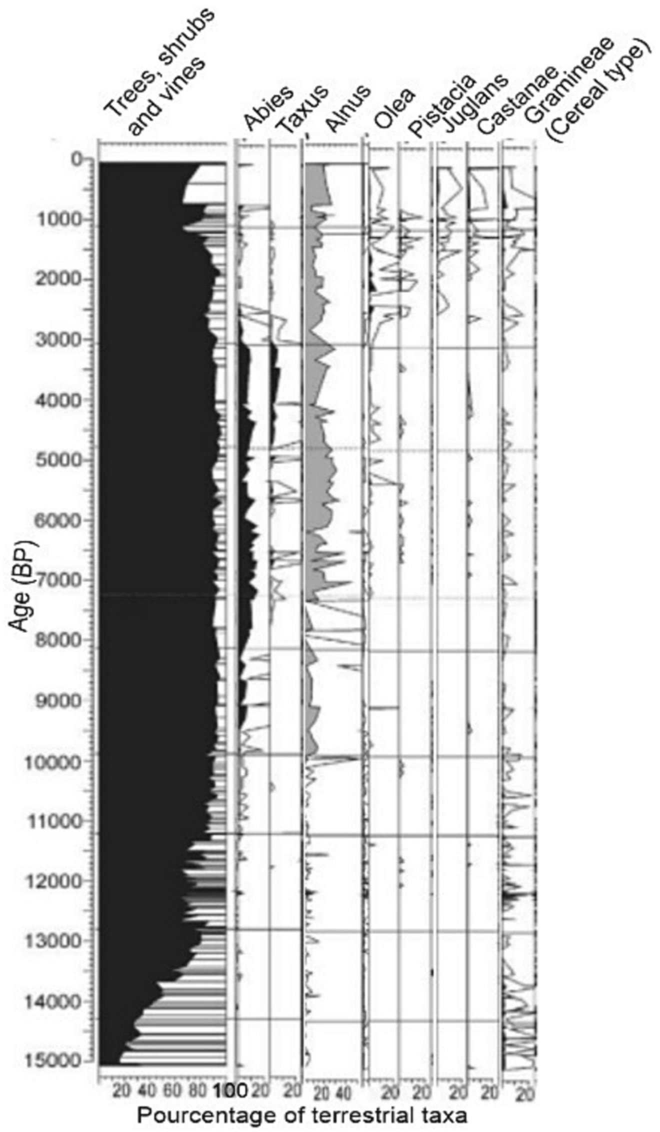

Fig. 12. Pollen diagram of Monticchio Lakes (modified after Allen et al., 2002).

the progress of marine geological research in Oceanography. Initially used for marine geophysical surveys, its application to lakes quickly provided information on lake level fluctuations, rapid change of sedimentary systems and facies (Mullins et al., 1996). Information on thickness, tectonic structure and extent of sedimentary patterns is provided by seismic profiles. This information allows optimization of the location of ideal long-core drilling sites with continuous paleoclimatic or paleoenvironmental records. From the seismic stratigraphy, it becomes more straightforward to identify undisturbed sediments for coring, to recognize unconformities, collapses, and gaps in the sedimentary layers. The identification of these features facilitates the comparison of different sedimentary sequences and the mapping of the extent of change in the lake system (Gilli et al., 2005; Anselmetti et al., 2009). Seismic profiles can be used to describe irregular bottom structures, typical for complex volcanic lakes. Thin sedimentary or eroded sequences will provide information on large time scales while thick sequences provide information on recurrent, high-resolution events (Anselmetti et al., 2009). When seismic facies are mapped, different sedimentary deposits can be distinguished (Niessen et al., 1993). A succession of large amplitude parallel reflections can define the stratigraphy between distinct units. A strong petrophysical signature will allow the correlation of reflections between different core zones.

Gas-rich zones show transparent seismic planes, suggesting that seismic waves do not penetrate these zones. The presence of such gas-rich layers can be an indication of potential hazard due to gas burst in present times, which implies that a gas burst could have occurred at the given lake. The recognition of mixed layers in the seismic stratigraphy at these lakes could hence also be caused by limnic gas burst, and not only by earthquakes, landslides or flood events.

5.2. *Sedimentary cores*

The results of the high-resolution seismic surveys can be used to chose the sites for sediment coring. The different sedimentary units as well as the lacustrine facies can be defined and described for the textural, biological, geochemical and mineralogical characteristics of the sediments. This description of the sedimentary facies will allow to reconstruct the paleoenvironment or the dynamics of the lake evolution, and will identify the layers indicative of limnic overturn which will probably be richer in iron or siderite. If combined with dating (next section) the study of the sediment cores can be a means of obtaining information on the frequency and mechanism of limnic eruptions. As for now, very few paleolimnological studies have been effectuated to enable sound evidence of Nyos-type gas bursts for many lakes. This implies that Nyos-type gas bursts did not occur in the past or, at least, did not leave evidence in the sedimentary record of cores.

5.3. *Dating*

In palaeolimnology, the most widely used dating method is radiocarbon dating. This method, which is applied to carbonate materials, dates back to about 40.000 years BP (Lowe and Walker, 1997). To avoid errors in dating with the contamination of juvenile or ancient carbon, one can date only terrestrial microfossils that are sometimes rare in the central or deep part of the lake. This is observed for example in lakes where juvenile volcanic CO_2 from sublacustrine springs can be assimilated by submerged macrophytes, resulting in overestimates of dates (Hajdas et al., 1997). The choice of analytical samples for radiocarbon dating is important in crater lakes with Nyos-type eruptions where there is a lot of carbon dioxide gas in the lake water.

Sediment varves are used for an accurate chronology. Depending on climate and lake morphology, varves tend to be rarely formed and preserved in lake sediments. However, deep crater lakes with an anoxic environment in the deep waters and a funnel-shaped basin favor the formation and preservation of varves (Zolitschka, 2006). The climatic regime or geology of the watershed dictates the type of annual varve laminations (Brauer, 2004). Varve countings of undisturbed sediments can be performed on the surface of the split core, its photograph, X-ray, or large-scale thin sections. Analysis of thin-section microfacies provides information on the seasonality of deposition and layer boundaries. The last decades of varve chronologies can be verified by ^{137}Cs and ^{210}Pb dating method and by historical events such as floods.

Explosive volcanic eruptions produce huge quantities of tephra that are distributed over large areas of land and water. The tephra from a well-defined eruption can be geochemically identified from major and trace elements (Lowe, 2011). The tephra layer can be used as isochronous time markers in the sedimentary record (Reinig et al., 2021). To date a tephra layer, it is best to use buried or intercalibrated ^{14}C radiometry in organics and radioisotope i.e. K/Ar, Ar/Ar, U/Th on phenocrysts. The results obtained can be correlated with other archives. This dating approach will allow the chronology of the different sedimentary facies, of which some can be disturbed by limnic gas bursts.

6. Conclusions

Based on a comprehensive review of limnological studies of Nyos-type lakes and “suspected Nyos-type lakes”, this study found that unambiguous detection of limnic gas explosions is rarely assessed due to the lack of reference event during historical times for single lakes. Lake Monoun and Nyos, the first and only lakes to have exploded in recent history, in 1984 and 1986, respectively, can hence be considered as natural laboratories to better understand limnic eruptions in maar lakes worldwide. Unfortunately, the well-studied aspects of the two Cameroonian "killer lakes" are based on the dynamics of gas explosions, hazard assessment based on water chemistry and gas discharges, risk mitigation by artificial venting, and the stability of the dam and its reinforcement (Rouwet et al., 2021b), and not on potential similar behavior in the recent geological past. Apart from the certainty that a limnetic gas explosion did occur, Lake Monoun has the advantage over Lake Nyos and other "suspected Nyos-type lakes" that it can be considered a natural laboratory. The lake has a smaller surface area, shallower depth favorable for sediment coring, easy access, and negligible residual gas content due to artificial degassing that released ~90% of the original gas content after 1984. Sediment cores may preserve the geochemical or sedimentological markers of past limnic eruptions. Unfortunately, the post-1984 coring campaigns at Lake Monoun were unsuccessful and future studies should: a) reconstruct the palaeoenvironment of Lake Monoun from geochemistry and lithology; b) identify favorable areas for long coring in the lake from seismic stratigraphy; c) establish the chronology of the event layers from different dating methods, and, d) establish a detailed chemostratigraphy of the sedimentary sequences from stable oxygen and carbon isotopes. Additional studies (e.g., magnetism, palynology, μXRF microscopy) could also provide evidence of limnic eruptions and probably reopen other avenues of debate in the assessment of limnic eruption risks, on Lake Monoun as well as on other lakes around the world.

Despite the rare occurrence of Nyos-type gas bursts around the world within historical times, surprisingly more volcanic lakes than here reported could be subjected to this particular type of hazards. Especially the deep lakes in tropical climates in degassing areas should be the target in future research, as their bottom waters and underlying sediment layers can store paramount information on the, respectively, current and past degassing state.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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