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Research paper

Bolătău sediment record – Chronology, microsedimentology and potential for a high resolution multimillennial paleoenvironmental proxy archive

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ABSTRACT

Finely laminated sediment records have been studied from a small landslide-dammed lake (Bolătău) located in Bukovina, Romania. An age-depth model for the Bolătău sediment record was established based on 8 AMS radiocarbon dates from terrestrial macrofossils and the double peaks of the ^{137}Cs flux (i.e. mid-1960s: global fallout maximum; 1986: Chernobyl accident). The onset of the lacustrine sedimentation is estimated to ~5–6.5 ka while the landslide event can be constrained by ~6.8–7 ka as an inferior age estimate. The laminated structure is interpreted as organic and clastic type varvite at the lower and upper part of the core, respectively. Major fluctuations found in the coarsely sampled (5 cm) stable carbon isotope data showed remarkable correspondence with nearby palynological records and a lacustrine δ^{13}C record. It suggests that the sediment record preserves environmental signals with a broader regional relevance. The established timescale provides the necessary chronological basis of the records from Lake Bolătău for further analysis.

1. Introduction

Reconstructing past climate conditions throughout ample time frames is becoming increasingly necessary in order to place current climate changes into a broader context. Lacustrine sediments typically integrate and preserve environmental signals into their structure and composition, therefore geochemical and sedimentological analyses of these archives have become an instrumental tool for monitoring environmental change by providing an important longer-term temporal perspective and enhancing environmental assessment (e.g., Smol, 1992; Anderson and Battarbee, 1994; Anderson, 1995; Smol, 2008; Akinyemi et al., 2013). A wide range of lake sediment-based analysis techniques pertaining to several research fields (i.e. geochemistry, geology, botany etc.) are currently employed for understanding the dynamics of local and regional climate over various time scales (Smol et al., 2001a,b; Birks and Birks, 2006).

Moreover, a robust age model is an essential prerequisite for understanding paleoclimate signals, for comparison of different records, and for resolving the successions and timing of different events detected in the sedimentary sequence.

Whereas the potential of mountain lake sediments for providing accurate climate change indicators has long been recognized and thoroughly studied, lakes throughout the Carpathian region from Romania, Slovakia and Ukraine remain as yet 'seriously under-investigated although they would be ideal objects of paleolimnological work', as concluded by Buczkó et al. (2009). Against this background, the potential for climate reconstructions of landslide-dammed lakes (such as Bolătău and Iezer in the northern area of the Eastern Romanian Carpathians) which are rather scarce (Cohen, 2003) was only recently acknowledged and came to the attention of paleolimnological research in Romania (Mindrescu et al., 2010a,b;

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Of the two, Lake Bolătău was first reported in the literature as late as the 1960s (Georgescu and Georgescu, 1964, brief mention regarding lake origin); however, it was completely overlooked in terms of research until recently (Mindrescu et al., 2010a,b). Along with lakes Iezer and Paşcanu (Georgescu and Georgescu, 1964), located in the nearby mountain area under largely similar geological conditions which favoured landslide damming of the respective streams, Bolătău is part of the 'Bukovinian Millennial Lakes' triangle.

The study of historical and cartographical data and preliminary assessments on sediments extracted from Lake Bolătău resulted in two hypotheses: (i) the lake is likely significantly older than previously thought and (ii) the sediments are varved and suitable for multi millenial-scale paleoenvironmental reconstructions, both of which we wanted to test.

Finally, we wanted to test the potential of Bolătău lacustrine sediment archive for future paleoclimate studies and acquire a preliminary impression on the achievable record which would guide subsequent detailed geochemical studies; to this purpose, stable carbon isotope composition of the bulk carbonate-free sediment was analysed and compared to coeval terrestrial records available from the broader region.

2. Materials and methods

2.1. Lake description and sampling

Lake Bolătău (1137 m a.s.l.) is located in Obcinele Bucovinei, an outer subdivision of the Eastern Romanian Carpathians (Fig. 1), which rise to an elevation of around 1300 m a.s.l. in the vicinity of the lake catchment. The lake formed in the southwestern area of Obcina Feredeului, in the drainage basin of a tributary of river Moldova on Bolătău stream (also known as Holohoşca on the lower course). As the toponym Bolătău (literally, *pond* or *puddle*, often with marshy characteristics) is rather common in the local and regional toponymy (Grădinaru et al., 2012), the lake is presently referred to in the literature as Lake Bolătău-Feredeu (Mindrescu et al., 2013).

The geology of the study area comprises Cretaceous ('Black shale formation') and Paleogene flysch formations pertaining to the Audia Nappe (Săndulescu, 1984). The stratigraphy consists mainly of sequences of glauconitic sandstones, red, green and striped clays, black marly shales etc. The lake catchment overlies truncated edges of near vertical folded flysch strata which were subjected to weathering and erosion, thus resulting in increased susceptibility to landsliding under triggering conditions, i.e. heavy rainfall, earthquakes etc. (Georgescu and Georgescu, 1964). Consequently, Lake Bolătău was created by the obstruction of a deep and narrow stream valley by landsliding of the surrounding Cretaceous flysch, which displaced roughly 9 M m^3 of rock. Currently the maximum depth of the lake ranges up to 5.4 m; the lake has a small inflow and an outflow stream.

The lake catchment (approx. 30 ha, see Table 1) is entirely covered by coniferous forest comprising to a large extent of *Picea abies* which dominates the landscape at the lake site.

Whereas the regional climate falls into the temperate continental type, the site located nearby Cîmpulung Moldovenesc (CM - 642 m a.s.l.) and Rarău Mts (1572 m a.s.l.) meteorological stations (Fig. 1) exhibits some distinctive features, particularly in terms of annual precipitation amounts ranging from 696 mm (CM) to 902 mm (Rarău), 73% of which fall during the warm season (April–September). Rarău station and the surrounding area are also included in the zone of maximum duration of rainfall within the Romanian territory (Rusu, 2002). The mean annual temperature is 6.4 °C (16.5 °C in July and −5.2 °C in January, from 1934 to 1987). Moreover, 41% (CM) to 48% (Rarău) of the duration of a year consists of days with temperatures below 0 °C, typically from October to April (Rusu, 2002) when the conditions are met for the lake to freeze. Depending on the temperature regime during late autumn, freezing may be delayed until December, as was often the case during the past decade (anecdotal data).

The sediment cores were retrieved in April 2013 using both a Russian corer and a gravity corer from the frozen surface of the lake (see Supplementary FigS1). The distance between the cores were less than 1 m since they were extracted from the same slot cut in the ice. The gravity core preserved the water–sediment interface intact; however the preservation of the unconsolidated sediment at the top of the Russian core is known to be imperfect and a couple of centimetres of sediment lost is conceivable. However, when characteristic stratigraphic levels were compared between the overlapping sections of the cores we found very good agreement (<1 cm) without any systematic shift, therefore the depth scale of the Russian core was used without modification subsequently. The Russian corer extracted 0.6 m long sediment units. The resulting cores (Russian corer: 401 cm, and gravity corer: 66 cm beneath the water–sediment interface) were visually inspected on site, described, photographed and sectioned at intervals of 1.0 cm into pre-labelled plastic bags. The samples were weighed and kept refrigerated before they were dried at 40 °C.

The occurrence of an apparent sharp change in the laminated lacustrine sediment at the depth of 387 cm was documented which indicated that the landslide body deposit was penetrated by the Russian corer at that depth in the coring point.

2.2. Microsedimentological study

Four sections (depth ranges: 72–73 cm, 178–179 cm, 298–299 cm, 352–353 cm) were selected for microsedimentological analysis. Dried sediment samples (soaked with Araldite) and petrographic thin sections have been prepared. The microsedimentological sections were studied by polarization microscopy using a Nikon Eclipse E600 Pol microscope and attached Spot insight camera.

Backscattered electron (BSE) images and elemental composition of carbon coated sections were studied by a JEOL Superprobe 733 electron microprobe with INCA Energy 200 Oxford Instrument Energy Dispersive Spectrometer. The analytical circumstances were: acceleration voltage: 20 keV, beam current: 6 nA, count time: 60 s for the spot measurement and 5 min for line scan analysis.

The mineralogical composition was determined by X-ray powder diffraction (XRD) analysis on oriented samples. XRD analysis was made on a Philips PW1710 type X-ray diffractometer with the following instrument parameters: CuKα radiation, graphite monochromator, 45 kV acceleration voltage, 35 mA intensity, 1° divergence slit.

Polarization and SEM microscopy, and XRD analyses were carried out at the Institute for Geological and Geochemical Research, Research Centre for Astronomy and Earth Sciences, MTA (Budapest, Hungary).

2.3. Gamma-spectrometry for ^{137}Cs activity

Radiocaesium (^{137}Cs, $t_{1/2} = 30.07$ yr) is originally absent in nature and has been produced and released by anthropogenic processes. Its most important global environmental source was the fallout from atmospheric thermonuclear weapon tests (from 1954 to 1963) which peaked in the early 1960s and declined rapidly in terms of intensity after the Nuclear Test Ban Treaty in 1963. Afterwards, the majority of Eurasia was affected by a subsequent