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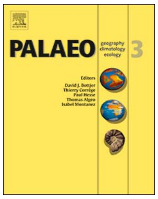

A 7000-year environmental history and soil erosion record inferred from the deep sediments of Lake Pavin (Massif Central, France)

Léo Chassiot[a,*], Yannick Miras[b,c], Emmanuel Chapron[a,d], Anne-Lise Develle[e], Fabien Arnaud[e], Mikaël Motelica-Heino[a], Christian Di Giovanni[a]

[a] *Institut des Sciences de la Terre d'Orléans (ISTO), UMR 7327, CNRS, Université d'Orléans, BRGM, 1A, rue de la Férollerie, 45071 Orléans Cedex 2, France*
[b] *GEOLAB, UMR 6042, CNRS, Université Clermont-Auvergne, F-63000 Clermont-Ferrand, France*
[c] *Histoire Naturelle de l'Homme Préhistorique (HNHP), UMR 7194, CNRS, Département de Préhistoire, Muséum National d'Histoire Naturelle, Institut de Paléontologie Humaine, 1, rue René Panhard, 75013 Paris, France*
[d] *Géographie de l'Environnement (GEODE), UMR 5602, CNRS, Université Toulouse 2 Jean Jaurès, Allée A. Machado, 31058 Toulouse Cedex, France*
[e] *Environnements, Dynamiques et Territoires de la Montagne (EDYTEM), UMR 5204, CNRS, Université Savoie Mont-Blanc, Bâtiment "Pôle Montagne", 73376 Le Bourget du Lac Cedex, France*

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ABSTRACT

A 14-m long sedimentary sequence (core PAV12) was collected in the deepest part of Lake Pavin, a maar lake located in the French Massif Central. The PAV12 sedimentary sequence documents the lake's environmental evolution since its formation 7000 years ago. The relationships between the catchment's vegetation cover, erosion processes and changes in trophic status were shown using a multi-proxy characterization of mineral and organic fractions supported by palynological data. The record shows a succession of lithological units starting at the base with volcanoclastic material corresponding to the early stage of Lake Pavin. The deposition of organic-rich and diatomaceous sedimentary units above volcanoclastic material indicates an evolution toward a pristine lacustrine state. The Late Holocene environmental history of this lake is marked by two tipping points reflecting major environmental disturbances at ca. 4000 cal BP and after the deposition of erosive mass-wasting deposits (MWDs) at 1350 cal BP (AD 600) and 650 cal BP (AD 1300). The upper unit of core PAV12, which corresponds to the past 700 years, indicates that one of these MWDs was likely the driving force behind a major limnological change marked by a shift in redox-sensitive elements (i.e., current meromictic lacustrine state). The palynological diagram indicates a forested catchment where woodland clearances and agro-pastoral activities have remained limited except over the last 700 years. These findings suggest restricted human impact within the watershed compared to other regional archives. The reconstruction of the Lake Pavin erosion record determined from titanium and red amorphous particle fluxes highlights phases of enhanced erosion at ca. 6.5–5.5, 4.1–3.8, 3.5, 2.8–2.6, 1.6–1.4 cal kyr BP and during the Little Ice Age (LIA). A comparison between this erosion record, palaeoenvironmental archives from Western Europe and palaeoclimatic data supports an Atlantic signal driving precipitation patterns over Lake Pavin at centennial to millennial timescales. The influence of local human activities, even on a small scale, cannot be completely discounted as their impact on erosional processes may be amplified in a steep catchment such as that found in Lake Pavin.

1. Introduction

Maar lake sediments can provide high-resolution records of landscape evolution under human and/or climate influence. Therefore, they are considered key-sites for palaeoenvironmental studies over the Holocene and beyond (e.g., Brauer et al., 1999; Ariztegui et al., 2001; Martin-Puertas et al., 2012; Striewski et al., 2013; Zolitschka et al., 2013; Bhattacharya et al., 2015; Marchetto et al., 2015). Two decades ago, maar lake sediments in the French Massif Central were studied to reconstruct environmental changes. This was done using magnetic properties (Thouveny et al., 1990), organic and inorganic geochemistry (Truze and Kelts, 1993; Sifeddine et al., 1996) and palynology (Coûteau, 1984; Juvigné and Stach-Czerniak, 1998). However, many of these maars were formed during the last glacial period and their relatively low sedimentation rates allow for long-term climatic reconstructions over the last Glacial and Interglacial cycles.

Located in the Mont-Dore area, Lake Pavin differs from other regional maar lakes because of its steep catchment and anoxic and

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[*] Corresponding author at: Eau Terre Environnement (ETE), Institut National de la Recherche Scientifique (INRS), 490 rue de la Couronne, Quebec City, QC G1K 9A9, Canada.
E-mail address: leo.chassiot@ete.inrs.ca (L. Chassiot).

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meromictic water column which has been intensively studied in recent decades (e.g., Meybeck et al., 1975; Martin et al., 1992; Michard et al., 1994; Viollier et al., 1995, 1997; Aeschbach-Hertig et al., 1999, 2002; Olive and Boulègue, 2004; Lehours et al., 2005, 2007; Assayag et al., 2008; Bura-Nakic et al., 2009; Bonhomme et al., 2011; Busigny et al., 2014; Cosmidis et al., 2014; Gal et al., 2015). By comparison, palaeoenvironmental investigations remain sparse with only two studies documenting the vegetation history and paleolimnology over the last 700 years (Stebich et al., 2005; Schettler et al., 2007). In 2012, one long-piston core (PAV12) was collected in the deep central basin of Lake Pavin. The sedimentary sequence, previously described in Chassiot et al. (2016a, 2016c), displays a 14 m thick deposit of which 7 m are related to a background sedimentation dominated by diatoms. This high-resolution sequence allowed the lake's environmental and aquatic evolution to be documented since its formation ca. 7000 years ago (Juvigné et al., 1996). Its steep catchment morphology differs from other regional paleoenvironmental records where landscapes have been strongly affected by human activities since the Neolithic (e.g., Guenet and Reille, 1988; Gay and Macaire, 1999; Miras et al., 2004; Lavrieux et al., 2013; Miras et al., 2015). Therefore, Lake Pavin sediments constitute a key paleoenvironmental archive within this region.

This study uses the PAV12 sequence to reconstruct the 7000-yr environmental history of Lake Pavin. It focuses on the relationships between the vegetation cover and the organic and minerogenic terrigenous fluxes to identify the driving forces between Holocene climatic variability and human impacts. To do this, we used a multi-proxy approach by gathering published data on X-ray Fluorescence (XRF) conducted using a non-destructive core scanner and bulk organic geochemistry (Rock-Eval) (Chassiot et al., 2016c). We also provided new data, including Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) analyses, quantitative organic petrography (i.e., palynofacies) and palynological analyses. The chronological framework also reused radiocarbon data published in Chassiot et al. (2016c) to perform a new age-depth model based on a Bayesian Analysis (Blaauw and Christen, 2011).

2. Settings

2.1. Geographical and geomorphological setting

Lake Pavin is a 92 m deep maar lake located in the Mont-Dore area (Massif Central, France) at an elevation of 1197 m a.s.l. (Fig. 1A). Its diameter is about 750 m with an area of 0.44 km^2 (Fig. 1B). Its bowl shape originates from a phreato-magmatic eruption that occurred ca. 7000 years ago (Juvigné et al., 1996). The volcanic fallout, mainly consisting of basaltic fragments and trachy-andesitic pumices, created a crater rim that encompasses the Montchal stratovolcano. This has marked out a steep and small topographic catchment area (0.36 km^2) that is now covered by a dense forest, mainly composed of beech (*Fagus sylvatica*) and fir (*Abies alba*), and planted areas that are mainly composed of spruce (*Picea abies*) (Stebich et al., 2005) (Fig. 1C). Water inputs are essentially due to precipitation along wit,h inflows coming from subaerial and subaquatic springs located all around the crater rim and at the foot of the Montchal stratovolcano. The outflow goes north through an outlet and reaches the Couze Pavin, a tributary of the Allier River belonging to the Loire drainage basin (Fig. 1A). The meteorological station located in Besse-et-Saint-Anastaise (5 km east of Lake Pavin) records a mean average temperature near zero degrees during the winter months that causes the lake surface to freeze (partially or completely) during this period (Stebich et al., 2005). At the same location, annual precipitation (rain and/or snow) varies from 1200 to 1600 mm·yr^{-1} (Meybeck et al., 1975; Stebich et al., 2005).

2.2. Limnology

Nowadays, Lake Pavin waters are permanently stratified, with an upper oxygenated, seasonally mixed water layer (i.e., mixolimnion) and a permanent anoxic and sulfidic water layer below 60 m depth (i.e., monimolimnion) (Fig. 2). In the last twenty years, numerous vertical profiles of physico-chemical parameters have been conducted on the water column (Michard et al., 1994; Viollier et al., 1995, 1997; Aeschbach-Hertig et al., 1999, 2002; Olive and Boulègue, 2004; Assayag et al., 2008), highlighting a strong vertical physico-chemical gradient between 60 and 70 m water depth (i.e., mesolimnion). Below this limit, enrichment in dissolved constituents (phosphorus, iron, manganese, arsenic, molybdenum and other redox-sensitive trace elements) increases water density, thus, favoring the stability of the bottom water (Viollier et al., 1995; Assayag et al., 2008). The lake's water balance between inflows and outflows shows a deficit. This suggests the existence of gas-rich groundwater inputs (Aeschbach-Hertig et al., 1999; Olive and Boulègue, 2004; Assayag et al., 2008) (Fig. 2) that contribute to maintaining the current meromixis (Bonhomme et al., 2011). According to hydrological equilibrium models and in-situ measurements, two subsurface springs have been inferred at 45 m and 90 m water depth, respectively (Viollier et al., 1997; Aeschbach-Hertig et al., 2002; Assayag et al., 2008). The physical and chemical properties of the Lake Pavin water column enhance many biochemical and hydrological processes, illustrated in Fig. 2. Within the monimolimnion, the decay of particulate organic carbon (POC) is catalyzed by anoxic microbial communities, mainly bacteria and archaea, to favor methanogenesis (MET) by acetate fermentation pathway. The resulting CH_4 goes upward and is progressively converted into CO_2 by anoxic methane oxidation (AMO) via archaea (Lehours et al., 2005, 2007). Iron and phosphorous cycles remain tightly coupled with an enrichment of dissolved species in the deep waters following an “iron-wheel” process (Busigny et al., 2014, 2016).

2.3. Sedimentary environments

Geophysical mapping techniques, including multibeam swath bathymetry and hydro-acoustic surveys, have already been used to illustrate the geometry of sedimentary deposits across the lake (Chapron et al., 2010, 2012; Chassiot et al., 2016a, 2016c) (Fig. 2). The results show the presence of a flat and circular basin surrounded by steep slopes that are incised by numerous canyons. Unfortunately, the gas-rich sediments in the deep basin do not allow acoustic signals to penetrate. However, a freeze-core retrieved in 2001 by a German team (core FC01) (Fig. 1B) shows an accumulation of annually laminated diatomaceous sediment (i.e., varves, e.g., Zolitschka et al., 2015) in the first two meters below the lake floor (Stebich et al., 2005; Schettler et al., 2007). In addition, core PAV12 displays 14 m of sediments that can be divided into the following four main units: (1) an upper diatomaceous unit (0–207 cm); (2) a mass-wasting deposit (MWD, 207–628 cm); (3) a lower diatomaceous unit (628–1045 cm); and (4) a basal unit (1045–1400 cm) made of laminated volcanoclastic materials interbedded with turbidites. A detailed description of these units is provided in Chassiot et al. (2016a).

The combination of hydro-acoustic images and sedimentary cores collected in three sedimentary environments (i.e., the littoral, the plateau and the deep basin) have allowed two major sedimentary events to be identified: (1) a 9 m lake-level fall following a crater outburst with a large subaquatic slump deposit on the plateau in ca. AD 600 (Chassiot et al., 2016a); and (2) an earthquake-triggered slope failure at the edge of the plateau in ca. AD 1300 (Chassiot et al., 2016b) (Fig. 2).

3. Materials and methods

3.1. Sampling

A continuous sequence was collected from the central part of the deep anoxic basin (92 m water depth) (Fig. 1B) using an UWITEC coring platform and 2-m long PVC tube sections. In the catchment, soil profiles