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Limnological changes in South Carpathian glacier-formed lakes (Retezat Mountains, Romania) during the Late Glacial and the Holocene: A synthesis

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Remains of aquatic biota preserved in mountain lake sediments provide an excellent tool to study lake ecosystem responses to past climate change. In the PROLONG project a multi-proxy study was performed on sediments of glacier-formed lakes from the Retezat Mountains, Southern Carpathians (Romania). The studied lakes (Lake Brazi and Gales) are situated on the northern slope of the mountain at different altitudes (1740 m and 1990 m a.s.l.). Our main objectives were 1) to describe the main limnological changes in these lakes during the last ca. 15,000 years and 2) to summarize the environmental history of the studied lakes based on taxonomical and functional patterns of the biological proxies. For this synthesis we used the results of diatom and chironomid analyses, and indirect biotic and abiotic parameters, including sediment organic matter (LOI) content, geochemical element concentrations (Al, Ca, S, Sr) and biogenic silica content. Using multivariate numerical approaches we analysed changes in the assemblage structure of siliceous algae and chironomids, compared temporal patterns among proxies, examined the relationship between potential driving factors, chironomid and diatom assemblage changes and identified paleolimnological phases of the lake successions. Changes in assemblage composition and aquatic ecosystem state apparently followed summer insolation, local climatic conditions and local productivity changes driven by these. Diatom and chironomid assemblages generally changed in a similar direction and at a similar time within a lake, but differed to some extent between Lake Brazi and Gales. At both lakes the strongest variations were observed in the Late Glacial and the first half of the Holocene. The strongest Holocene assemblage changes took place in the earliest Holocene in Lake Brazi, but extended into the mid-Holocene in Lake Gales, following long-term insolation changes and climatic changes. In addition, three common zone boundaries were identified: at ca. 14,200 and at ca. 6500 cal yr BP for every records and at ca. 3100 cal yr BP for diatom records in both of the lakes and for the chironomid record of Lake Brazi. This multi-proxy synthesis provides comprehensive data that increase our understanding of the past variability of lake ecosystem functioning and biodiversity in East-Central Europe.

1. Introduction

Lake sediments and the fossils preserved in them are important archives of past environmental, limnological and climatic events and thereby provide us the possibility to understand the natural development of lake ecosystems as well as regional climatic and

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ecological processes on historic and prehistoric time scales (Battarbee, 2000). Detailed knowledge on recent patterns of species-environment and assemblage-environment relationships may allow inferences about the past environmental circumstances based on biotic assemblages in lake sediment records, and in some cases to establish modern calibration-based quantitative reconstructions of certain environmental variables (e.g. Birks et al., 1990; Walker et al., 1997; Heiri et al., 2011). In order to obtain the most complete and balanced interpretation, many proxy records combined in a multi-proxy study are the most advantageous to evaluate alternative hypotheses and explanations (Birks et al., 1990; Birks and Birks, 2006). Moreover, several proxies are sensitive to human impact, and thus paleoecological records may also supplement the available archaeological information on land use development as well as its effects on terrestrial and aquatic ecosystems (Birks et al., 2014).

In this study we present a paleolimnological synthesis of environmental changes in and around two glacial lakes in the Retezat Mountains (Southern Carpathians) covering the Late Glacial and Holocene. The South Carpathian Mountains received relatively little attention in paleolimnological studies until recently when both local (e.g. Magyari et al., 2009a) and larger scale projects (e.g. Catalan et al., 2009; Heiri et al., 2014) started. Within the multi-proxy paleoecological project PROLONG (Magyari et al., 2009a) several biotic and abiotic proxies have been studied on sediment cores of four mountain lakes including sediment organic matter (as loss on ignition) and biogenic silica content, geochemical element concentrations, diatoms, chrysophycean cysts, cladocera, ostracods and chironomids (Korponai et al., 2011; Braun et al., 2012; Buczkó et al., 2012; Iepure et al., 2012; Tóth et al., 2012; Buczkó et al., 2013; Soróczki-Pintér et al., 2014; Tóth et al., 2015). In this study we concentrate on proxy records from two lakes on the northern slope of the Retezat Mountains. We primarily discuss proxies that are available from both lakes and provide information about past limnological changes. These are loss on ignition, biogenic silica content, selected major element concentrations, as well as diatom and chironomid assemblages. A wide range of biotic and abiotic proxies have been analysed from the same sediment cores from two lakes with contrasting hydromorphology and environment. This study therefore provides the opportunity to compare the different proxies and develop a holistic interpretation of the limnological changes during the Late Glacial and Holocene.

Our specific objectives are 1) to describe the most important limnological changes and 2) to summarize the environmental histories of the studied lakes.

2. Study sites

The Retezat Mountains, located in the South Carpathians, are among the wettest massifs (annual rainfall 1400 mm yr^{-1} at 1500–1600 m a.s.l.) in Romania due to vapour supply by both Mediterranean and Atlantic air masses (Jancsik, 2001; Magyari et al., 2013). The climate of the Retezat is temperate continental modified by a distinct mountain mesoclimate (Spinoni et al., 2015). The mean annual temperature is around +6 °C in the foothill zone and −2 °C at the top of the mountains (2500 m a.s.l.). At present, July is the warmest and January the coldest month characterized by mean temperatures of 11.9 °C and −5.9 °C around Lake Brazi at 1740 m a.s.l. (calculated using CARPATCLIM data for the period 1961–2010, Spinoni et al., 2015). At the elevation of Lake Gales (1990 m), mean July and January temperatures are 10.1 and −6.8 °C respectively.

In this study, the multi-proxy results of two sediment profiles are compared. The first was obtained from Lake Brazi (Tăul dintre Brazi, 1740 m, 45°23′47″N, 22°54′06″E; Fig. 1), a small and shallow lake with maximum water depth of 1.1 m and a surface area of 0.4 ha (Magyari et al., 2009a). Nowadays, the lake is oligotrophic, its summer pH ranges between 6.1 and 6.7 and its conductivity between 10 and 16 μS cm^{-1} (Magyari et al., 2013; Kövér, 2016). The lake is situated in the subalpine belt, on the western marginal side of the Galeş glacial valley, in a mixed Norway spruce (*Picea abies*) and stone pine (*Pinus cembra*) forest.

Lake Gales (Lacul Galeş, 45°23′6″N, 22°54′33″E) is located in the same valley, but at higher altitude (1990 m a.s.l.), *ca.* 150 m above the timberline in the dwarf pine (*Pinus mugo*) zone. Lake Gales is deeper than Lake Brazi with a maximum depth of 20 m and a surface area of 3.68 ha (Magyari et al., 2009a). Nowadays, the lake is oligotrophic, its summer pH is between 7.1 and 7.67 and its conductivity is about 16.2–16.4 μS/cm (Magyari et al., 2013; Kövér, 2016). This higher lake has a small inflow and a relatively large outflow.

3. Methods

3.1. Fieldwork and sediment description

From Lake Brazi a 490-cm long sediment core (TDB-1; 111–600 cm depth measured from the water surface) was taken in the central part of the lake (water depth 1.1 m) in August 2007 with a modified Livingstone piston corer (diameter 7 cm). From Lake Gales a 328-cm sediment core (Gales-3; 0–328 cm, measured from the sediment surface) was taken in the central part of the lake (water depth 19.5 m) using a modified Kullenberg corer (diameter 7 cm; Emery and Broussard, 1954). Gales-3 was drilled in one section using a 4-m long plastic pipe supplied with a piston; therefore, correlation problems between core sections were avoided.

The sediment stratigraphy and organic content record of the lakes investigated were described in detail in Magyari et al. (2009a, 2012), Buczkó et al. (2013) and Hubay et al. (2016).

3.2. Chronology

The chronological framework of TDB-1 was established using 21 AMS ^{14}C dates, and suggests that sediment accumulation started prior to 15,000 cal yr BP (at 490 cm sediment depth) and was continuous throughout the Late Glacial and the Holocene (Hubay et al., 2016; and Supplementary Fig. 1).

The chronological framework of Gales-3 was established using 20 AMS ^{14}C dates and relative chronological marker points via the comparison of the Lake Gales and Lake Brazi pollen diagrams (Hubay et al., 2016). The bottom layer at 328 cm is also estimated to be >15,000 cal yr BP old in Lake Gales using a smooth spline age-depth model (see Hubay et al., 2016; and Supplementary Fig. 1). From the Holocene part of this lake a *Pinus* twig dated to *ca.* 2060 cal yr BP at 15 cm sediment depth suggests that the coring started below the sediment surface and therefore, the Gales-3 sediment core likely does not represent the last *ca.* 1800 years (see Hubay et al., 2016).

3.3. Loss-on-ignition and geochemical analyses

The total organic matter of the sediment was determined by loss-on-ignition (LOI) at 550 °C for 4 h following Heiri et al. (2001).

For the elemental analyses 1 cm^3 dried samples were digested with 5 mL HNO_3 (65%) and 2 mL H_2O_2 (30%). Acid-soluble element concentrations were determined by inductively coupled plasma optical emission spectrometry (Spectroflame ICP-OES). In a preliminary Principal Components Analysis (PCA) including all of the measured acid-soluble element concentrations, Al, Ca, S and Sr