



HAL
open science

Lakes as Recorders of Earth Surface Dynamics From Yearly to Plurimillennial Time-Scales

Fabien Arnaud, Pierre Sabatier

► **To cite this version:**

Fabien Arnaud, Pierre Sabatier. Lakes as Recorders of Earth Surface Dynamics From Yearly to Plurimillennial Time-Scales. Reference Module in Earth Systems and Environmental Sciences, Elsevier, 2021, 10.1016/b978-0-12-819166-8.00125-0 . hal-03478550

HAL Id: hal-03478550

<https://hal.science/hal-03478550>

Submitted on 14 Dec 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Lakes as Recorders of Earth Surface Dynamics From Yearly to Plurimillennial Time-Scales[☆]

Fabien Arnaud, and Pierre Sabatier, Environment Dynamics and Territories of the Mountain (EDYTEM), CNRS, Université Savoie Mont-Blanc, Chambéry, France

© 2021.

Introduction

Lakes are defined as in-land bodies of standing water. As such they represent zones of drastically reduced water velocity along stream courses and thus—almost—perfect sediment traps. Indeed, whereas, in most cases, the amount of water flowing in a lake is almost equal to the amount flowing out of it (+/- evaporation), most of the solid charge brought by stream water is trapped within the lake. This is nicely exemplified at the outlet of Lake Geneva where the alpine Rhône river gets out of the lake free of any sediment and is met by its tributary Arve river which is by contrast extremely turbid. Whereas both streams originate from a high-altitude glaciated area producing massive amounts of sediment, the difference in particles load is only explained by the presence of Lake Geneva which traps most of the sediment coming from the Upper-Rhône River catchment area (**Fig. 1**).

The quantity and quality of river's solid charge depend on a multitude of processes acting within a given catchment area. They hence potentially bear a lot of information about the evolution of inland areas, both submitted to natural and human-triggered forcing mechanisms. This information is subsequently stored in stratigraphic order at the bottom of lakes within sediment strata. This is why lakes are particularly interesting archives of the Earth Critical Zone dynamics (**Fig. 2**).

The Earth Critical Zone (ECZ) is a conceptual space defined as the thin active layer at the surface of the Earth where all the energy, matter and information exchanges that are necessary to sustain life do operate (**Banwart et al., 2013**). It has been defined by the US National Research Council as spanning the whole space from the top of the canopy down to the base of groundwater (**Gaillardet et al., 2018**). Among the recent advances in environmental sciences, the concept of ECZ theorizes the fact that social-ecological systems strongly depend on the imbrication of biotic and abiotic processes that interact at various time scales, from the second to several millennia. It is hence crucial to better know all those interacting processes, their kinetic and long-term interactions in order to understand global changes and their potential effects on planet Earth habitability (**Lade et al., 2020**). In this chapter, we will detail how some of the information stored in lake sediment can be extracted in order to reconstruct the evolution of the ECZ along with the complex interactions driving its dynamics.

Production and export of eroded matter within the Earth Critical Zone

Erosion processes are the main path for matter and thus information to be transferred within the Earth critical zone. They may be schematized into four phases (**Fig. 3**): weathering, grabbing, transport and accumulation.

Main forcing factors of weathering, grabbing and transport process may be climate- (temperature, precipitation, wind) and/or human-triggered (land-use, including agro-pastoral activities and civil engineering, such as urbanization or dam building, for instance). They are also related to natural functioning of the ECZ, such as vegetation changes or geodynamics. As a consequence, the quantity and quality of eroded material potentially bring information about all those processes.

Documenting climate-triggered changes in erosion patterns

Streams are one of the most efficient sediment conveyors on Earth and as such, they play a key role in the erosion cycle (**Aksoy and Kavvas, 2005**). Reconstructing changes in river-borne sediment flux and origin from lake sediment might hence reflect the history of the in-land hydrology (Arnaud et al., 2012, 2016). Dust mobilization and emission by wind into the atmosphere may also be important erosive mechanisms (**Shao et al., 2011**). Since the dust flux can contribute > 10% of the global river sediment flux, dust deposition from the atmosphere plays an important role in the biogeochemistry of the ECZ (**Derry and Chadwick, 2007**) and can be imprinted within lake sediment (**Sabatier et al., 2020**).

[☆] This article was reviewed for the Encyclopedia of Inland Waters, Second Edition by Section Editors Marie Elodie Perga and Damien Bouffard.



Fig. 1 *Left panel:* this Sediment plume entering the Cayuga Lake, New York, United States, illustrates the huge amount of sediments that are transferred from catchment areas toward Lake basins. *Right panel:* the Arve river, loaded with glacial sediment from Mont-Blanc Massif, joins the Rhône river at the output of Lake Geneva. When it enters the lake, some 80 km upstream, the Rhône river was as much loaded as the Arve river, but Lake Geneva acted as a perfect sediment trap and only let the clear water pass through.

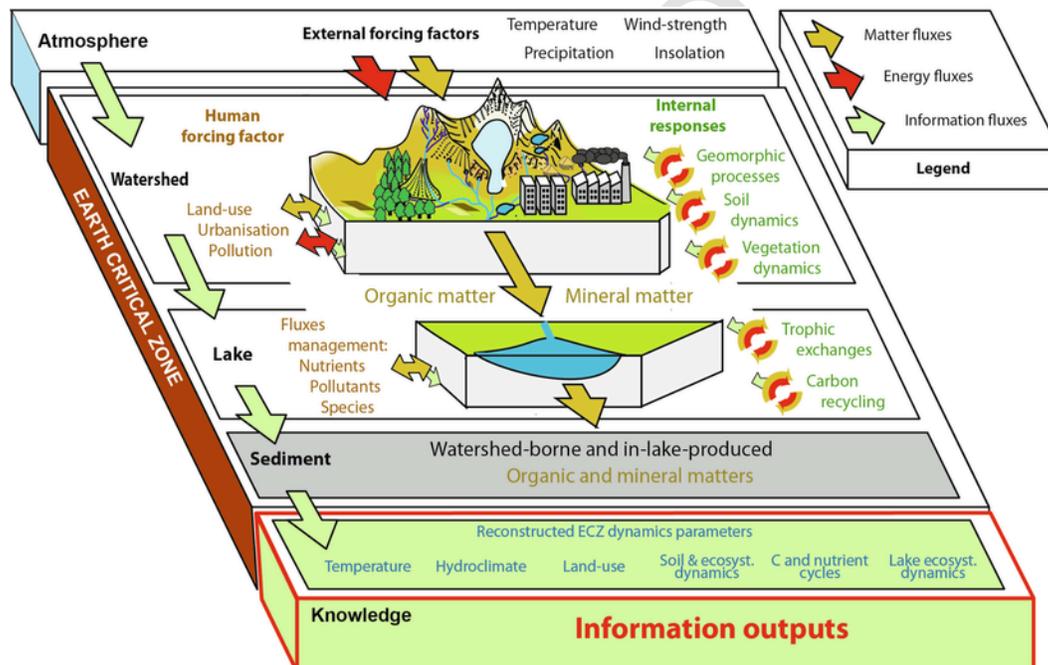


Fig. 2 Conceptual view of matter, energy and information fluxes through the Earth Critical Zone and toward a lake basin. Lake floors accumulate matter from the catchment that carries information about the ECZ dynamics. Limnogeology is the science that permits to reveal this information, hence turning mud into information.

Most methods used to record erosion fluxes from lake sediment archives lie upon the geochemical contrast of this river-borne fraction, named “allochthonous” or “terrigenous,” compared to the in-lake produced matter, named “autochthonous.” In this chapter, we will focus on the use of the terrigenous fraction, as a marker of the Critical Zone dynamics. For the use of the autochthonous fraction, refer to the “Paleolimnology” chapter. However, a good knowledge of the mineral autochthonous fraction is required in order to well-distinguish it from the terrigenous one. The autochthonous fraction preserved in lake sediment can be made of bio-precipitated skeletons, typically made of carbonate or silicon and/or of organic matter. In tempered hard-water lakes, the mineral autochthonous fraction is largely dominated by bio-chimio-precipitated carbonates (see chapters on “drivers and implications of lake pH” and “the lacustrine carbon

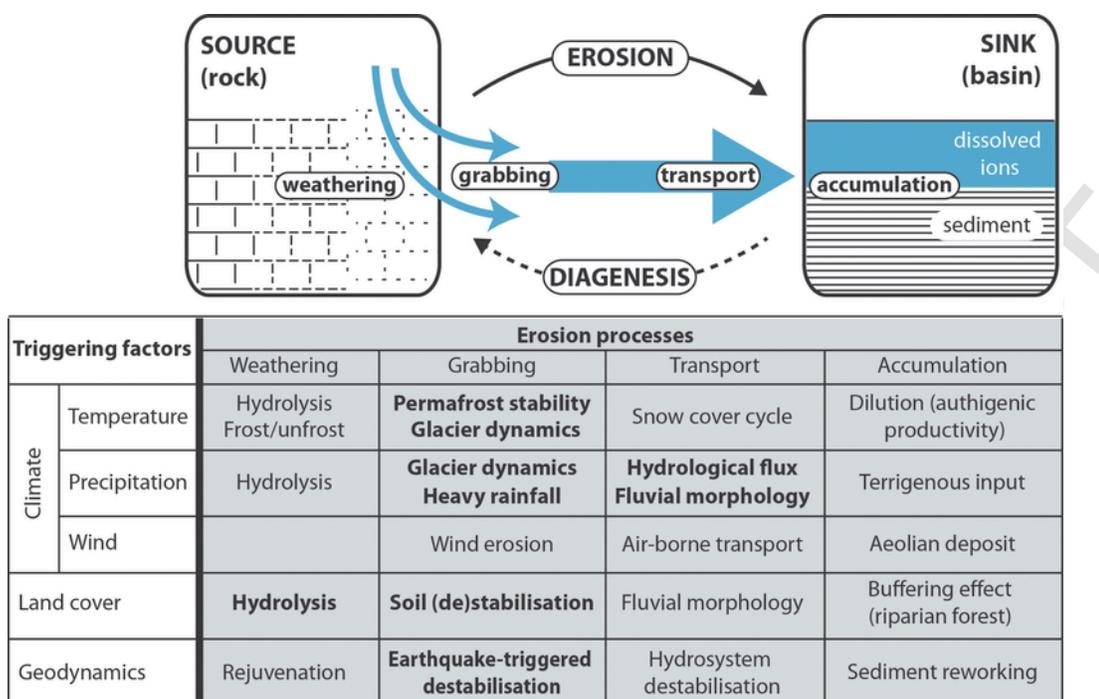


Fig. 3 Schematic view of the erosion cycle (upper panel) and its processes as well as triggering factors (lower panel). Modified after Arnaud F, Poulencard J, Giguet-Covex C, Wilhelm B, Révillon S, Jenny JP, Revel M, Enters D, Bajard M, Fouinat L, Doyen E, Simonneau A, Pignol C, Chapron E, Vannière B and Sabatier P (2016) Erosion under climate and human pressures: An alpine lake sediment perspective. *Quaternary Science Reviews* **152**: 1–18. doi: 10.1016/j.quascirev.2016.09.018.

cycle”). In high altitude and/or high latitude, colder conditions preclude the precipitation of calcite and the autochthonous fraction is commonly dominated by biogenic silica (mostly diatoms remains) and organic matter.

Whatever the composition of the autochthonous fraction, measuring the evolution of a marker of one the two fractions permits assessing the erosion-borne contribution to the sediment flux. The magnetic susceptibility of sediments generally increases with higher erosion-derived material contribution and is commonly used as such a marker. Inversely, one may measure chemical proxies of organic matter, such as the total organic carbon, the abundance of chlorophyll-like pigments or the bromine content, which are often negatively correlated to the erosion-triggered sediment input.

Recording airborne erosion through dust deposit

Recent advances about very high altitudes lakes systems in granitic contexts with a low to very low watershed/lake surface ratio leading to low local erosive inputs by stream allow to reconstruct past airborne dust fluxes (Fig. 4; Jiménez-Espejo et al., 2014; Sabatier et al., 2020). These lakes present very low accumulation rates, generally 1–2 m for the entire Holocene with a strong in situ organic matter component. Hence, they can be considered as rain gauge lakes where the sediment is a mixture of autochthonous organic matter and atmospheric inputs. Tracers such as clay mineralogy allows to assess the arid dust contributions (palygorskyte) and their origins (ratio Illite/Kaolinite and Chlorite/Kaolinite) (Sabatier et al., 2020; Scheuvs et al., 2013). Other techniques such as mineral geochemistry and Sr/Nd isotopic composition allow quantitative reconstructions of past dust flux and dust origin fingerprinting.

Recording glacier fluctuations

A classic example of a direct relationship between climate and erosion is given by the reconstruction of glacier fluctuations from lake sediments. The amount of glacial sediment produced by glacier erosion is indeed related to the surface of the glacier (Dahl et al., 2003; van der Bilt et al., 2016). As a consequence, reconstructing the flux of glacier-eroded material into a lake permits to reconstruct past glacier fluctuations.

In this case, the cold lake water precludes the precipitation of carbonates. The terrigenous input is hence assessed through the relative proportions of terrigenous fraction and in-lake produced organic matter. This can be done using any of the techniques exposed above, magnetic susceptibility being among the most cost- and time-efficient and thus the most used ones (van der Bilt et al., 2016). Recent

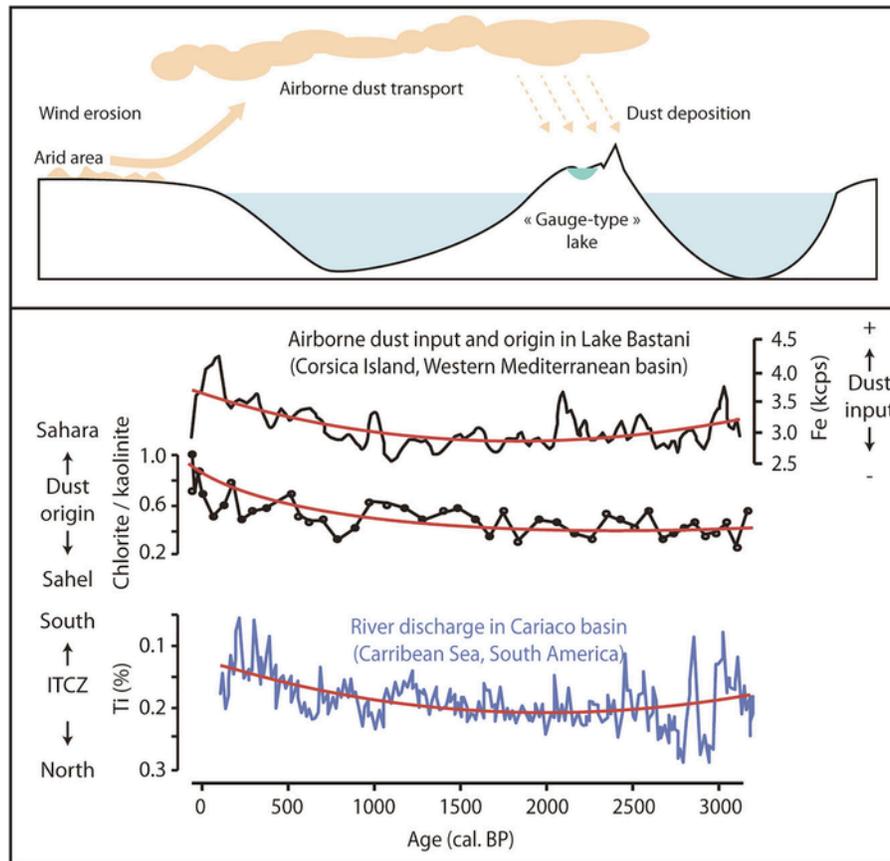


Fig. 4 (A) Schematic principle of the record of wind-driven erosion from arid area in gauge-type lake through dust deposition signal. (B) Example from Lake Bastani, Corsica (Sabatier et al., 2020), where the sediment geochemistry gave a record of dust input, while clay mineralogy gave a signal of dust origin (Sahel vs. Sahara desert). The river discharge in Cariaco Basin (Haug, 2001) illustrates how such a signal enables paleoclimatic interpretations: the increase in dust and the change in its origin reflects the independently evidenced southward migration of the Intertropical Convergence Zone (ITCZ). Modified after van der Bilt, WGM, Bakke J, Vasskog K, Røthe T and Støren EWN (2016) Glacier-fed lakes as palaeoenvironmental archives. *Geology Today* 32: 213–218. doi: 10.1111/gto.12166.

development in spectrocology also brought promising results by accurately assessing the fluctuation in organic matter content (Fouinat et al., 2017).

Such an approach has been extensively used in Scandinavia where large ice-cap glaciers have tongues flowing onto ancient glacier valley (van der Bilt et al., 2016). When those valleys get dammed, often relatively low in the catchment area, the lakes hence trap efficiently the glacier-derived terrigenous flux (Fig. 5). Moreover, their moderate altitude permits the development of primary producers whose organic matter will dilute the erosion flux whereas the surrounding forested environment provides sufficient organic macroremains for dating. On the contrary, the method is sometimes hard to apply in inner mountain ranges where glacier-fed lakes are located higher in altitude and surrounded by steep slopes. Steep slopes reduce the glacier surface and short distance between the glacier and the lake may indeed lead to a hard-to-interpret non-buffered signal. Moreover, the scarcity of datable organic macroremains in high altitude lake sediments may make them hard to date. However, applying a detailed sedimentological study may in such cases permit to construct accurate glacier fluctuations chronologies (Fouinat et al., 2017).

Erosion and paleohydrology

Large rivers may bring huge amount of sediment to lake basins (Fig. 5). In such cases, the evolution of the terrigenous input may reflect changes in regional paleohydrological conditions, assuming there is a positive feedback between more humid conditions and both accentuated erosion in the lake catchment area and more efficient transport (Arnaud et al., 2016; Wessels, 1998). Hence, high resolution continuous paleohydrological reconstructions can be established, provided one may verify that hydrology is the prime forcing factor of changes in erosion flux. This is often the case in the early times of the Holocene, because the emergence of agro-pastoralism, a human-triggered perturbation of the erosion cycle, may alter the climate-erosion relationship (Arnaud et al., 2016). As early human perturbations

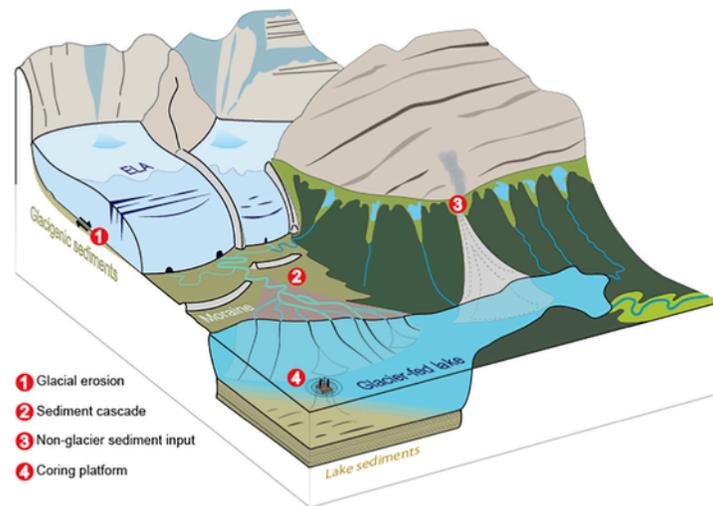


Fig. 5 Schematic view of a lake basin fed by a partially-glaciated catchment area (van der Bilt et al., 2016).

of the erosion rarely affected large surface areas, the choice of a large and deep lake, fed by a large catchment area will hence be more favorable for climate reconstruction than a small lake, more sensitive to human disturbances. At high altitude, landscapes are losing their interest for human activities such that highest altitude lake records are directly connected to climate changes, especially if there is a glacier in their catchment area (Arnaud et al., 2016; Fig. 6). However, in any case, it is crucial to critically assess the climatic interpretation of fluctuation in erosion fluxes. This must first be done through a deep sedimentological investigation in order to track any sign of non-climatically induced changes. In particular, any change in the composition of the terrigenous fraction must be documented and interpreted regarding the local geological setting.

One must always keep in mind that any paleo-reconstruction depends on an array of assumptions that are often impossible to be verified altogether. As a consequence, they must be interpreted very cautiously. Beyond the study of the sediment itself, it is hence crucial to confront results to independent markers, both within the same core and from independent regionally close archives. Indeed, even if precipitation may vary following more regional patterns than temperature, they are still coherent over large areas and all records based on the same assumptions should hence react together.

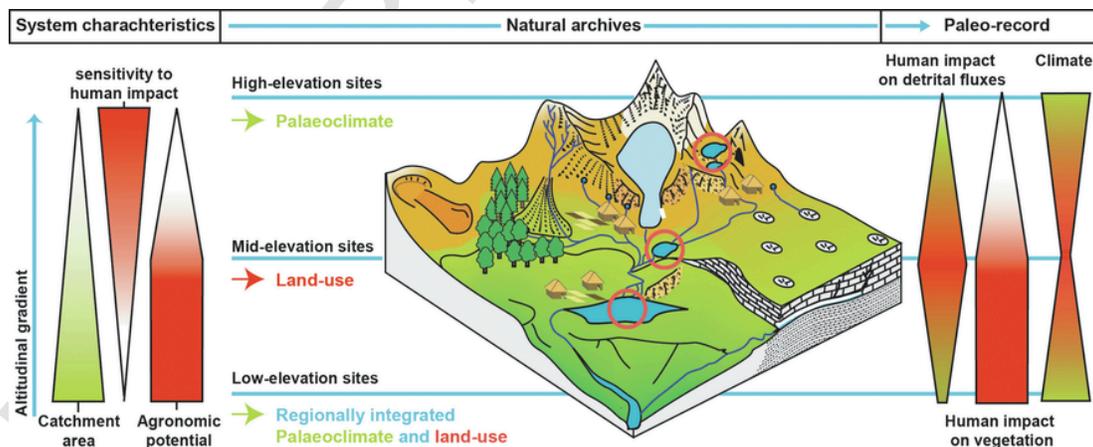


Fig. 6 Schematic representation of lake sediment sensitivity to climate and human forcing factors depending on the setting in a mountainous landscape (Arnaud et al., 2016). Arnaud F, Poulencard J, Giguët-Covex C, Wilhelm B, Révillon S, Jenny JP, Revel M, Enters D, Bajard M, Fouinat L, Doyen E, Simonneau A, Pignol C, Chapron E, Vannière B and Sabatier P (2016) Erosion under climate and human pressures: An alpine lake sediment perspective. *Quaternary Science Reviews* 152: 1–18. doi: 10.1016/j.quascirev.2016.09.018.

Geological record of flood chronicles

While they generally appear as quiet bodies of standing waters, lakes are also subject to violent sedimentation events. An abundant literature has been dedicated to the identification and documentation through time of geological deposits deriving from flood events (Gilli et al., 2013; Schillereff et al., 2014; Støren and Paasche, 2013). Potentially mobilized techniques are here very numerous, however they all lie upon the same concept of seeking for anomalous layers interbedded within the so-called “continuous sedimentation.” By contrast, such layers are often called “instantaneous deposits” or “event layers” (see the chapter on “Sedimentology”). Naked eyes have been, and still are, the first tool used to identify such layers (Fig. 7). Laser grainizers were largely used in sedimentology lab since the late 1990s². They offered a precise description of sediment layers that was since then used to document and characterize flood layers (Arnaud et al., 2002; Wilhelm et al., 2012a). Magnetic parameters, among which magnetic susceptibility is the easiest to measure, were also intensively used since the years 1980s³ (Støren et al., 2016). Since years 2000s⁴ the multiplication of XRF core scanners enabled the efficient acquisition of high resolution geochemical logs hence marking a major milestone in the development of new approaches (Wilhelm et al., 2012b). These new methods enable the detection of much thinner layers (Fig. 7) along with the measurement of their composition. It was then possible to reveal information about their source area, but also about their grainsize which reflects flood intensities (Wilhelm et al., 2012b). Even more recently, hyperspectral image of sediment cores surface was applied to the detection and characterization of unconsolidated sediment, hence opening new promising perspectives (Jacq et al., 2020).

Erosion processes are essential links between the occurrence of a flooding event and the transfer of this information toward the sediment accumulation. However, this link may be biased by a number of intermediate processes within the catchment area, the watershed or the lake itself. Sedimentologists thus developed a panel of techniques and concepts in order to verify the climatic relevance of hence reconstructed past floods chronicles. The two main potential misinterpretations are the false attribution of a given deposit to an actual flooding event and the false attribution of an apparent change in flood deposits recurrence rate to a change in climatic conditions.

How to relate an instantaneous deposit to a flooding event?

Attributing a given sediment layer (or sequence of layers) to a single flooding event that occurred maybe hundreds or thousands of years ago is a quite challenging task. In particular, one must remember that various processes may trigger the occurrence of instantaneous deposits. For instance, earthquakes induced deposits in lake sediment records which might be mistakenly interpreted as flood-triggered (Arnaud et al., 2002). In order to trustfully attribute an instantaneous deposit to a flooding event, it is important to study the sedimentology in detail. In particular, facies recognition is crucial as it permits to identify and characterize the different sedimentation patterns that are recurrent throughout a given sediment accumulation and thus to sort the huge amount of information stored in it. To do

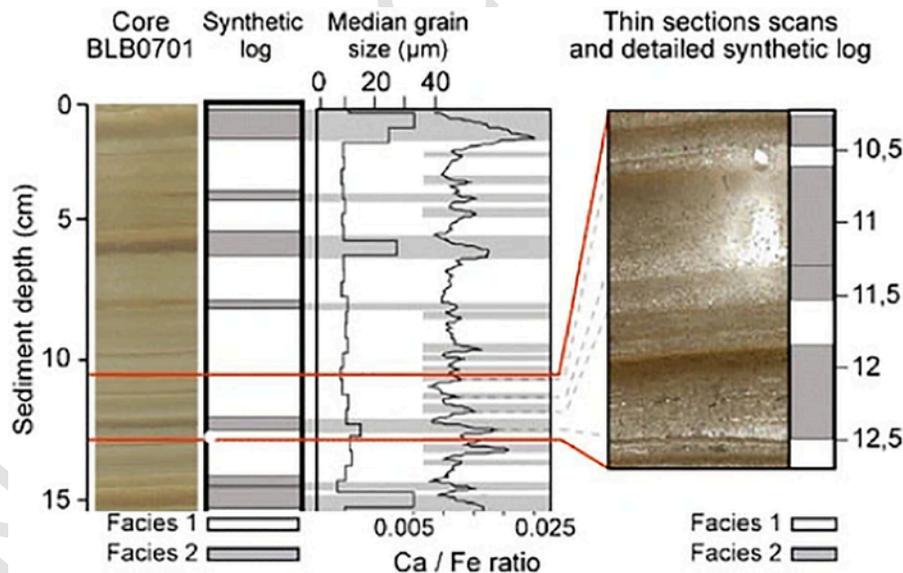


Fig. 7 Identification of flood-triggered deposits in a sediment core at various scales. From left to right: visual identification of interbedded coarser sediment layers, facies determination based on visual observation, grainsize increases (5 mm-step), XRF core scanner-based geochemical identification of coarser sediment layers that are enriched in calcium vs. iron and microscopic observation on embedded thin section showing complete flood-triggered sequences of layers: (i) basal coarsest grains, (ii) gradual upward decrease in grainsize and (iii) final “clay cap”, here marked as a brown opaque layer. Modified after Wilhelm B, Arnaud F, Enters D, Allignol F, Legaz A, Magand O, Révillon S, Giguët-Covex C and Malet E (2012a) Does global warming favour the occurrence of extreme floods in European Alps? First evidences from a NW Alps proglacial lake sediment record. *Climatic Change* **113**: 563–581. doi: 10.1007/s10584-011-0376-2.

so, naked eyes are the primary tool, but they must be supported by quantitative information about grainsize, chemical and/or mineralogical composition and/or colorimetry. Among those parameters, the size distribution of particles is often a good indicator of the triggering mechanism.

Floods can generate turbid currents that flow on the bottom of the lake (Hsü, 1989; Lambert et al., 1984). According to the historical experiment of Hjulström (1935), in such a case, one given current velocity permits the deposition of one given particle size. This results, within a single flood-triggered deposit, in a succession of well-sorted layers of various particle sizes. Within the thickest sequences, it is possible to measure an increasing particle size from bottom to top at the base of the sequence that mirrors the increasing current velocity at the beginning of the flood event (Figs. 7 and 8). Then the deposited grainsize diminishes toward the top of the sequence as the velocity drops. In most cases, a clay cap then tops the summit of the sequence while the flood-triggered lake water turbidity settles over some days, weeks, or even months in the case of extreme floods within large and deep lakes. This whitish clayey top layer is hence often one the most convenient markers to identify a flood as a triggering mechanism. On the contrary, subaqueous slides generate matrix-supported flows which can be assimilated to subaqueous avalanches. Resulting deposits are made of a mixture of fine and coarse grains. The difference between those deposit types can be revealed by several grain-size parameters. The representation proposed by Passega in the 1960s' (Passega, 1964), i.e., a bi-plot of Q99 vs. Q50 is one them, which can be particularly useful when the event layers are thick enough to perform several grainsize measurement in them.

In some cases, generally when deposits are particularly thin or, on the contrary particularly thick, sedimentological investigation are not sufficient to clearly determine the triggering mechanism of instantaneous deposits. The geometry of the deposit, at the lake basin scale, then brings essential information. Flood deposits will forcedly originate from the lake inlet and flow toward the lake bottom following the steepest slopes. On the contrary gravity reworking may originate from anywhere in the lake and will slide in mass toward the lake bottom. The geometry of a given deposit maybe determined using geophysical approaches, like reflection seismic, when it is thick enough (typically > 20 cm). It may also be determined using an array of numerous cores which will have to be carefully correlated in order to determine in which of them the layer is present or not (Wilhelm et al., 2012a,b).

An increase in flood deposit frequency does not necessarily track an actual increase in flood frequency

Human land-use affected erosion processes as early as in the Neolithic period through deforestation, livestock tumbing and early cropping. Later on, deep ploughing, stream damming and soil artificialization further reinforced the human pressure on erosion fluxes. This resulted in more efficient runoff erosion, increasing both the frequency of recordable flood events and the amount of displaced sediment for a given flood intensity. In the geological record, this may result in an apparent increase in flood-layers frequency and thicknesses, independently of any climatic change. This point is still tricky for Holocene geologists which may only rely on comparison with independent markers, such as pollen, to infer the human origin of observed changes in flooding patterns. Few studies however went further by showing human-reinforced flood patterns resulted in a disruption in the grainsize-thickness relationship among flood-layers. In a human-disturbed catchment area the erodibility of soil is higher. As a consequence, a flood event of a given magnitude is able to

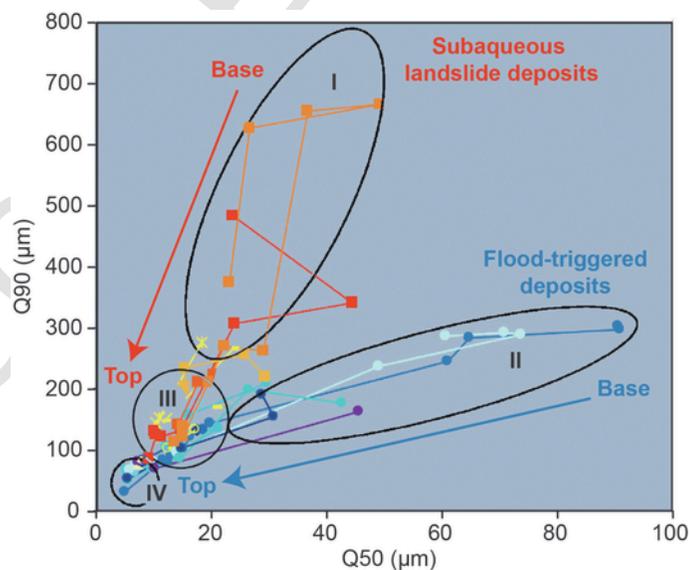


Fig. 8 Q50 vs. Q90 bi-plot, inspired from Passega (1964), from 12 subaqueous landslides deposits (in red and orange) and nine flood-triggered deposits (in blue) from Lake Anterne (Northern French Alps). Each same-color linked dots set corresponds to a single event deposit sampled every 5 mm from base to top. Note that all flood-triggered points are aligned along the same line (from sectors II, to III and IV) which is close to the 1:1 line. By comparison, samples from subaqueous landslide deposits are aligned from the high Q90 and low Q50 sector I to sector III and never reach sector IV (low Q90, low 50). See Arnaud et al. (2002) for further details.

transport more sediment, resulting in thicker deposits than it would have been without human soil disturbance (Giguet-Covex et al., 2011). However, the maximum transported grain size is far less impacted as it depends on the river stream velocity (Hjulström, 1935) and thus on river discharge (Hsü, 1989). As a consequence, the observation of an increase in flood-layers thickness, without a marked rise in maximum grain size is a good marker for human-triggered soil destabilization (Giguet-Covex et al., 2012).

Human disturbance of Earth Critical Zone dynamics

As stated above, human activities emerged all along the Holocene as one of the major triggering mechanisms of erosion patterns. Lake basins all around the globe witnessed this emergence which chronicle has been archived within their sediment. The effect of agro-pastoralism upon erosion was probably empirically known by the very first farmers. It was later well-known during Hellenistic period and stated for instance in Plato's dialogues *Critias* relating the dramatic loss of fertile soil due to bad land-use management. However, it has only been possible to document scientifically the history of Human-enhanced erosion in the last decades of the 20th century. Following the pioneer works by Franck Oldfield and John Dearing, notably in Papua New Guinea (Oldfield et al., 1980), lake basins appeared as particularly good candidate to record such an history. The rich information contained in lake sediment further permits to acquire information about human land-use (pollen) as well as its effect both on land and within the lakes themselves from the same archive. Quantities of biotic and abiotic markers were then developed until recently when the development of organic geochemical markers (Dubois and Jacob, 2016) as well as lake sediment DNA (Giguet-Covex et al., 2019) was propagated, extending the range of investigation permitted by the study of lake sediment.

From erosion record to soil development history

At the difference of their geological substratum, soils are highly dynamic even at a human-life time-scale. Their current state results from a dynamic equilibrium between the weathering of underlying rocks and the erosion of the soil surface. In the absence of human forcing factors, the balance between those two processes tends to reach a steady state, hence maintaining a stable layer on which ecosystems may grow. Human activities might break this balance by soil surface destabilization. Studying past erosion fluxes permits to reconstruct the evolution of soils and downstream to identify periods of human-triggered soil disturbances. This can be done not only by recording the total amount of eroded material, but also by identifying its provenance source in the lake catchment area, as well as its weathering degree.

When the geology of the catchment area is diverse enough, the provenance source may be tracked using mineral geochemistry, or mineralogy. Isotopic indicators of rock ages are here particularly efficient. In several cases, major elements also proved to be quite good markers of provenance, however, they are also strongly affected by weathering processes and may hence not be used alone to track the sediment provenance.

Chemical weathering is the dominant process of soil formation. It results in the selective removal of the most mobile elements (e.g., potassium). More developed soils are hence depleted in such elements, when compared the bedrock from which they were formed. This degree of depletion can be assessed using a ratio of mobile over immobile (e.g., aluminium or titanium) elements. When applied to terrigenous lake sediment this may be used to track the degree of evolution of the soils that were eroded at a given time (Arnaud et al., 2012). This permitted to show that human soil disturbance results in apparent rejuvenation of soils evidenced by a relative enrichment in mobile elements in eroded material. Some isotopic markers, such as lithium, bore or uranium (Rothacker et al., 2018) are currently under development to track the weathering degree of eroded soils (Fig. 9).

Soils are basically made of organo-mineral complexes. Soil evolution is thus strongly linked to the evolution of organic matter. Just as for the mineral fraction, the study of the organic compounds of eroded material trapped in lake sediment brings a lot of information about soil evolution. Rather simple techniques, such the microscopic identification of organic matter types, may be completed by more sophisticated ones. Element concentration of carbon, hydrogen and oxygen in variously refractory and oxidizable organic matter fractions is extensively used in petroleum geology. It applies also perfectly to characterize the degree of maturity of organic matter in soils and downstream in lake sediment. Hence it has been shown that a human-triggered erosion event following a deforestation starts with a flux of fresh organic matter from the litter and while the erosion is eroding deeper and deeper horizons, the organic matter signal tends to be dominated by more and more refractory fractions. Inversely when human pressure weakens, or at least a new equilibrium is reached, the refractory organic matter is retained in the soil and the eroded organic matter then originates from soils of upper and fresher horizons. Using molecular organic geochemistry opens possibilities for even more detailed investigation of past soil dynamics. For instance, branched glycerol dialkyl glycerol tetraethers (brGDGTs) have recently been proved to be markers of soil pH, which is a key parameters of soil evolution, particularly in regard with organic matter dissolution and fluxes.

Tracking land-use changes

Because they are highly integrative archives, lake sediments bear information about catchment reactions but also about what caused these reactions. Pollen are of course the main and most anciently used marker of vegetation dynamics that may be acquired from lake sediment. They have long been the only way to get valuable information about human land-use, through the filter of vegetation changes. However, pollen fly in the air and are thus not strictly representative of a given catchment area. Over the last decade, a number of studies proved lake sediment DNA (sedDNA) to be a valuable complementary information source about vegetation changes (Capo et al., 2021).

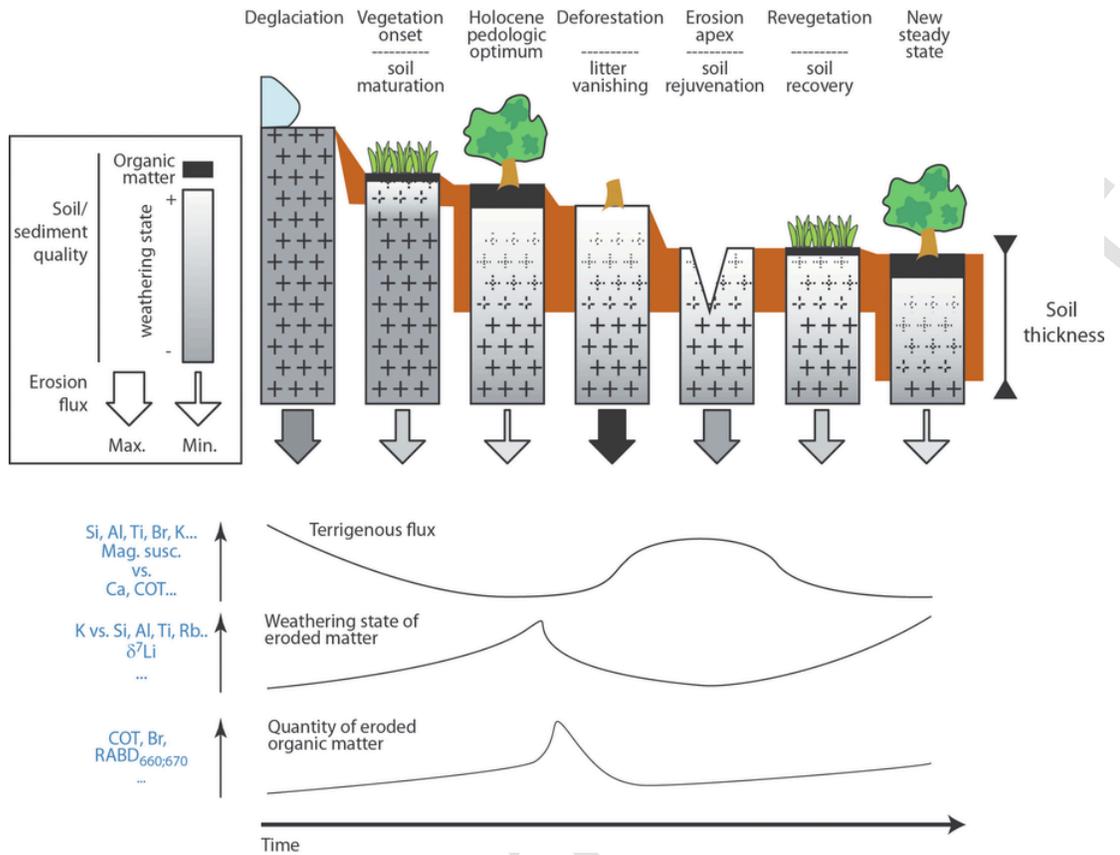


Fig. 9 Schematic representation of soil evolution following the last deglaciation (upper panel) and the corresponding theoretical record in lake sediment (curves in lower panel). Shades of grey and crosses materialize the weathering state, from bedrock (darker grey with solid crosses) to the most weathered terms (lighter grey with dotted crosses); black color represents the soil litter rich in organic matter. The soil itself is the layer overlying the non-weathered bedrock. Its thickness varies through time, as it is underlined by the brown surface. Arrows materialize the output of material due to erosion: their thickness represent the flux, whereas their color illustrates the nature of eroded material, as for soil state: shades of grey represent the degree of weathering and black represents the litter. Without human action, soil thickness tends to increase through time whereas the uppermost layer is more and more depleted in mobile elements and enriched in organic matter. Human-induced deforestation results in increasing erosion. First the litter is removed, inducing a peak organic matter transfer to the lake. If the process continues, the erosion reaches less and less depleted soil horizons, hence eliminating thousand years of soil formation within only some decades. Inspired from Bajard et al. (2017).

Sediment DNA data are not yet quantitative, but they differ from pollen information by a different taxonomic resolution and a drastically different taphonomic behavior. Indeed, taxonomic resolution of DNA results highly depends on DNA sequence libraries that are still under development. In the case of graminiae and in general, non-tree species, sedDNA taxonomic resolution may be more precise than what is allowed by pollen. It has recently been understood that catchment-derived sedDNA is strongly linked to erosion processes. Indeed, most of terrestrial DNA arriving into lake sediment has been freshly eroded from soil where it was stored under the form of organo-mineral complexes, hence protected from bacterial degradation. As a consequence, terrestrial SedDNA signal tracks the dynamic of the lake catchment area only. This also implies that a certain amount of catchment erosion is necessary to properly transfer the environmental signal that is transported by SedDNA toward the lake bottom (Giguët-Covex et al., 2019).

One of the greatest advances that was made possible by SedDNA is to provide taxonomically-specific information about livestock (Giguët-Covex et al., 2014). The identification, alongside pollen, of coprophilous fungi had permitted to complete the vegetation data with an assessment of the livestock pressure upon a lake catchment area. However, this did not allow to identify which mammal species generated the feces that permitted the development of fungi (Etienne et al., 2012). With SedDNA this information is completed at a higher taxonomic level, permitting to attest the former presence of livestock as well as the relative composition of herds. Hence in a near future it will probably be possible to analyze the long-term effects of livestock farming upon the environment with a detail that had never been reached before.

Direct and indirect pollutions

Among human-triggered threats upon ECZ, the dispersion of extracted or man-made substances is particularly damaging for ecosystems' and downstream, humans' health. As local sediment sinks, lakes have the capacity to record the history of dispersion of those substances.

Metals were dispersed throughout the Earth environment as early as metallurgy was invented. Numerous reconstructions of metal contamination chronicles have been published over the last decades, providing a comprehensive scheme of world history of human-triggered metal dispersion. In lake sediment, the attribution of a metal peak to human activities is made difficult by the presence of the sediment matrix which can be metal-rich on its own. It is then necessary to assess the contribution of human-spread vs. naturally-present metals (see [Dunnington et al., 2020](#) for a methodological review). The isotopic composition of some metals can be helpful to identify the origin of contamination. Lead is particularly interesting and has been extensively for such a purpose, as it is the most stable element of several radioactive decay chains. However, case studies using zinc, mercury, copper and silver, just to cite some, can be found in the literature. In case, studying both the temporal evolution of metal contamination and its potential sources permitted to better identify the causes of contamination, which is the primary stage for reducing human impact upon the environment.

Over the 20th century the chemical industry produced thousands of artificial compounds used for manufacturing processes or helping agriculture to face natural plagues. Most of them happened to be persistent in the environment, causing various threats upon ecosystems health. Those chemical species are often referred as persistent organic pollutants (POPs). They include among others all kind of pesticides, fire delayers, solvents, fossil fuels etc. Reconstructing the concentration of those POPs in lake sediment series permits to better understand their contamination histories and pathways. It was hence possible to show that Polychlorinated biphenyl (PCBs), a fire delayer used in electric transformers until its production was progressively banned between 1978 (in the United States) and 2001 (worldwide) may move from a surface area, such as a lake or soil, toward another ECZ compartment by a succession of evaporations under warm conditions and condensations under cold conditions ([Naffrechoux et al., 2015](#)). Lake sediment-based POPs contamination history may also evidence combined effect of pollutants. It has hence been shown that the use of a powerful herbicide, the glyphosate since 1990s, was responsible in vineyards of a drastic rise in soil erosion (due to the destruction of herbs-associated rhizosphere that is an agent of soil stabilization) which downstream led to the remobilization of insecticide, such as DDT that had been applied for decades and then banned since 1973 but stored in agricultural soils ([Sabatier et al., 2014](#)). This last example shows the ECZ is a complex reactive layer in which all process may interfere together, leading to strong and potentially harmful retroactions ([Fig. 10](#)).

Even the mountains can be shaken: recording how inner-Earth dynamics affects the ECZ over human time-scale

The Earth Critical Zone is also the interface between inner and outer Earth dynamics. As such it may be affected by geodynamics, even at a human life time-scale when paroxysmal events, such as volcanic eruptions and earthquakes, occur. The strongest of those events may be particularly threatening for life beings and especially for human societies. Because they are rare at human time-scale, it is necessary to document them beyond the historical period in order to assess their returning period in a given place. In this aim, only geological records can be mobilized. Among them, lake sediment may record volcanic eruptions and earthquakes through three mechanisms: (i) atmospheric fall-out, (ii) in-lake reworking processes, (iii) indirect post-event terrigenous fluxes.

Atmospheric fall-out of volcanic products

This way of recording is quite obvious and generally simple to apply. In most cases volcanic deposits are clearly different from the continuous lake sedimentation and may be identified by visual observation or any mineralogical (including magnetics) or mineral geochemistry approaches. However, the documentation of past volcanic events can be disturbed by post-depositional reworking of the volcanic deposits. Such a reworking may occur within the lake itself, under the form of subaqueous slides, or within the catchment area where volcanic products may accumulate during the eruption and be more or less abruptly released in the following day to years through erosional processes. A detailed sedimentological study of the whole lake basin is then required in order to demonstrate that the volcanic-triggered layers came purely from the atmosphere and were thus strictly contemporaneous of an eruption ([Fig. 11](#)).

Earthquake-triggered in-lake reworking processes

Earthquake-triggered mass-wasting deposits are very common in lakes, making them natural seismographs ([Strasser et al., 2013](#)). They are favored by a high terrigenous sedimentation flux and the presence of a delta at the tributary inlet. Indeed, higher sedimentation rates result in less stable delta slopes, hence favoring the triggering of subaqueous slides ([Wilhelm et al., 2016](#)). Several triggering mechanisms may be invoked for those slides, but earthquakes are the more common ones. The main difficulty here is to distinguish those mass wasting deposits from flood triggered deposits. There is no universal recipe to do such and a detailed sedimentological study is here also required. The texture of the deposit is a meaningful information as mass wasting deposits are less well-sorted than flood deposits ([Arnaud et al., 2002](#)). The Earthquake may also trigger internal lake motions that can be large enough to resuspend sediment at the whole basin scale and ultimately lead to a typical homogenous sediment deposition layer called "homogenite" ([Chapron et al., 1999](#)). When deposits are thick

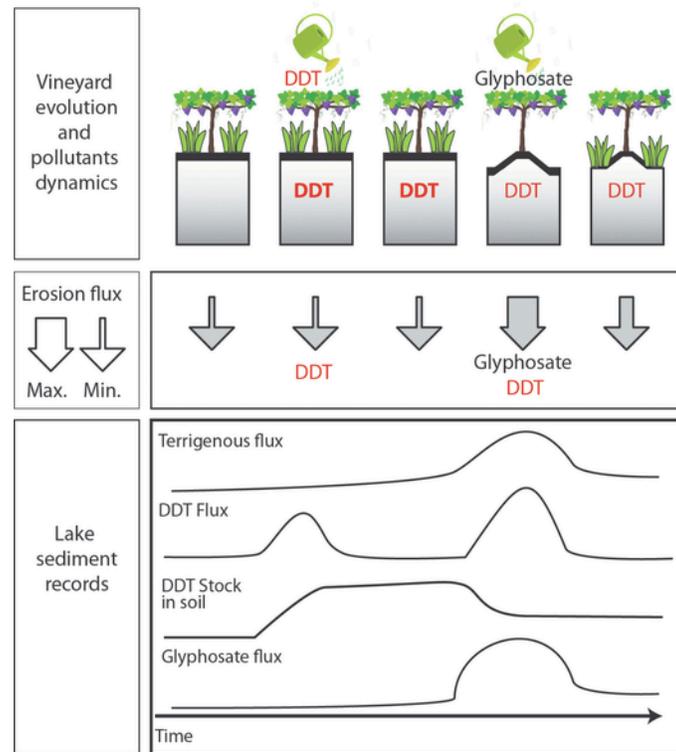


Fig. 10 Schematic representation of DDT spreading, incorporation in soil and Glyphosate-triggered released from a Vineyard (upper panel), the resultant impact in terms of erosion and pollutant fluxes (middle panel) and the corresponding theoretical record in sediment (lower panel). Inspired from Sabatier P, Poulenard J, Fanget B, Reyss JL, Develle AL, Wilhelm B, Ployon E, Pignol C, Naffrechoux E, Dorioz JM, Montuelle B and Arnaud F (2014) Long-term relationships among pesticide applications, mobility, and soil erosion in a vineyard watershed. *Proceedings of the National Academy of Sciences of the United States of America* doi: 10.1073/pnas.1411512111.

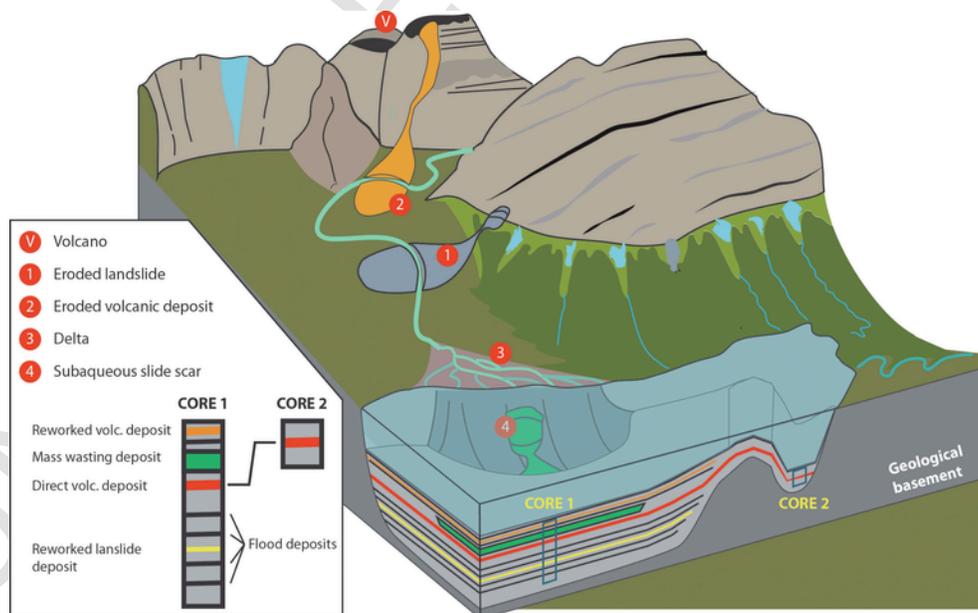


Fig. 11 Schematic representation of a lake sediment basin connected to a volcanic catchment-area submitted to regular earthquakes.

enough, the geophysical imagery of the lake sediment pile brings usually precious information about the deposits shape and downstream, about their triggering mechanisms (van Rensbergen et al., 1999).

Indirect post-event terrigenous fluxes

When a powerful earthquake hit a mountainous region, it often generates massive landslides (Keefer, 2002). Those landslides result in river dams that are more or less abruptly eroded (Wang et al., 2015). When such a dam breaks, the resulting outburst may be recorded in lakes under the form of a specific layer due the sudden arrival of terrigenous sediment (Zhang et al., 2019). It may also occur that the excess in eroded material in the river course gets eroded slowly, hence increasing the sedimentation rate over several years.

One must finally notice that any combination of processes may occur (Zhang et al., 2019). For instance, an earthquake may generate a rock slide, triggering a snow avalanche, itself triggering a destabilization of a lake delta as well as a tsunami-like wave that will erode the shores of the lake, far from the delta. The sedimentologist studying lake basin must be aware of those potential mechanisms. It is necessary to propose falsifiable hypothesis in order to lead the required measurement which will finally lead to a careful interpretation of the lake basin sedimentological behavior.

Conclusion/synthesis

We aimed in this chapter at providing a non-exhaustive, but yet large overview of the strong potential of lake sediment studies when it comes to reveal the history of in-land social-ecological systems and interactions within the ECZ. Lake sediment may indeed be seen as the Swiss knife of natural archives as they are submitted to a quasi-infinite number of forcing factors, acting both outside and within the lake itself. This diversity of forcing factors has long been seen as a weakness because of the complexity of the resulting archives. However, no other natural archive has seen more developments of new investigation techniques than lakes over the last decades. Scientists interested in the evolution of any aspect, biotic or biotic, natural and human-triggered, over recent or pluri-millennial periods, etc. of the ECZ may hence rely on a vast scientific literature and an extended methodological toolbox in order to find in lake sediments the stored information they are looking for.

Remaining challenges

- Modelling the processes from catchment area to sediment deposition.
- Developing spatial approaches based on multiple cores.
- Developing an integrated approach of main triggering mechanisms that affect the critical zone dynamics (climate, humans, geodynamics, ecological responses).

References

- Parducci, L., Unneberg, P., Ågren, R., Schenk, F., Rattray, J.E., Han, L., Muschitiello, F., Pedersen, M.W., Smittenberg, R.H., Yamoah, K.A., Slotte, T., Wohlfarth, B., 2018. Archaeal community changes in Lateglacial lake sediments: Evidence from ancient DNA. *Quaternary Science Reviews* 181, 19–29. <https://doi.org/10.1016/j.quascirev.2017.11.037>.
- Aksoy, H., Kavvas, M.L., 2005. A review of hillslope and watershed scale erosion and sediment transport models. *Catena* 64, 247–271. <https://doi.org/10.1016/j.catena.2005.08.008>.
- Arnaud, F., Lignier, V., Revel, M., Desmet, M., Beck, C., Pourchet, M., Charlet, F., Trentesaux, A., Tribouillard, N., 2002. Flood and earthquake disturbance of 210Pb geochronology (Lake Anterne, NW Alps). *Terra Nova* 14, 225–232. <https://doi.org/10.1046/j.1365-3121.2002.00413.x>.
- Arnaud, F., Révillon, S., Debret, M., Revel, M., Chapron, E., Jacob, J., Giguet-Covex, C., Poulencard, J., Magny, M., 2012. Lake Bourget regional erosion patterns reconstruction reveals Holocene NW European Alps soil evolution and paleohydrology. *Quaternary Science Reviews* 51, 81–92. <https://doi.org/10.1016/j.quascirev.2012.07.025>.
- Arnaud, F., Poulencard, J., Giguet-Covex, C., Wilhelm, B., Révillon, S., Jenny, J.-P., Revel, M., Enters, D., Bajard, M., Fouinat, L., Doyen, E., Simonneau, A., Pignol, C., Chapron, E., Vannièrre, B., Sabatier, P., 2016. Erosion under climate and human pressures: An alpine lake sediment perspective. *Quaternary Science Reviews* 152, 1–18. <https://doi.org/10.1016/j.quascirev.2016.09.018>.
- Banwart, S.A., Chorover, J., Gaillardet, J., Sparks, D., White, D., Anderson, S., Aufdenkampe, A., Bernasconi, S., Brantley, S.L., Chadwick, O., Dietrich, W.E., Duffy, C., Goldhaber, M.B., Lehnert, K., Nikolaidis, N.P., Ragnarsdottir, K.V., 2013. Sustaining Earth's Critical Zone Basic Science and Interdisciplinary Solutions for Global Challenges. The University of Sheffield, United Kingdom.
- Capo, E., Giguet-Covex, C., Rouillard, A., Nota, K., Heintzman, P.D., Vuillemin, A., Ariztegui, D., Arnaud, F., Belle, S., Bertilsson, S., Bigler, C., Bindler, R., Brown, A.G., Clarke, C.L., Crump, S.E., Debroas, D., Englund, G., Ficotola, G.F., Garner, R.E., Gauthier, J., Gregory-Eaves, I., Heinecke, L., Herzsuh, U., Ibrahim, A., Kisand, V., Kjær, K.H., Lammers, Y., Littlefair, J., Messenger, E., Monchamp, M.-E., Olajos, F., Orsi, W., Pedersen, M.W., Rijal, D.P., Rydberg, J., Spanbauer, T., Stoof-Leichsenring, K.R., Taberlet, P., Talas, L., Thomas, C., Walsh, D.A., Wang, Y., Willerslev, E., van Woerkom, A., Zimmermann, H.H., Coolen, M.J.L., Epp, L.S., Domaizon, I., Alsos, G.I., Parducci, L., 2021. Lake sedimentary DNA research on past terrestrial and aquatic biodiversity: Overview and recommendations. *Quaternary* 4, 6. <https://doi.org/10.3390/quat4010006>.
- Chapron, E., Beck, C., Pourchet, M., Deconinck, J.-F., 1999. 1822 earthquake-triggered homogenite in Lake Le Bourget (NW Alps). *Terra Nova* 11, 86–92. <https://doi.org/10.1046/j.1365-3121.1999.00230.x>.
- Dahl, S.O., Bakke, J., Lie, J., Nesje, A., 2003. Reconstruction of former glacier equilibrium-line altitudes based on proglacial sites: An evaluation of approaches and selection of sites. *Quaternary Science Reviews* 22, 275–287. [https://doi.org/10.1016/S0277-3791\(02\)00135-X](https://doi.org/10.1016/S0277-3791(02)00135-X).

- Derry, L.A., Chadwick, O.A., 2007. Contributions from Earth's atmosphere to soil. *Elements* 3, 333–338. <https://doi.org/10.2113/gselements.3.5.333>.
- Dubois, N., Jacob, J., 2016. Molecular biomarkers of anthropic impacts in natural archives: A review. *Frontiers in Ecology and Evolution* 4, 1–16. <https://doi.org/10.3389/fevo.2016.00092>.
- Dunnington, D.W., Gregory, B.R.B., Spooner, I.S., White, C.E., Gagnon, G.A., 2020. Evaluating the performance of calculated elemental measures in sediment archives. *Journal of Paleolimnology* 64, 155–166. <https://doi.org/10.1007/s10933-020-00123-3>.
- Etienne, D., Wilhelm, B., Sabatier, P., Reyss, J.-L., Arnaud, F., 2012. Influence of sample location and livestock numbers on *Sporormiella* concentrations and accumulation rates in surface sediments of Lake Allos, French Alps. *Journal of Paleolimnology* 49, 117–127. <https://doi.org/10.1007/s10933-012-9646-x>.
- Fouinat, L., Sabatier, P., Poulénard, J., Etienne, D., Crouzet, C., Develle, A.-L., Doyen, E., Malet, E., Reyss, J.-L., Sagot, C., Bonet, R., Arnaud, F., 2017. One thousand seven hundred years of interaction between glacial activity and flood frequency in proglacial Lake Muzelle (western French Alps). *Quaternary Research* 87, 407–422. <https://doi.org/10.1017/qua.2017.18>.
- Gaillardet, J., Braud, I., Hankard, F., Anquetin, S., Bour, O., Dorfliger, N., de Dreuzy, J.R., Galle, S., Galy, C., Gogo, S., Gourcy, L., Habets, F., Laggoun, F., Longuevergne, L., Le Borgne, T., Naaim-Bouvet, F., Nord, G., Simonneaux, V., Six, D., Tallec, T., Valentin, C., Abril, G., Allemand, P., Arènes, A., Arfib, B., Arnaud, L., Arnaud, N., Arnaud, P., Audry, S., Comte, V.B., Batiot, C., Battais, A., Bellot, H., Bernard, E., Bertrand, C., Bessière, H., Binet, S., Bodin, J., Bodin, X., Boithias, L., Bouchez, J., Boudevillain, B., Moussa, I.B., Branger, F., Braun, J.J., Brunet, P., Caceres, B., Calmels, D., Cappelaere, B., Celle-Jeanton, H., Chabaux, F., Chalikakis, K., Champollion, C., Copard, Y., Cotel, C., Davy, P., Deline, P., Delrieu, G., Demarty, J., Dessert, C., Dumont, M., Emblanch, C., Ezzahar, J., Estèves, M., Favier, V., Fauchoux, M., Filizola, N., Flammarion, P., Flourey, P., Fovet, O., Fournier, M., Francez, A.J., Gandois, L., Gascuel, C., Gayer, E., Genthon, C., Gérard, M.F., Gilbert, D., Gouttevin, I., Grippa, M., Gruau, G., Jardani, A., Jeanneau, L., Join, J.L., Jourde, H., Karbou, F., Labat, D., Lagadeuc, Y., Lajeunesse, E., Lastennet, R., Lavado, W., Lawin, E., Lebel, T., Le Bouteiller, C., Legout, C., Lejeune, Y., Le Meur, E., Le Moigne, N., Lions, J., Lucas, A., Malet, J.P., Marais-Sicre, C., Maréchal, J.C., Marlin, C., Martin, P., Martins, J., Martinez, J.M., Massei, N., Mauder, A., Mazzilli, N., Molénat, J., Moreira-Turcq, P., Mougin, E., Morin, S., Ngoupayou, J.N., Panthou, G., Peugeot, C., Picard, G., Pierret, M.C., Porel, G., Probst, A., Probst, J.L., Rabatel, A., Raclot, D., Ravanel, L., Rejiba, F., René, P., Ribolzi, O., Riotte, J., Rivière, A., Robain, H., Ruiz, L., Sanchez-Perez, J.M., Santini, W., Sauvage, S., Schoeneich, P., Seidel, J.L., Sekhar, M., Sengtaheuanghoung, O., Silvera, N., Steinmann, M., Soruco, A., Tallec, G., Thibert, E., Lao, D.V., Vincent, C., Viville, D., Wagnon, P., Zitouna, R., 2018. OZCAR: The French network of critical zone observatories. *Vadose Zone Journal* 17, 180067. <https://doi.org/10.2136/vzj2018.04.0067>.
- Giguet-Covex, C., Arnaud, F., Poulénard, J., Disnar, J.-R., Delhon, C., Francus, P., David, F., Enters, D., Rey, P.-J., Delannoy, J.-J., 2011. Changes in erosion patterns during the Holocene in a currently treeless subalpine catchment inferred from Lake sediment geochemistry (lake Anterne, 2063 m a.s.l., NW French Alps): The role of climate and human activities. *The Holocene* 21, 651–665. <https://doi.org/10.1177/0959683610391320>.
- Giguet-Covex, C., Arnaud, F., Enters, D., Poulénard, J., Millet, L., Francus, P., David, F., Rey, P.-J., Wilhelm, B., Delannoy, J.-J., 2012. Frequency and intensity of high-altitude floods over the last 3.5ka in northwestern French Alps (Lake Anterne). *Quaternary Research* 77, 12–22. <https://doi.org/10.1016/j.yqres.2011.11.003>.
- Giguet-Covex, C., Pansu, J., Arnaud, F., Rey, P.-J., Griggo, C., Gielly, L., Domaizon, I., Coissac, E., David, F., Cholier, P., Poulénard, J., Taberlet, P., 2014. Long livestock farming history and human landscape shaping revealed by lake sediment DNA. *Nature Communications* 5, <https://doi.org/10.1038/ncomms4211>.
- Giguet-Covex, C., Ficotola, G.F., Walsh, K., Poulénard, J., Bajard, M., Fouinat, L., Sabatier, P., Gielly, L., Messenger, E., Develle, A.L., David, F., Taberlet, P., Brisset, E., Guiter, F., Sinet, R., Arnaud, F., 2019. New insights on lake sediment DNA from the catchment: Importance of taphonomic and analytical issues on the record quality. *Scientific Reports* 9, 14676. <https://doi.org/10.1038/s41598-019-50339-1>.
- Gilli, A., Anselmetti, F.S., Glur, L., Wirth, S.B., 2013. Lake sediments as archives of recurrence rates and intensities of past flood events. In: Schneuwly-Bollschweiler, M., Stoffel, M., Rudolf-Miklau, F. (Eds.), *Dating Torrential Processes on Fans and Cones*, *Advances in Global Change Research*. Springer Netherlands, pp. 225–242. https://doi.org/10.1007/978-94-007-4336-6_15.
- Haug, G.H., 2001. Southward migration of the intertropical convergence zone through the Holocene. *Science* 293, 1304–1308. <https://doi.org/10.1126/science.1059725>.
- Hjulström F (1935) *Studies of the Morphological Activity of Rivers as Illustrated by the River Fyris*, Thèse de doctorat, Uppsala.
- Hsu, K.J., 1989. *Physical Principles of Sedimentology a Readable Textbook for Beginners and Experts*. Springer Berlin Heidelberg, Berlin, Heidelberg.
- Jacq, K., William, R., Alexandre, B., Didier, C., Bernard, F., Perrette, Y., Sabatier, P., Bruno, W., Maxime, D., Arnaud, F., 2020. Sedimentary structures discriminations with hyperspectral imaging on sediment cores (preprint). *EarthArXiv* <https://doi.org/10.31223/osf.io/4ue5s>.
- Jiménez-Espejo, F.J., García-Alix, A., Jiménez-Moreno, G., Rodrigo-Gámiz, M., Anderson, R.S., Rodríguez-Tovar, F.J., Martínez-Ruiz, F., Giral, S., Delgado Huertas, A., Pardo-Igúzquiza, E., 2014. Saharan aeolian input and effective humidity variations over western Europe during the Holocene from a high altitude record. *Chemical Geology* 374–375, 1–12. <https://doi.org/10.1016/j.chemgeo.2014.03.001>.
- Keefer, D.K., 2002. Investigating landslides caused by earthquakes—A historical review. *Surveys in Geophysics* 23, 473–510. <https://doi.org/10.1023/A:1021274710840>.
- Kisand, V., Talas, L., Kisand, A., Stivrins, N., Reitalu, T., Alliksaar, T., Vassiljev, J., Liiv, M., Heinsalu, A., Seppä, H., Veski, S., 2018. From microbial eukaryotes to metazoan vertebrates: Wide spectrum paleo-diversity in sedimentary ancient DNA over the last ~ 14,500 years. *Geobiology* 16, 628–639. <https://doi.org/10.1111/gbi.12307>.
- Lade, S.J., Steffen, W., de Vries, W., Carpenter, S.R., Donges, J.F., Gerten, D., Hoff, H., Newbold, T., Richardson, K., Rockström, J., 2020. Human impacts on planetary boundaries amplified by earth system interactions. *Nature Sustainability* 3, 119–128. <https://doi.org/10.1038/s41893-019-0454-4>.
- Lambert, A., Kelts, K., Zimmermann, U., 1984. Trübestrome in Seen: Sauerstoffeintrag durch grundnah eingeschichtetes Flusswasser. *Schweizerische Zeitschrift für Hydrologie* 46, 41–50.
- Naffrechoux, E., Cottin, N.N., Pignol, C., Arnaud, F., Jenny, J.-P., Perga, M.-E., 2015. Historical profiles of PCB in dated sediment cores suggest recent lake contamination through the “Halo Effect”. *Critical Reviews in Environmental Science and Technology* 49, 1303–1310. <https://doi.org/10.1021/es5043996>.
- Olajos, F., Bokma, F., Bartels, P., Myrstener, E., Rydberg, J., Öhlund, G., Bindler, R., Wang, X., Zale, R., Englund, G., 2018. Estimating species colonization dates using DNA in lake sediment. *Methods in Ecology and Evolution* 9, 535–543. <https://doi.org/10.1111/2041-210X.12890>.
- Oldfield, F., Appleby, P.G., Thompson, R., 1980. Palaeoecological studies of lakes in the highlands of Papua New Guinea: I. The Chronology of Sedimentation. *Journal of Ecology* 68, 457. <https://doi.org/10.2307/2259416>.
- Parducci, L., Bennett, K.D., Ficotola, G.F., Alsos, I.G., Suyama, Y., Wood, J.R., Pedersen, M.W., 2017. Ancient plant DNA in lake sediments. *The New Phytologist* 214, 924–942. <https://doi.org/10.1111/nph.14470>.
- Passega, R., 1964. Grain size representation by cm patterns as a geological tool. *Journal of Sedimentary Research* 34, 830–847.
- Rothacker, L., Dosseto, A., Francke, A., Chivas, A.R., Vigier, N., Kotarba-Morley, A.M., Menozzi, D., 2018. Impact of climate change and human activity on soil landscapes over the past 12,300 years. *Scientific Reports* 8, 247. <https://doi.org/10.1038/s41598-017-18603-4>.
- Sabatier, P., Poulénard, J., Fanget, B., Reyss, J.-L., Develle, A.-L., Wilhelm, B., Ployon, E., Pignol, C., Naffrechoux, E., Dorioz, J.-M., Montuelle, B., Arnaud, F., 2014. Long-term relationships among pesticide applications, mobility, and soil erosion in a vineyard watershed. *Proceedings of the National Academy of Sciences of the United States of America* <https://doi.org/10.1073/pnas.1411512111>.

- Sabatier, P., Nicolle, M., Piot, C., Colin, C., Debret, M., Swingedouw, D., Perrette, Y., Bellingery, M.-C., Chazeau, B., Develle, A.-L., Leblanc, M., Skonieczny, C., Copard, Y., Reyss, J.-L., Malet, E., Jouffroy-Bapicot, I., Kelner, M., Poulenard, J., Didier, J., Arnaud, F., Vannière, B., 2020. Past African dust inputs in the western Mediterranean area controlled by the complex interaction between the intertropical convergence zone, the North Atlantic oscillation, and total solar irradiance. *Climate of the Past* 16, 283–298. <https://doi.org/10.5194/cp-16-283-2020>.
- Scheuvs, D., Schütz, L., Kandler, K., Ebert, M., Weinbruch, S., 2013. Bulk composition of northern African dust and its source sediments—A compilation. *Earth Science Reviews* 116, 170–194. <https://doi.org/10.1016/j.earscirev.2012.08.005>.
- Schillereff, D.N., Chiverrell, R.C., Macdonald, N., Hooke, J.M., 2014. Flood stratigraphies in lake sediments: A review. *Earth Science Reviews* 135, 17–37. <https://doi.org/10.1016/j.earscirev.2014.03.011>.
- Shao, Y., Wyrwoll, K.-H., Chappell, A., Huang, J., Lin, Z., McTainsh, G.H., Mikami, M., Tanaka, T.Y., Wang, X., Yoon, S., 2011. Dust cycle: An emerging core theme in earth system science. *Aeolian Research* 2, 181–204. <https://doi.org/10.1016/j.aeolia.2011.02.001>.
- Støren, E.N., Paasche, , 2013. Scandinavian floods: From past observations to future trends. *Global and Planetary Change* <https://doi.org/10.1016/j.gloplacha.2013.12.002>.
- Støren, E.W.N., Paasche, , Hirt, A.M., Kumari, M., 2016. Magnetic and geochemical signatures of flood layers in a Lake system: Signatures of floods in lake sediments. *Geochemistry, Geophysics, Geosystems* 17, 4236–4253. <https://doi.org/10.1002/2016GC006540>.
- Strasser, M., Monecke, K., Schnellmann, M., Anselmetti, F.S., 2013. Lake sediments as natural seismographs: A compiled record of late quaternary earthquakes in Central Switzerland and its implication for alpine deformation. *Sedimentology* 60, 319–341. <https://doi.org/10.1111/sed.12003>.
- van der Bilt, W.G.M., Bakke, J., Vasskog, K., Rothe, T., Støren, E.W.N., 2016. Glacier-fed lakes as palaeoenvironmental archives. *Geology Today* 32, 213–218. <https://doi.org/10.1111/gto.12166>.
- van Rensbergen, P., de Batist, M., Beck, C., Chapron, E., 1999. High-resolution seismic stratigraphy of glacial to interglacial fill of a deep glacial Lake: Lake Le Bourget, northwestern Alps, France. *Sedimentary Geology* 128, 99–129. [https://doi.org/10.1016/S0037-0738\(99\)00064-0](https://doi.org/10.1016/S0037-0738(99)00064-0).
- Wang, J., Jin, Z., Hilton, R.G., Zhang, F., Densmore, A.L., Li, G., West, A.J., 2015. Controls on fluvial evacuation of sediment from earthquake-triggered landslides. *Geology* 43, 115–118. <https://doi.org/10.1130/G36157.1>.
- Wessels, M., 1998. Natural environmental changes indicated by late glacial and Holocene sediments from Lake Constance, Germany. *Palaeogeography Palaeoclimatology Palaeoecology* 140, 421–432. [https://doi.org/10.1016/S0031-0182\(98\)00026-1](https://doi.org/10.1016/S0031-0182(98)00026-1).
- Wilhelm, B., Arnaud, F., Enters, D., Allignol, F., Legaz, A., Magand, O., Révillon, S., Giguët-Covex, C., Malet, E., 2012. Does global warming favour the occurrence of extreme floods in European Alps? First evidences from a NW Alps proglacial lake sediment record. *Climatic Change* 113, 563–581. <https://doi.org/10.1007/s10584-011-0376-2>.
- Wilhelm, B., Arnaud, F., Sabatier, P., Crouzet, C., Brisset, E., Chaumillon, E., Disnar, J.-R., Guiter, F., Malet, E., Reyss, J.-L., Tachikawa, K., Bard, E., Delannoy, J.-J., 2012. 1400years of extreme precipitation patterns over the Mediterranean French Alps and possible forcing mechanisms. *Quaternary Research* 78, 1–12. <https://doi.org/10.1016/j.yqres.2012.03.003>.
- Wilhelm, B., Nomade, J., Crouzet, C., Litty, C., Sabatier, P., Belle, S., Rolland, Y., Revel, M., Courboux, F., Arnaud, F., Anselmetti, F.S., 2016. Quantified sensitivity of small lake sediments to record historic earthquakes: Implications for paleoseismology. *Journal of Geophysical Research - Earth Surface* 121, 2–16. <https://doi.org/10.1002/2015JF003644>.
- Zhang, F., Jin, Z., West, A.J., An, Z., Hilton, R.G., Wang, J., Li, G., Densmore, A.L., Yu, J., Qiang, X., Sun, Y., Li, L., Gou, L., Xu, Y., Xu, X., Liu, X., Pan, Y., You, C.-F., 2019. Monsoonal control on a delayed response of sedimentation to the 2008 Wenchuan earthquake. *Science Advances* 5, eaav7110 <https://doi.org/10.1126/sciadv.aav7110>.

Glossary

Accumulation (of sediment) When the transporting media gets not competent enough to ensure the transport of erosion products, they may accumulate in a so-called depocenter. Within their watershed, lakes are often such a final sink in which erosion products and the information they bear are trapped. Moreover, because lake bottoms are generally quiet, this accumulation of sediment is regular enough to preserve the chronological succession of information, just like pages in a book. This is why lake sediment can be considered as “natural archive.”

Anthropocene The Anthropocene is a neologism forged by Paul Crutzen to designate the moment in the history of the Earth when humans emerged as a new geological force. The international commission on Stratigraphy is currently addressing the question of making the Anthropocene an official geological Era which should have started in 1950 CE with the first worldwide dispersal of artificial radionuclides due to a period of intense nuclear weapons atmospheric tests.

Erosion cycle The erosion cycle designates the succession of any processes leading to the movement of matter teared from the Earth surface and subsequently deposited. It is commonly divided in four phases: weathering, grabbing, transport and accumulation of sediment.

Grabbing Any process permitting the extraction of weathered matter (cf. weathering) from a rock or a soil, usually through a meteoric agent: rain, wind, waves.

Holocene The Holocene is the most recent geological epoch; it conventionally started 11,700 years ago with the termination of the Pleistocene Stage 4 glacial period. It is hence the most recent interglacial stage of the Pleistocene, but also the period that has witnessed the rise of organized human civilizations which eventually became one of the driving forces of the Earth dynamics. This growing influence of humans led several scientists to propose the Holocene epoch is now over and should be replaced by the Anthropocene Era.

Natural archive A natural archive is the common name given to Earth surface systems that have the capacity to record environmental conditions through time. They are the study object of paleosciences.

Paleosciences A corpus of scientific approaches aiming at reconstructing past Earth dynamics.

Transport (of sediment) Once weathered and grabbed, erosion products need a sufficiently competent flow of matter in order to be carried away from their source area; this is generally stream water, but may also be wind, avalanche, glaciers, humans etc.

Weathering Physical or chemical reworking of rocks that generate an outgoing flux of dissolved and/or particulate matter toward the Earth Critical Zone; it includes in particular all processes of soil formation from non-weathered bedrocks.

UNCORRECTED PROOF