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Late-glacial and Holocene history of the northeast Mediterranean mountains - New insights from *in situ*-produced ^{36}Cl-based cosmic ray exposure dating of paleo-glacier deposits on Mount Olympus, Greece

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ABSTRACT

In this study, we present a new glacial chronology based on 20 *in situ*-produced ^{36}Cl-based cosmic ray exposure datings from moraine boulders and bedrock from the Throne of Zeus (TZ) and Megala Kazania (MK) cirques on Mount Olympus. The ^{36}Cl derived ages of glacial landforms range from 15.6 ± 2.0 to 0.64 ± 0.08 ka, spanning the Late-glacial and the Holocene. The Late-glacial, recorded in both cirques, is partitioned in three distinct phases (LG1-3): an initial phase of moraine stabilization at 15.5 ± 2.0 ka with subsequent deglaciation starting at ~14 ka (LG1), followed by a shift to marginal conditions for glaciation at 13.5 ± 2.0 ka (LG2), sustained by large amounts of wind-blown snow, despite regional warming. Glacial conditions returned at 12.5 ± 1.5 ka (LG3) and were characterized by low air temperatures and glacier shrinking. The Holocene glacial phases (HOL1-3) are recorded only in the MK cirque, likely due to its topographic attributes. An early Holocene glacier stillstand (HOL1) at 9.6 ± 1.1 ka follows the regional temperatures recovery. No glacier activity is observed during the mid-Holocene. The Late Holocene glacier expansions, include a moraine stabilization phase (HOL2) at 2.5 ± 0.3 ka, during wet conditions and solar insolation minima, while (HOL3) corresponds to the early part of the Little Ice Age (0.64 ± 0.08ka). Our glacial chronology is coherent with glacial chronologies from several cirques along the northeast Mediterranean mountains and in pace with numerous proxies from terrestrial and marine systems from the north Aegean Sea.

1. Introduction

Glaciers are very good indicators of climate change due to their mass balance sensitivity to variations in precipitation, temperature and solar insolation (Oerlemans, 2005). Therefore, the knowledge of the history of mountain glaciers, as recorded in a variety of glacial landforms, allows for reconstruction of local and regional paleoclimatic conditions. Glaciers usually form above the local climate-dependent equilibrium line altitude (ELA). In climates that are marginal for glaciation, like the ones found in Mediterranean mountains, small cirque glaciers are often formed in protected locations in response to local topoclimatic factors such as excess snow accumulation through the deposition of wind-blown and avalanching snow (e.g. Hughes et al., 2006a; b). Under these conditions, small cirque glaciers can even occur at elevations lower than the ELA, when the accumulation rates are four times higher than the local precipitation (e.g. González-Trueba et al., 2008; Hughes, 2009, Huss and Fischer, 2016 and references therein). The advance, stabilization and retreat phases of these small cirque glaciers can thus be triggered by local topoclimatic factors as well as by variations in the regional climate, making them overall invaluable, albeit discontinuous, recorders of past climate variability.

The Mediterranean basin with its mid-latitudinal position and its proximity to the North Atlantic, Eurasian and North African climatic regimes, has undergone significant changes in the terrestrial and marine systems during the late Pleistocene, and this is also reflected in the glacial records of the Mediterranean mountains (e.g. Kuhlemann et al., 2008, Hughes and Woodward, 2008, 2017). The glacial history of the mountains surrounding the Mediterranean basin has been conceived as one of the best recorders of

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ocean-continent climate interactions and their external forcing mechanisms during periods of major glacier advances as the Last Glacial Maximum – LGM (e.g. Kuhlemann et al., 2008; Domíniguez-Villar et al., 2013). To a smaller geographical extent, the sub-region of the northeast Mediterranean (southern Balkans, north Aegean and Marmara Seas, Fig. 1), has been also characterized by complex Late Pleistocene and Holocene marine and terrestrial environmental dynamics, as it comprises a transition region where W-E and N–S contrasting climatic and hydrological regimes collide and interact with each other (e.g. Lawson et al., 2005; Digerfeldt et al., 2007; Kotthoff et al., 2008; Marino et al., 2009; Pross et al., 2009; Tzedakis et al., 2009; Schmiedl et al., 2010; Francke et al., 2013; Zhang et al., 2014; Styllas and Ghilardi, 2017; Koutsodendris et al., 2017).

The recent advances in surface exposure dating (SED) techniques of glacial landforms using *in situ*-produced cosmogenic nuclides such as beryllium-10 (^{10}Be) and chlorine-36 (^{36}Cl) (e.g. Balco, 2011), have resulted in an increasing number of studies that have considerably improved our understanding of the Late Pleistocene glacial extents and timing of Mediterranean mountains (Hughes and Woodward, 2017 and references there in). In the late 1990's Mount Olympus, Greece's highest mountain, saw one of the earliest attempts for dating glacial deposits along the Mediterranean mountains using ^{36}Cl (Manz, 1998). The results of more recent studies that followed this pioneering attempt, suggest that the Mediterranean paleoglaciers generally advanced during two periods after the global LGM (*c.* 27.5–23.3ka, Hughes and Gibbard, 2015), confined between 16-15 ka and 13-10 ka, and in phase with the GS-2a and GS-1 stadials in the Greenland oxygen isotope record (Ribolini et al., 2017 and references therein).

Accordingly, during the last decade, an augmented volume of research based on geomorphological evidence, paleoclimatic reconstrunctions and SED of glacial deposits and landforms, allowed assessing a general framework of the glacial evolution of the southern Balkan and northwestern Turkey mountains during the LGM and the Late Glacial (e.g. Pindos Range: Tymphi Mountain and Mount Smolikas – Hughes et al., 2006a, b, Sara Range – Kuhlemann et al., 2009, Mount Uludağ - Zahno et al., 2010, Rila Mountains - Kuhlemann et al., 2013, Mount Chelmos – Pope et al., 2015, Mount Pelister – Ribolini et al., 2017, Galicica Mountains – Gromig et al., 2017, Fig. 1). With the exception of Mount Uludağ in NW Anatolia, the number of SED studies in the northeast Mediterranean mountains is, however, still limited and does not provide a well-constrained glacial chronology.

Despite the fact that glaciers are uncommon in Greece, we present here for the first time a glacier chronology spanning the Late-glacial and the Holocene, derived from ^{36}Cl in situ cosmogenic dating of two small (<0.5 km^2) cirque glaciers on Mount Olympus, based on 20 rock samples from bedrock and glacially transported boulders (Fig. 2). Our glacial chronology is compared to the existing SED studies from glacial cirques situated along the headwaters of the northeast Mediterranean Sea (north Aegean and Marmara seas), in an effort to reconstruct a regional and robust signal of glacier fluctuations. By correlating our findings with well-studied terrestrial (lacustrine, fluvial sequences and speleothems) and marine records from the same region (Fig. 1), we interpret our new glacier chronology in terms of external and the underlying local and regional climate forcing. The density of sampled boulders in Megala Kazania cirque further allows us to propose a chronology of glacier oscillations, and to correlate the findings with glacier and other proxy records from other northeast Mediterranean.

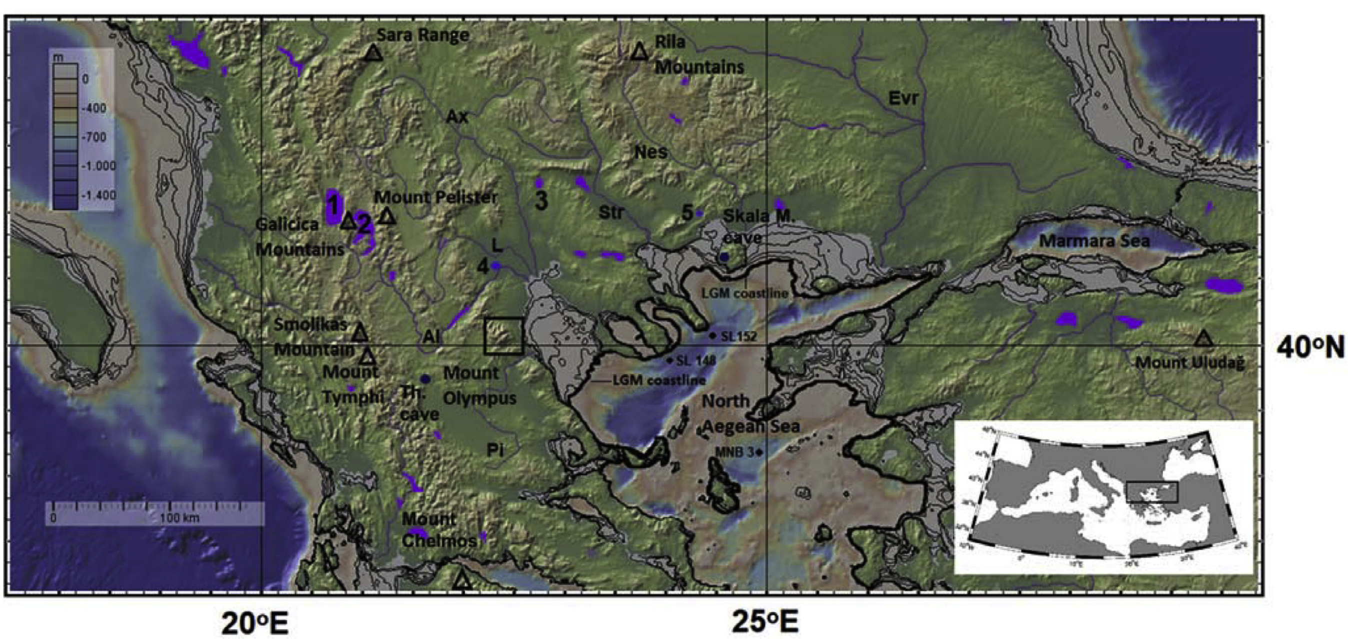

Fig. 1. Location of the study area (black rectangle) and of the northeast Mediterranean mountains (black triangles) where cosmogenic surface exposure dating of glacial landforms (SED), or glacier equilibrium line altitude (ELA) reconstrunctions are available since the Last Glacial Maximum (LGM). Purple areas correspond to major lakes, while more specifically, numbers 1, 2, 3, 4 and 5 correspond to Lakes Ohrid, Prespa, Dorjan, Loudias and Tenaghi Phillipon swamp. Also shown are the main fluvial systems discharging into the north Aegean Sea (Pi: Pinios River, Al: Aliakmon River, L: Loudias River, Ax: Axios River, Str: Strymonas River, Nes: Nestos and Evr: Evros/Meriç River). Blue circles show the locations of speleothem and sediment cave records (Th: Theopetra Cave, Duhlata Cave, Skala M: Skala Marion Cave). The locations of north Aegean marine cores SL 152, SL 148 and MNB 3 are also shown (black dots). The bathymetric contours between −120 and −20m, representing the LGM (thick black line) and early Holocene coastlines, are also shown. Topographic and bathymetric background is provided by Geomapapp® (http://www.geomapapp.org, Ryan et al., 2009). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)