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Multiproxy analyses of Lake Allos reveal synchronicity and divergence in geosystem dynamics during the Lateglacial/Holocene in the Alps

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A B S T R A C T

Palaeoenvironmental reconstructions of ecosystem responses to external forcing are generally limited by the difficulty of understanding the geosystem as a whole, because of the complex interactions between ecological compartments. Therefore, identifying which geosystem compartments or proxies co-vary is a prerequisite in unravelling the propagation of disturbances (e.g. climatic or anthropogenic) from one compartment to another. A multiproxy study of a continuous 13,500-year sedimentary profile cored in Lake Allos (European Alps, 2200 m a.s.l) was carried out on the basis of high-resolution sedimentological, geochemical, and botanical analyses, as well as determination of aquatic biotic proxies (diatoms, ostracods). These multiproxy datasets are rare at these high altitudes. Major changes occurred in the course of the palaeoenvironmental history of this alpine watershed at 12,000, 8600, 7200 and 3000 cal. BP. During the Holocene, two main transitions were recorded in all the ecological compartments (8600 and 3000 cal. BP), but the period 4500-3000 cal. BP stands out because of major changes that concerned only the lacustrine ecosystem. The frequent switches in lake level might correspond to the 4.2 ka climatic event. Proximity of this alpine lake to climatically-sensitive thresholds (ice-cover, thermal stratification, hydrological balance) may have amplified climatic signals in the lake ecosystem. This study illustrates the difficulties inherent to the use of common intra-Holocene stratigraphical limits, given that ecological compartments are likely to have different responses to forcing factors depending on the characteristics of the watershed and its capacity to accommodate disturbances.

1. Introduction

Alpine ecosystems, located above the upper limit of forest growth, are particularly influenced by cold temperatures and duration of the snow-free period (Körner, 1995). Increase in temperatures and changes in precipitation regime, expected in the European Alps throughout the 21st century (Gobiet et al., 2014), may expose mountain landscapes to profound and unprecedented modifications. These modifications might include upward movement of the treeline (Harsh et al., 2009), extinction of plant communities (Cannone et al., 2007), and pronounced soil drought (Heinrich and Gobiet, 2012). Climate change is also likely to affect natural lake physical and biological properties (Wolfe et al., 2003; Parker et al., 2008; Rühland et al., 2008; Perga et al., 2015), with severe consequences on lacustrine ecosystem services (e.g., water quality, leisure activities). On the other hand, local drivers of environmental change such as land use (pastoral activities), soil development, and geomorphic processes (e.g., erosion) will continue to play a major role in the trajectories of alpine ecosystems in a complex interaction with climate (Bennion et al., 2011; Macias-Fauria and Johnson, 2013). In addition, most systems are

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not in a steady state, and are characterised by natural variability and species succession (Hilderbrand et al., 2005). Disentangling the factors that control ecosystem functioning is a prerequisite for a better understanding of climate- or human-related environmental changes (Birks and Birks, 2006). Differences in temporal behaviour can be used to distinguish long-term autogenic successional trends from higher-frequency fluctuations that are driven mainly by external forcing (Adrian et al., 2009). Thus, improving knowledge on alpine ecosystem functioning requires a global understanding of how the diverse compartments of the environment (i.e., both biotic and abiotic, and terrestrial and aquatic) respond to perturbations at a multi-millennial timescale.

Multiproxy datasets on lacustrine and terrestrial ecosystems covering the Lateglacial-Holocene period are rare at these high altitudes, even in the relatively well-studied mountains of Europe. Noteworthy examples of multiproxy studies have been carried out in Lakes Basa de la Mora and Enol in the Pyrenees (respectively by Pérez-Sanz et al., 2013, and Moreno et al., 2011), and in Lakes Brazi and Gales in the Carpathians (Tóth et al., 2017). Regarding the Alps, multiproxy studies have been carried out in Sägistalsee (Lotter and Birks, 2003) and Bachalpsee (Lotter et al., 2006) in the Swiss Alps, and in the Oberer Landschitzsee in Austria (Schmidt et al., 2006). In the central Alps, the impact of ancient anthropogenic pressure in generating mountain vegetation changes has been demonstrated. The concomitance of the first expansion of alder trees and replacement of fir by spruce forests, the increase of ruderal plants associated with pastoral farming, and that of anthropogenic fires aimed at creating open landscapes during the Late Neolithic (5900-5200 cal. BP), show clearly that vegetation changes during this period did not result from climate change, but were determined by land use (Gobet et al., 2003; Tinner et al., 2005). In the same vein, looking for synchronicity between anthropogenic-driven proxies and other proxies is a good way of identifying this human influence on local geosystem changes. Various methods have proved their efficiency in this regard, including tracking nutrient-rich plants using pollen (Rey et al., 2013) and sediment DNA (Pansu et al., 2015), and that of the presence of animals through coprophilous fungi (Schwörer et al., 2014), coprophilous coleopterans (Ponel et al., 2011), and sediment DNA (Giguet-Covex et al., 2014). For periods prior to anthropogenically-induced vegetation changes, it is also frequent having aquatic biota changes that follow catchment dynamic in the Alps, especially as regards vegetation succession. For example, whilst climate-induced lake-level changes during the Mid-Holocene may have been a cause of chironomid succession in the Sägistalsee (Heiri and Lotter, 2003), a concomitant upward migration of spruce resulting in denser woodlands in the lake's catchment (~6500 cal. BP) may also have caused this trend. The close link between lake biota and terrestrial dynamics is just as strong in the Late Holocene during which large nutrient loadings due to soil erosion and pasturing resulted in anoxia of bottom lake waters (Heiri and Lotter, 2003). Finally, when investigating all geosystem compartments through large multiproxy datasets, the role of climate changes may be still unclear. At the Sägistalsee (Lotter and Birks, 2003), for instance, where independent climate proxies (e.g. solar insolation and North Atlantic cold events) have been confronted statistically with all the environmental proxies, no significant results have been found. Conversely, when vegetation change is proposed as an explanatory variable, all commonly employed datasets (i.e. cladoceran, chironomids, grain-size, elemental geochemistry, magnetic susceptibility) are statistically well-explained. Obviously, one cannot expect to strictly identify climate forcing based on a mono-proxy study during the Lateglacial-Holocene, whether or not there is a human impact, because of the 'cascade' response of geosystem compartments. This pattern is met in numerous partial multi-proxy studies of the Alps (e.g. Giguet-Covex et al., 2011; Bajard et al., 2017; Pini et al., 2017). Thus, an appropriate way of tracking climate oscillations is first to identify which geosystem compartments or proxies co-vary, in order to then proceed by elimination.

As a result of complex environmental responses during the Holocene, and the variability of the proxies studied, no formal subdivision of the Holocene exists in the Quaternary community, even though a tripartite subdivision including an "early", "mid", and "late" Holocene has been largely employed in research papers in the last few decades (Walker et al., 2012). The first attempts to propose a formal division of the Holocene were based on palynological stratigraphy but time lags in vegetation responses and a lack of robust age-depth models limited the use of this subdivision at the global scale (Mangerud et al., 1974). More recently, advances in geochronology and palaeoclimatic archives (e.g. dendrochronological series, ice core data) have led to the emergence of another tripartite division based on two climatic events at 8200 and 4200 cal. BP (Walker et al., 2012). However, the benefits of applying this scheme to the description of new Holocene records still need to be discussed, as these subdivisions might not be consistent with the main boundaries highlighted by environmental proxies.

In this context, the transition from the Mid-to the Late-Holocene period assumes particular significance since major environmental changes in the European Alps and Mediterranean regions have been highlighted in connection with large palaeohydrological events (Magny et al., 2013) and contemporaneously with increasing human impact (this period has been termed the "Mid-Holocene melange" (Roberts et al., 2011)). At the interface between these two geographic domains, the Mediterranean Alps have been particularly well-investigated, providing 14 continuous sedimentary records for this time period (Brisset et al., 2015 and references therein). All the study sites recorded major vegetation changes during this Mid-to Late-Holocene transition. However, with the exception of the records from Lake Long Inférieur (including pollen, insect and chironomid analyses; Ponel et al., 2001; Gandouin and Franquet, 2002), and Lake Vens (coupling sedimentology and pollen analysis; Brisset et al., 2015), all other records were exclusively based on pollen analysis (i.e. Beaulieu de, 1977; Dijkstra et al., 1990; Kharbouch, 2000; Finsinger, 2001). Moreover, age controls were also disparate between sediment cores (Brisset et al., 2015), and many of these records were solely constrained with palynostratigraphy (Beaulieu de, 1977).

The present study aims at reconstructing past alpine environment functioning and the driving forces in the Mediterranean Alps by characterizing, at a high resolution, palaeoenvironmental changes of the Allos geosystem (Fig. 1) during the Lateglacial and the Holocene. To achieve this goal, we use a compartment-oriented approach (i.e., to access the main environmental components within the same sediment archive) that includes geomorphic processes (derived from sedimentology and geochemistry), vegetation changes (pollen), characterization of the lacustrine environment (diatoms, ostracods, geochemistry), together with a well-constrained chronostratigraphy (radiocarbon dates). This approach will enable identification of synchronicity and divergence between proxies and geosystem compartments particularly during the Mid- and Late-Holocene periods, deciphering of the processes involved, and determination of the types and timing of environmental responses. Finally, the common environmental boundaries between proxies will be confronted with the traditional tripartite subdivision of the Holocene.