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# Dynamics of the last four glacial terminations recorded in Lake Van, Turkey

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ABSTRACT

A well-dated suite of Lake Van climate-proxy data covering the last 360 ka documents environmental changes over 4 glacial/interglacial cycles in Eastern Anatolia, Turkey. The picture of cold and dry glacials and warm and wet interglacials emerging from pollen, organic carbon, authigenic carbonate content, elemental profiling by XRF and lithological analyses is inconsistent with classical interpretation of oxygen isotopic composition of carbonates pointing to a more complex pattern in Lake Van region. Detailed analysis of glacial terminations allows for the constraining of a depositional model explaining different patterns observed in all the proxies. We hypothesize that variations in relative contribution of rainfall, snowmelt and glacier meltwater recharging the basin have a very important role for all sedimentary processes in Lake Van. Lake level of glacial Lake Van, predominantly fed by snowmelt, was low, the water column was oxic, and carbonates precipitating in the epilimnion recorded the light isotopic signature of inflow. During terminations, increasing rainfall and significant supply of mountain glaciers' meltwater contributed to lake level rise. Increased rainfall enhanced density gradients in the water column, and hindered mixing leading to development of bottom-water anoxia. Carbonates precipitating during terminations show large fluctuations in their isotopic composition. Full interglacial conditions in Lake Van are characterized by high or slowly falling lake level. Rainfall and snowmelt feed the lake but due to re-established mixing, the isotopic composition of authigenic carbonates is heavier and closer to that of evaporation-influenced lake water than that of runoff representing snowmelt and atmospheric precipitation.



## 1. Introduction

Since their first discovery in the 19th century (for review see Imbrie and Imbrie, 1979) the imprint of Quaternary glacial/interglacial cycles on atmospheric and oceanic circulation has been documented in numerous marine and continental climate archives (Shackleton and Opdyke, 1973; McManus et al., 1999; Jaccard et al., 2005; Prokopenko et al., 2006; Jouzel et al., 2007; Martrat et al., 2007; Meckler et al., 2012; Melles et al., 2012). As proposed originally by Milankovich, the main pacemaker of Ice Ages are the changes in Earth's orbital parameters (Hays et al., 1976) with internal feedbacks playing a significant role (Ruddiman, 2003). Terminations of Ice Ages are the most spectacular examples of near-synchronous global and abrupt climate change. The structure of termination after Denton et al. (2010) includes following scenario: rising Northern Hemisphere summer insolation leads to ice-sheet melting, which delivers meltwater into the Atlantic. Reduced Atlantic Meridional Overturning Circulation (AMOC) facilitates the spread of winter sea ice, hampers the heat transport to the mid-latitudes and tropics, and weakens the Asian monsoon. The Intertropical Convergence Zone (ITCZ) and westerly winds of both hemispheres shift southwards, with southern westerlies warming Antarctica and triggering degassing of the Southern Ocean deep $CO_2$ reservoir. Released $CO_2$ promotes further warming and sustains interglacial conditions. The consistency of singular elements of this comprehensive layout and their temporal arrangement has been reported from the marine realm (McManus et al., 2004; Jaccard

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et al., 2005; Marchitto et al., 2007; Meckler et al., 2013), however, the detailed structure and the sequence of changes occurring during terminations have been to date rarely studied in continental archives. In particular, it is difficult to follow the response of the continental ecosystem to climate forcing (e.g., deglacial warming) over a course of several cycles; most of the continental sedimentary sequences are too short or of insufficient resolution. While studies of past interglacials shed light on different aspects of climate change in a warmer world (Tzedakis and Bennett, 1996; Frogley et al., 1999; Brauer et al., 2008), very few comparative approaches of several glacial terminations recovered from the same continental archive exist (Prokopenko et al., 2006; Cheng et al., 2009). The Eastern Mediterranean region yielded a couple of continental records covering at least one full glacial/interglacial cycle (Bar-Matthews et al., 2000; Torfstein et al., 2009; Develle et al., 2011; Djamali et al., 2012; Stevens et al., 2012), or capturing the termination or the glacial inception (e.g. Bartov et al., 2003; Jones et al., 2007; Waldmann et al., 2009). Not all of these records have an independent chronology and most of them focus on one proxy only (e.g.: pollen assemblages, isotopic composition of speleothems, isotopic composition of lacustrine carbonates, lake level). Consequently reconstructions of the past Eastern Mediterranean hydrological regime are not always consistent and provoke a debate between two competing hypothesis: wet interglacials/dry glacials versus dry interglacials/wet glacials (Gasse et al., 2011).

Here we present the last four glacial/interglacial cycles recorded in sedimentary proxies of Lake Van in Eastern Anatolia, Turkey. In order to gain insight into paleoenvironmental changes, we analyzed elemental intensities, amount of total organic carbon and carbonate, oxygen isotope composition of sedimentary carbonates and pollen assemblages. Detailed lithological analyses of Lake Van sediments by Stockhecke et al. (2014a), including organic carbon and carbonate data, constituted the conceptual framework for the present study. We took advantage of this work and juxtaposed extended geochemical and pollen time-series with interpretation based on the facies analysis. The age model of Lake Van record is robust, but not independent; therefore we focus primarily on the relation between different proxies from the same profile over the course of the last four glacial/interglacial cycles rather than compare our record with other archives. This work emphasizes three issues: (1) documenting the internal consistency of the events in the glacial/interglacial sequence; (2) understanding mechanisms responsible for the regional climate change at the glacial/interglacial transition (termination); (3) testing the hypothesis of wet interglacials/dry glacials versus dry interglacials/wet glacials in the context of entire Eastern Mediterranean region.

## 2. Regional setting

Lake Van is a terminal alkaline lake in Eastern Anatolia, Turkey, located on a high plateau at 1648 m above sea level (m a.s.l). In the south, the lake is surrounded by Bitlis Massif and in the north by several volcanoes reaching the altitude of 4000 m a.s.l. (Schweizer, 1975). The ~400 m deep bowl-shaped basin has relatively wide and shallow slopes (Cukur et al., 2012). Its water chemistry and the regional climate, in winter influenced by the position of the westerly jet stream and in summer by the extension of subtropical high-pressure belt (Wigley and Farmer, 1982), make Lake Van an excellent witness of environmental changes (Fig. 1). As is the case with many terminal lakes in volcanically active regions, Lake Van's water column is characterized by Na–$CO_3$–Cl chemistry and is saturated with respect to carbonate (Lemcke, 1996; Reimer et al., 2008). Today, the pronounced seasonality of regional climate is essential for depositional processes in Lake Van. Atmospheric precipitation of Mediterranean origin falls during the cold and long winters as snow. As winter snowfall changes to spring rainfall, the amount of precipitation increases. The summers are hot and dry and the precipitation increases again in autumn. $Ca^{2+}$ is supplied to the lake along with clastic particles by the increased river discharge during the spring (snowmelt and rainfall peak). Clastic constituents tend to settle directly to the lake bottom, while part of the $Ca^{2+}$ precipitates immediately in form of whitings. The remaining $Ca^{2+}$ is retained in the upper water column where it precipitates in late summer and early autumn facilitated by phytoplankton activity and wind-driven mixing of the lake (Stockhecke et al., 2012). Light autochthonous organic matter settles during winter. The physical expression of this annual cycle is a deposition of dark (clastic particles, organic matter) and light (carbonate) laminae (Lemcke, 1996;

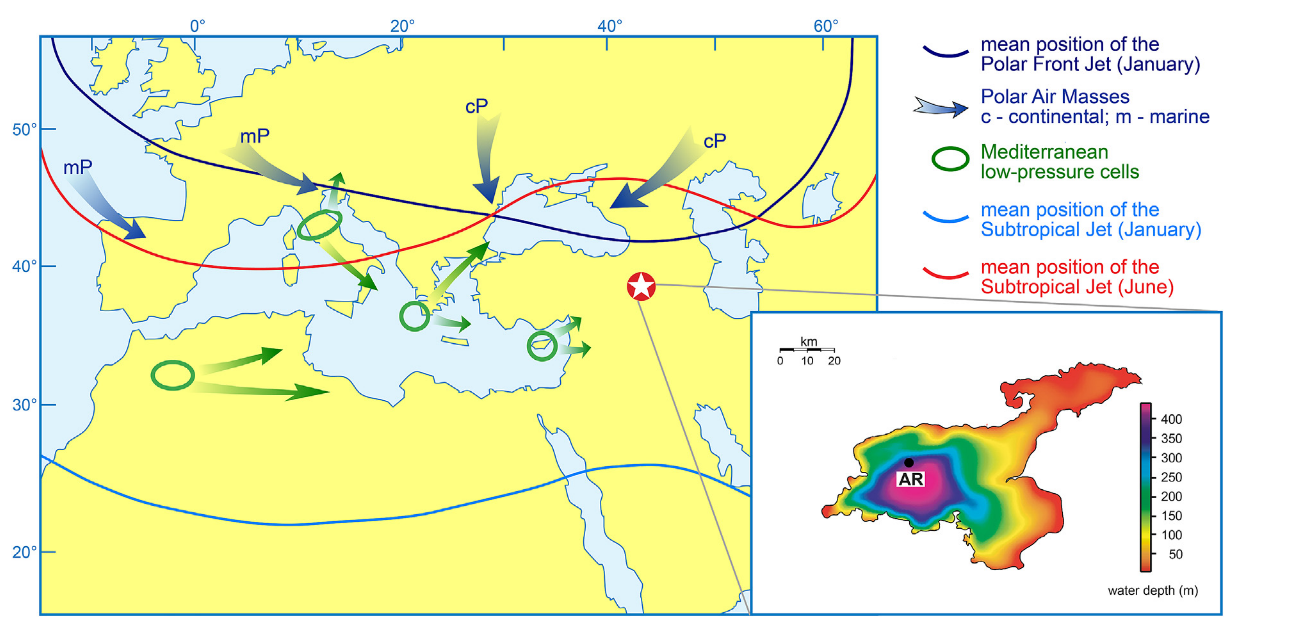


**Fig. 1.** Climatic setting of Lake Van, modified after Wigley and Farmer (1982) and Akcar and Schlüchter (2005), and location of the Ahlat Ridge (AR). Bathymetry modified after Cukur et al. (2012).