Holocene and earlier glaciations in the Mediterranean Mountains

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Introduction

The Mediterranean region constitutes an almost enclosed basin in between the Iberian Peninsula (west), Anatolia (east), the southern fringe of the European continent (north) and northern Africa (south). It encompasses a surface of ca. 2.5×10^6 km², and it is only connected with the rest of the oceans through the narrow Strait of Gibraltar (min. 15 km wide) that opens to the Atlantic Ocean. The term Mediterranean comes from the Latin ‘*medius*’ (middle) and ‘*terra*’ (land), which suggests a common feature of the lands across the Mediterranean regions: the existence of mountains near the sea. Surrounding the Mediterranean coastline, there are several mountain ranges and volcanoes exceeding 2000–2500 m a.s.l., with several of them exceeding 3000 m.

The location of the semi-closed Mediterranean basin between latitudes 30° and 45° N determines a climate regime ruled by the influence of continental and subtropical high-pressure systems as well as the mid-latitude westerlies. Seasonal shifts of this major climate centres condition the prevailing climate evolution in the region, with high inter-annual variability. This, together with its rough orography composed of large peninsulas, islands, intricate coastlines and high mountain ranges near the coast, conditions a wide range of topoclimate regimes across the region. Consequently, the landscape of the Mediterranean mountains shows a great diversity driven by the diversity of hydrological, edaphic, geomorphological and biological processes occurring in the region, along with the intense historical

impact of communities that have settled in the area since prehistoric times (Woodward 2009).

In addition, mountains of the Mediterranean region have been subject to large climate oscillations during the Quaternary that have favoured periglacial processes (Oliva et al. 2018) and glacial activity that have shaped the middle and high lands of the main mountain ranges (Hughes and Woodward 2016). Outside the Alps, where abundant information is available for most of the range (Ivy-Ochs 2015), the chronology and spatial domain of glacial oscillations in the Mediterranean mountains is known for some ranges although there are still important knowledge gaps in others. Depending on the temperature and moisture regimes, glaciers expanded and retreat asynchronously across the region, with substantial spatio-temporal differences between the areas (Hughes et al. 2006; Hughes and Woodward 2016).

The maximum ice extent of the Last Glacial Cycle occurred during the Marine Isotopic Stage (MIS)-4 in some regions, whereas in others it took place during the MIS-2, almost synchronously with the global Last Glacial Maximum (Hughes and Woodward 2016; Oliva et al. 2019). In most ranges, as in most mid-latitude mountain regions and Northern Hemisphere ice sheets, glaciers started shrinking by 19–20 ka (Clark et al. 2009; Hughes et al. 2013). Within the long-term retreat occurred during Termination-1, there were some colder periods of glacial re-advance, namely during the Oldest and Younger Dryas. The timing and extent of these phases have significantly improved over the last decades (e.g., Iberian mountains; García-Ruiz et al. 2016; Palacios et al. 2017), though still remains poorly investigated in other ranges (e.g., Atlas, Apennine). However, it is still the current interglacial, the Holocene, the period that has been less understood with regards to glacial activity, with less studies focusing on the timing of glacial fluctuations (Solomina et al. 2015, 2016).

With the purpose of better understanding the spatial and temporal pattern of glaciation during the Holocene in Mediterranean mountains, this Special Issue includes 11 research articles from several different mountains across the region (Fig. 1):

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Fig. 1 Location of the research articles included in this special issue

1. Oliva et al. reconstructed phases with the presence of glaciers in Sierra Nevada using different paleoenvironmental sources such as geomorphic evidence, lake sediments and historical records. Whereas the Younger Dryas glaciers disappeared from the highest cirques during the Early Holocene, small features developed again at 2.8–2.7, 1.4–1.2 cal. ka BP and during the Little Ice Age (LIA), melting away during the mid-twentieth century.
2. García-Ruiz et al. examined the occurrence of Holocene glaciations in the Central Pyrenees, where evidence of colder phases is revealed by a wide number of paleoenvironmental sources. These authors have identified several periods with the presence of glaciers during the current interglacial, namely around 6 ka, before 3.4 ka, 1.5–1 ka, and during the LIA, when three main glacial advances took place between 1620 and the early nineteenth century.
3. Jomelli et al. analysed geomorphological features of glacial origin distributed in several valleys of the French Pyrenees. They introduce new surface exposure dates that reveal several periods of moraine formation during the Younger Dryas and Early Holocene, with evidence of subsequent phases of glacier development during the Late Holocene. The authors also provide chronological data for the development of rock glaciers during the Early Holocene as a result of paraglacial readjustment.
4. Sarıkaya et al. focused on Croatian Dinarides, where they presented the first cosmogenic ^{36}Cl glacial chronology from the region. They studied a moraine complex known as the “Rujanska Kosa” in the Southern Velebit Mountain. Well-preserved inner and outer moraine ridges gave surface exposure ages of 20.7 ± 2.2 ka and 22.7 ± 2.7 ka, respectively. Their results indicate a Last Glacial Maximum retreat of glaciers from the Southern Velebit Mountain of Croatia.
5. Leontaritis et al. reviewed the current knowledge of glaciations in Greece and the spatial extent of glaciers during the Holocene. In all cases, glaciers were small and confined within deep-cirques at the foot of steep rock walls surviving because of the strong local topoclimatic controls.
6. Styllas focused also on Greece, namely on Mt Olimpos. Here, he investigated the occurrence of glaciers in this mountain area using surface exposure dates on glacial features. He detected three phases with evidence of glacial activity in the highest cirques, namely occurring at 9.6 ± 1.1 , 2.5 ± 0.3 and 0.64 ± 0.1 ka, the last of which corresponding to the LIA cold phase.
7. Gachev reviewed the existing chronological data on Holocene glaciations in Bulgaria. He concluded that glaciers only existed during the Holocene in the two highest mountains: Rila and Pirin. The author examines the spatial extent of glacierets and snow patches and their recent evolution over the last decades.
8. Altınay et al. examined the spatial and temporal extent of Late-Glacial and Holocene glaciers in Turkey. They reviewed five mountain areas where Holocene glacial chronologies were available in earlier studies. They re-

calculated the published cosmogenic ages using up-to-date production rates and scaling schemas. All these glacial chronologies are located in the western and central Taurus Mountain Ranges and in central Anatolia. The timing of the glaciations has been established mainly by cosmogenic ^{36}Cl surface exposure dating.

9. Bayrakdar et al. focused on Mount Akdağ, SE Turkey, where extensive glaciers formed on what is a relatively low-lying mountain compared to other glaciated areas in Turkey. This is significant because it shows that significant moisture supply sustained these glaciers in the Late Pleistocene, near the southern coast of Turkey.
10. Azzoni et al. presented the most recent Turkish glacier inventory based on up-to-date high-resolution satellite images. They identified 51 ice bodies covering a total area of 12.29 km². Recent Turkish glaciation is characterized by an ice-cap (i.e., Mount Ararat ice cap), many small glaciers or glacierets distributed around the eastern Anatolia. Turkish glaciers are in retreating phase. For instance, Mount Ararat ice cap was digitized for the years of 1990, 1994, 2000 and 2016, and it has been shown that it lost 29% of its initial surface area. Their results are showing a reduction rate dramatically higher than the main glacierized mountain ranges of the world.
11. Hughes et al. provided new insights into the presence of late-lying snow in the High Atlas where there is also evidence of potential niche glaciers in the Little Ice Age. The disappearance of many perennial snow patches in the last few decades coincides with a strong trend towards warmer summer air temperatures since the 1970s (> 2 °C).
12. These papers provide a state-of-the-art update of recent glacier history in the Mediterranean mountains. The state of the cryosphere through the Holocene in the mountains of this region is especially important for human populations, which have prospered and developed societies throughout the Mediterranean region over this period from the societies of ancient Greece and Rome, which spanned the Mediterranean lands, to the historical times and the present. Water resources associated with the seasonal melt of snow and glaciers is vitally important in a region characterised by strong seasonality with cool wet winters yet hot and dry summers (Köppen 1936; Geiger 1954). The replenishment of groundwater and river flow in the lowlands by snow and ice melt in the mountains (García-Ruiz et al. 2011) is arguably a key influence on the sustenance and development of human society in a region characterised by one of the richest archaeological and historical legacies on Earth. Thus, Holocene glaciers in the Mediterranean region are not just of geomorphological and climato-

logical interest, but also of direct relevance to human society.

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