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Invited review

Erosion under climate and human pressures: An alpine lake sediment perspective

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ABSTRACT

We review the scientific efforts over the last decades to reconstruct erosion from continuous alpine lake sediment records. We focused both on methodological issues, showing the growing importance of non-destructive high resolution approaches (XRF core-scanner) as well as progresses in the understanding of processes leading to the creation of an "erosion signal" in lakes. We distinguish "continuous records" from "event-records". Both provide complementary information but need to be studied with different approaches. Continuous regionally-relevant records proved to be particularly pertinent to document regional erosion patterns throughout the Holocene, in particular applying the source to sink approach. Event-based approaches demonstrated and took advantage of the strong non-linearity of sediment transport in high altitude catchment areas. This led to flood frequency and intensity reconstructions, highlighting the influence of climate change upon flood dynamics in the mountain.

The combination of different record types, both in terms of location (high vs. low elevation), sedimentology (high vs. low terrigenous contribution) and significance (local vs. regional) is one of the main outputs of this paper. It allows the establishment of comprehensive histories of NW French Alps erosion, but also and consequently, soil dynamics and hydrological patterns throughout the Holocene. We also discuss the influence of glacier dynamics, one of the major agents of erosion in the Alps.

A major feature is the growing human influence upon erosion at a local scale since at least the middle of the Bronze Age (3500 cal. BP). However and according to the regional record from Lake Bourget, only few periods of rising erosion at local scales generated a regional record that can be discriminated from wetter climatic periods. Among them, the period between 200 BCE and 400 AD appeared to be marked by a generalised rise in human-triggered erosion at local scales in the northern French Alps.

This review highlights the importance of modern high-resolution and interdisciplinary studies of lake sediments, in order to better understand the complex relationships between humans, climate and the Earth system in general. We strongly argue that regional integration of data is now required to move a step further. Such an integration is easier with cost- and time-effective methods as well as after a better definition of approaches and their limits. This should lead to a stronger collaboration between paleo-data producers and modellers in the near future.

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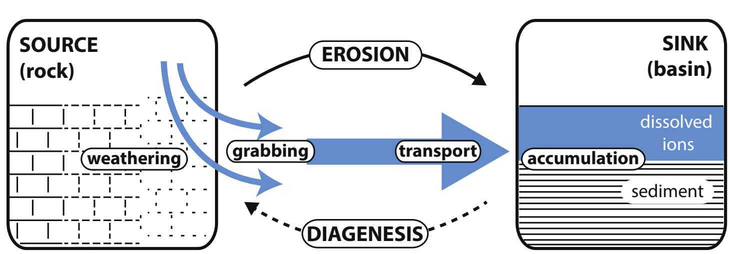
1. Introduction

Erosion processes dynamically link the lithosphere, the atmosphere, the hydrosphere and to some extent the biosphere and the sociosphere. They are thus involved in most processes affecting the “Earth critical zone”. In this paper we aim at showing how a regional scale study of alpine lake sediments allowed reconstructing the evolution of different erosion processes throughout the Holocene. Our aim is both to detail and discuss the methods and to synthetize the results obtained from a variety of geologic records that were studied over the last 15 years. We finally propose new perspectives upon both climate and human histories over the last millennia and show perspectives to pursue the effort toward a better knowledge of erosion dynamics throughout the Anthropocene.

Erosion is a generic term used to describe a set of processes leading to the dismantling of the most elevated parts of Earth's surface (sources) while lower parts (sinks) are mantled by erosion products. Erosion comprises i) surface processes, that prepare the dismantling of rocks – i.e. physical and/or chemical weathering – ii) grabbing processes by carrying fluids – mostly running water and wind – iii) transport processes by those fluids and iv) the accumulation of solid or dissolved matter into a sink. Erosion should be defined as an ensemble of Earth surface processes that transfer matter from a source to a - more or less remote - sink (Fig. 1). Floods for instance, generate erosion through their grabbing effect. But in return the nature and intensity of weathering processes modulate their solid load and thus how much they are hazardous. Vegetation cover is also an important component modulating Earth critical zone processes. On the one hand, it favours the formation of weathered rock surfaces that are easier to erode than non-weathered rocks, but on the other hand roots and aerial vegetation act as a physical protection of soils against erosion. The flux of matter from sources to sinks thus depends primarily on climate, pedogenesis and vegetation. The two latter forcing factors have been affected for millennia by human activities (Dearing and Jones, 2003; Pope and van Andel, 1984). However, the recent and worldwide spread of human control on Earth surface processes, including urban soil sealing, intensive river damming or large scale water management, completely overpasses natural processes in many regions of the world (Syvitski, 2005; Syvitski and Kettner, 2011), including the European Alps (Jenny et al., 2014). Our study includes the last century together with longer time-scales. However, we focused on longest time-scales aiming at replacing Earth-climate-human interactions into a long-term perspective. This is indeed required to understand the processes underlying the Anthropocene (Costanza et al., 2007; Dearing et al., 2010).

Because it affects pedogenesis, soil dynamics and vegetation, human land-use is an important forcing factor of erosion. Moreover, growing intensity of water management throughout the last centuries completely modified the erosion budget on a worldwide scale (Skalak et al., 2013; Syvitski, 2005). Indeed, the growing impact of human practices on erosion is one of the main manifestations of the Anthropocene (Brown et al., 2013; Poirier et al., 2011; Syvitski and Kettner, 2011) that is defined as the period when humans became a planet-wide geological factor (Zalasiewicz et al., 2011). However, whereas the concept of the Anthropocene is very young (Crutzen, 2002), the complex interplay between humans and erosion is well-known for millennia. As early as the IVth century BC, the Antique Greek philosopher Plato reported in his dialogue *Critias,* the threats due to erosion in terms of fertile soil loss (Jowett, 1892). Indeed, it is in the Mediterranean realm and in connection with archaeological studies, that modern science addressed the question of human-erosion relationships through millennia (van Andel et al., 1990). First studies were based on the compilation of outcrop observations which were related to population assessments based on archaeological discoveries (Pope and van Andel, 1984). This participated in the idea that humans became, as early as in the Bronze Age, a major geological agent, at least at local to regional scales. Such an approach is still very viable, in particular in regions like Greece, where erosion processes challenge the current societal development and where archaeological legacy is important (e.g. Butzer, 2005; Lespez, 2003). However, this does not permit to reconstruct processes and triggering factors both continuously and along a common chronological framework. Recent studies of modern-time erosion took advantage of the sediment cascade concept to understand and model erosion fluxes (Burt and Allison, 2010). However, at our knowledge no studies yet transposed it to paleo records. There is also an abundant literature aiming at describing and quantifying current erosion processes in the Alps, especially from debris flows (e.g. Berger et al., 2011) and colluvial fans (e.g. Hornung et al., 2010) analysis. However, to quantify the current erosion in mountain areas remains challenging (Konz et al., 2012).

Lake sediment can be used to bridge the gap between past discontinuous records and the study of modern erosion dynamics.



Triggering factors	Erosion processes			
	Weathering	Grabbing	Transport	Accumulation
Temperature	Physical (cold) vs. chemical (warm)	Permafrost stability Glacier dynamics	Snow cover cycle	Dilution (authigenic productivity)
Rainfall patterns	Intensification of chemical weathering	Glacier dynamics Heavy rainfall events	Hydrological flux Fluvial morphology	Lake basin morphology
Land cover	Biochemical weathering	Soil (de)stabilisation	Fluvial morphology	Buffering effect (riparian forest)

Fig. 1. Conceptual model of the erosion cycle and effects of the three main triggering factors (temperature, rainfall patterns and land cover) upon the four stages of the erosion cycle (weathering, grabbing, transportation, accumulation).