The glacial history of Greece: a comprehensive review

A. D. Leontaritis[1] · K. Kouli[2] · K. Pavlopoulos[1,3]

Abstract

This paper reviews the glacial history of the mountains of Greece at the southernmost tip of the Balkans, providing a new synthesis of our current understanding of glaciations. The ice cover during the largest Middle Pleistocene glaciations (MIS 12/MIS 6) was more extensive than previously thought. Latest evidence from Mt Chelmos suggests that valley glaciers radiated from a central plateau ice field, whereas the findings of other glacial studies in western Balkans further indicate that extensive ice field/ice caps formed on mountains throughout this region during the Middle Pleistocene glaciations. Ice extent was considerably smaller during the Tymphian Stage (MIS 5d–MIS 2) and this has been confirmed by cosmogenic exposure ages in recent studies on Mt Olympus and Mt Chelmos. During the Holocene, only very small glaciers formed in some deep cirques where they survived because of strong local topoclimatic controls. A comparative analysis with the findings of other glacial and palaeoclimatic studies in the Balkans is also presented to highlight correlations between them. Moisture supply seems to have been the most critical factor for the formation of glaciers in the mountains of Greece. The comparison of Late Pleistocene Equilibrium Line Altitudes (ELAs) across the Balkans indicates a wetter climate in southern Greece that can be attributed to different palaeoatmospheric circulation mechanisms and precipitation regime in central Mediterranean. Conclusively, whilst important information has been added in the last 2 decades, this paper highlights the need for further research in Greece and the wider Balkans to establish the timing and extent of glaciations.

Keywords Glacial history · Glacial geomorphology · Pleistocene · Greece · Mediterranean · Balkans

Introduction

Mainland Greece is highly mountainous with 42% of its surface characterized as mountainous (Bassiouka 2011). Its topography is dominated by the Pindus mountain range that extends from NNW to SSE (Fig. 1). The mountains of Greece represent part of the Alpine–Himalayan orogenic system that formed due to the collision between the African and Eurasian plates (King et al. 1997; Jolivet and Faccenna

2000; van Hinsbergen et al. 2009). Its main peaks exceed 2200 m a.s.l. and countless minor peaks exceed 1800 m a.s.l.

Evidence of former glaciation episodes is abundant throughout the mountains of Greece (Fig. 1; Table 1) and was first identified by pioneer researchers/geographers at the beginning of the twentieth century such as Niculescu (1915), Cvijic (1917), Sestini (1933), Mistardis (1937a), and Messerli (1967). It has been argued that glacial evidence is confined only on the higher parts of mountains that exceed 2200 m a.s.l. (Woodward and Hughes 2011; Boenzi and Palmentola 1997). However, even though the Geological Sheets of the Greek Institute for Geological and Mineral Exploration (IGME) often misinterpret glacial deposits, in reality, evidence suggests that some mountains even below 2000 m a.s.l. have been quite extensively glaciated in the past (Pavlopoulos et al. 2018).

These glacial environments, similarly to other mountains in the Mediterranean during glacial episodes, are dynamic landscape systems that are highly responsive to regional or local climate variability, and due to their geographical position in the mid-latitudes, they are very important

✉ A. D. Leontaritis
   aleod@hua.gr

1 Department of Geography, Harokopio University, 70 El. Venizelou str. 17671, Athens, Greece

2 Department of Historical Geology and Palaeontology, Faculty of Geology and Geoenvironment, National and Kapodistrian University of Athens, University Campus, Zografou, Athens, Greece

3 Sorbonne University Abu Dhabi, P.O. 38044, Abu Dhabi, United Arab Emirates
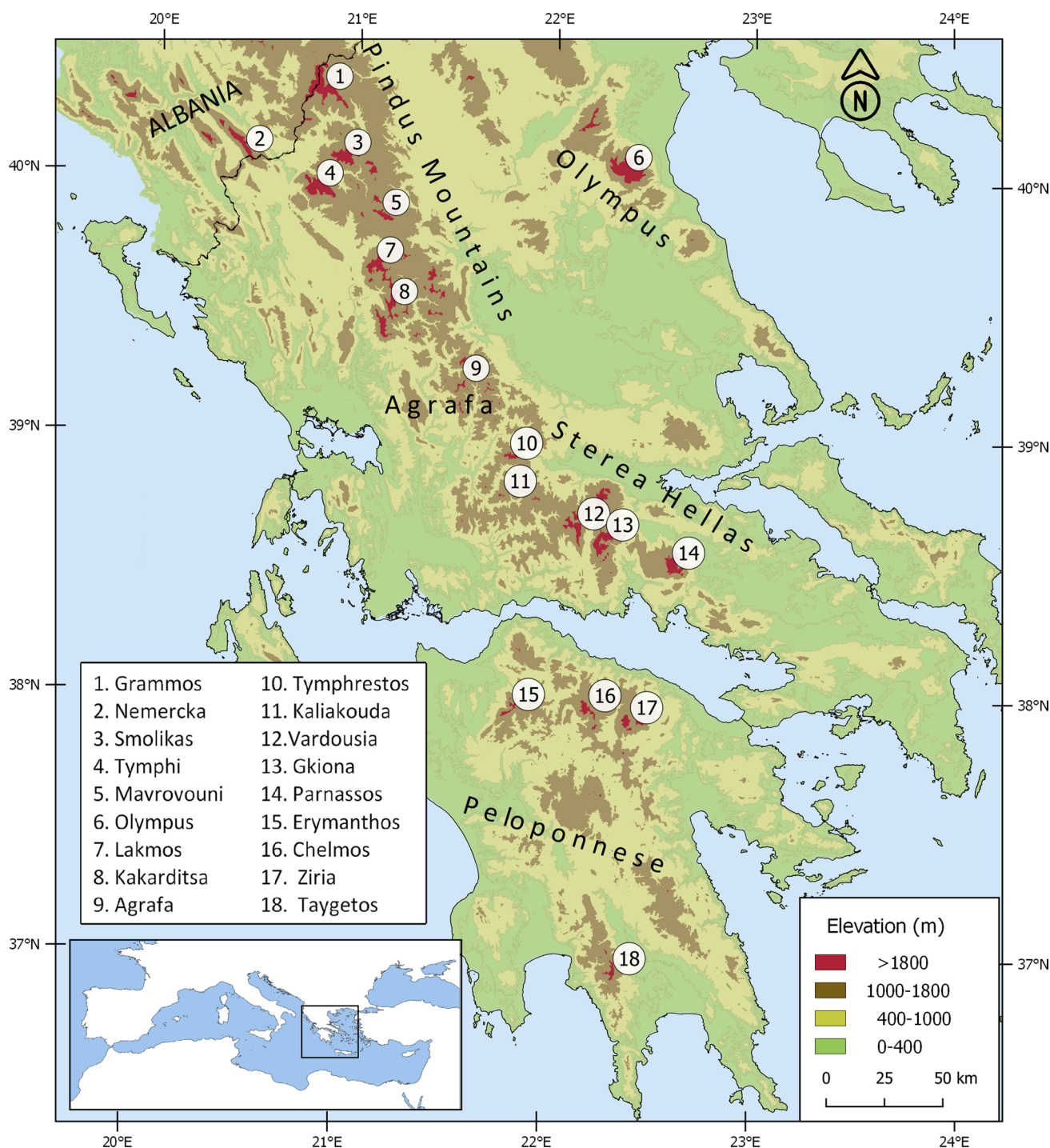
Fig. 1 Mountains of Greece. Numbered mountains are those with identified glacial evidence. See Table 1 for references

for palaeoclimate research (Oliva et al. 2019; Hughes and Woodward 2017; Tzedakis et al. 2004; Regato and Salman 2008; Woodward 2009; Vogiatzakis 2012).

In particular, palaeoglaciological reconstructions can be used to infer the climate of the past based on the fact that glaciers respond to changes in air temperature and moisture supply by adjusting their mass balance, with a consequent advance or retreat of the glacier's front (Oerlemans 2005). This mass balance can be quantified with empirical equations that link temperature and precipitation at the equilibrium line altitude (ELA) like the one proposed by Ohmura and Boettcher (2018). The glacial record can thus be

Table 1 References table for the glaciated mountains shown in Fig. 1

Massif	References	Massif	References
1. Grammos	Bourcart (1922); Louis (1926)	2. Nemercka	Louis (1926)
3. Smolikas	Niculescu (1915); Mistardis (1937a); Boenzi et al. (1992); Hughes (2004); Hughes et al. (2006c)	4. Tymphi	Mistardis (1935); Palmentola et al. (1990); Smith et al. (1998); Woodward et al. (2004); Hughes et al. (2006a)
5. Mavrovouni	Leontaritis et al. (unpublished data)	6. Olympus	(Cvijić (1917); Wiche (1956) Messerli (1967); Faugeres (1969); Smith et al. (1997); Manz (1998) Styllas et al. (2016, 2018)
7. Lakmos	Sestini (1933)	8. Kakarditsa	Sestini (1933)
9. Agrafa	Hunt and Sugden (1964)	10. Tymphrestos	Klebelsberg (1932)
11. Kaliakouda	Mistardis (1937a)	12. Vardousia	Maull (1921); Mistardis (1937a)
13. Gkiona	Mistardis (1937a); Pechoux (1970)	14. Parnassos	Renz (1910); Maull (1921) Mistardis (1937a); Pechoux (1970)
15. Erymanthos	Mistardis (1937a)	16. Chelmos	Philipson (1892); Maull (1921) Mistardis (1937a, 1937b, 1937c, 1946); Mastronuzzi et al. (1994); Pope et al. (2017); Pavlopoulos et al. (2018)
17. Ziria	(Pope et al. 2017)	18. Taygetos	Maull (1921); Mistardis (1937a) Mastronuzzi et al. (1994); Pope (2010); Kleman et al. (2016)

Fig. 2 Major regional palaeoclimatic and palaeoenvironmental proxies in relation to best dated glaciated mountains in Greece
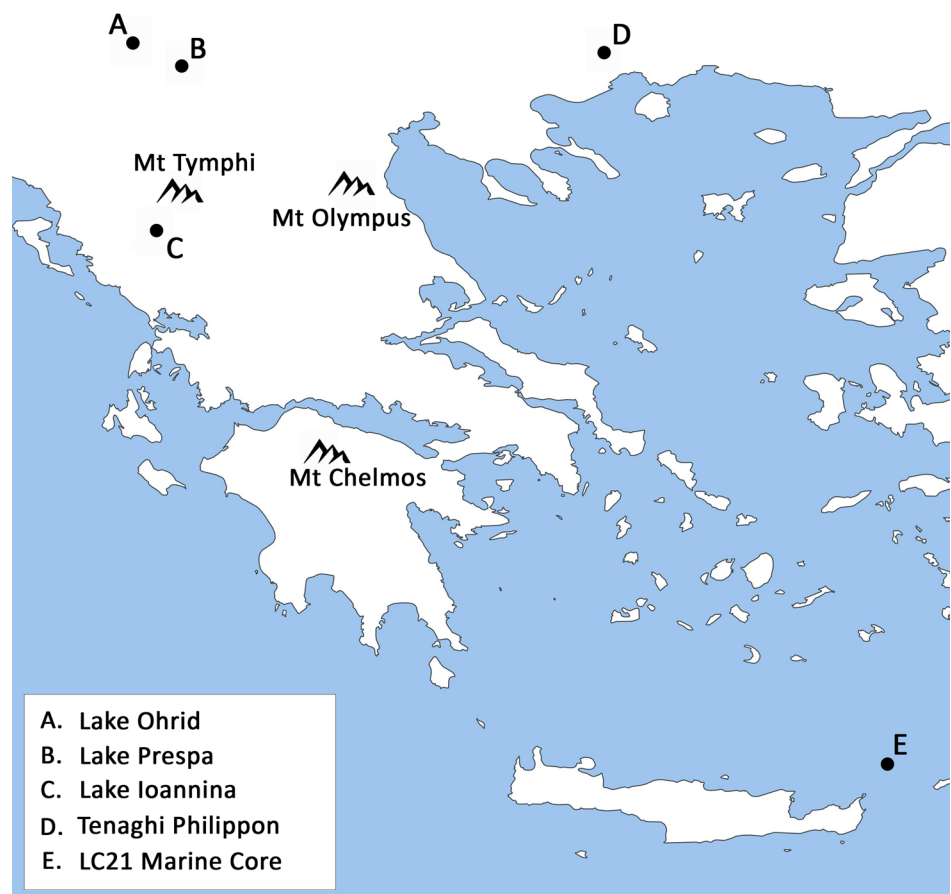
compared with modern climate data to generate information on the nature of winter moisture supply and summer temperatures during Pleistocene cold stages (Hughes and Woodward 2017). These data usefully complement the rich body of proxy climate data that has been retrieved from other Mediterranean archives, including lacustrine sediments,

speleothems, and the marine sedimentary record (Woodward 2009). Overall, the chronology and reconstruction of palaeoglaciers can provide a regional perspective on how and when glaciers responded to past climate oscillations across the Mediterranean, and how hemispherical/regional climate changes were modulated at the regional to local scale in terms of air temperature and precipitation.

As regards precipitation and palaeoatmospheric circulation patterns across the central-eastern Mediterranean, the underlying mechanisms of change and their persistence are poorly elucidated (Kuhlemann et al. 2008). Thus, a proxy record that covers multiple glacial–interglacial cycles and is sensitive to changes in the Mediterranean hydroclimate is key to addressing long-standing questions regarding the underlying mechanisms, such as timing and amplitude of precipitation variability under different climate boundary conditions (Wagner et al. 2019).

The glacial records of the Balkans, and Greece in particular, could prove very useful in answering these questions; both due to their geographical position and the availability of numerous well-dated proxies in the region (Fig. 2), such as the LC21 marine sediment core from the Aegean Sea (Grant et al. 2012) and the lacustrine pollen records from Tenaghi Philippon (Wulf et al. 2018), Lake Ioannina (Tzedakis et al. 2002), Lake Ohrid (Sadori et al. 2016; Wagner et al. 2019), and Lake Prespa (Panagiotopoulos et al. 2014). For example, changes in the regime of westerly atmospheric depressions generated both in the North Atlantic and in central Mediterranean along with southward outbreaks of the polar front (Florineth and Schlüchter 2000; Lionello et al. 2006; Kuhlemann et al. 2008) and the consequent southerly track of atmospheric depressions through the Mediterranean (Florineth and Schlüchter 2000; Luetscher et al. 2015; Oliva et al. 2019) could have affected glacier viability on the mountains of Greece. At the same time, these changes would also be recorded in the proxy records.

The glacial sequence in northwest Greece (Mount Tymphi) is one of the first mountainous areas in the Mediterranean where the full progression from pioneer to advanced glacial research phases has taken place and is very well dated (Woodward et al. 2004; Hughes et al. 2006a, b; Woodward and Hughes 2011). In recent years, new dating evidence has been published from southern Greece (Mt Chelmos in the Peloponnese—Pope et al. 2017; Pavlopoulos et al. 2018) and from Mt Olympus in the northeast (Styllas et al. 2018) providing a robust chronostratigraphical framework for the mountains of Greece (Fig. 1). This paper will, therefore, review in detail the glacial records from these areas with the aim to provide an insightful synthesis of our current understanding of glaciations in the mountains of Greece. Moreover, a comparison with the glacial chronology of other mountains in the Mediterranean as well as with other palaeoclimatic records will be attempted to highlight possible

correlations and the significance of these records in a wider palaeoclimatic perspective.

Review of the glacial geomorphologic studies in Greece

The Pindus Range in northwest Greece

The extensive glacial landforms and sediments in the mountains of northern Greece attracted the attention of the first pioneer explorers. In the northernmost part of Epirus, on the Greek-Albanian borders, cirques and moraines have been described on the mainly ophiolitic Mt Grammos (2520 m a.s.l.) (Bourcart 1922; Louis 1926). Further south, with ophiolites and flysch still dominating local lithology, stands Mt Smolikas (2637 m a.s.l.) the second highest mountain of Greece after Mt Olympus (2918 m a.s.l.). Its glacial geomorphology was first identified by Niculescu (1915) and Mistardis (1937a), while the first detailed geomorphological mapping was conducted by Boenzi et al. (1992).

Some 15 km to the south lies the impressive Mt Tymphi (2497 m a.s.l.—limestone) with probably the most extensive and well-preserved glacial deposits in Greece (Mistardis 1937a; Woodward and Hughes 2011). Mistardis (1935) was the first to report glacial evidence on Mt Tymphi, while detailed geomorphological mapping was first conducted by Palmentola et al. (1990) and later on by Smith et al. (1998) who used satellite imagery to map the extent of glacial deposits. Just 20 km to the west, on the borders with Albania, impressive glacial cirques and moraines were also observed by Louis (1926) on Mt Nemercka (2482 m a.s.l.— limestone). On the ophiolitic Mt Mavrovouni (2157 m a.s.l.), about 15 km in the south-east of Mt Tymphi, a complete glacial sequence, has been recorded and dated by Leontaritis et al. (unpublished data). Finally, Sestini (1933) identified further south the traces of the extensive former glaciation of Mt Kakarditsa (2429 m a.s.l.—limestone) and Mt Lakmos (2295 m a.s.l.—limestone).

The first advanced study of the Pindus Mountains was the geomorphological study of Mt Tymphi and Mt Smolikas by Hughes (2006a, c; 2004) and Woodward et al. (2004), which was supported by geochronological control. This provides the chronostratigraphical framework for glaciations in Greece (Hughes et al. 2005). The studies on these mountains are, therefore, presented in detail next.
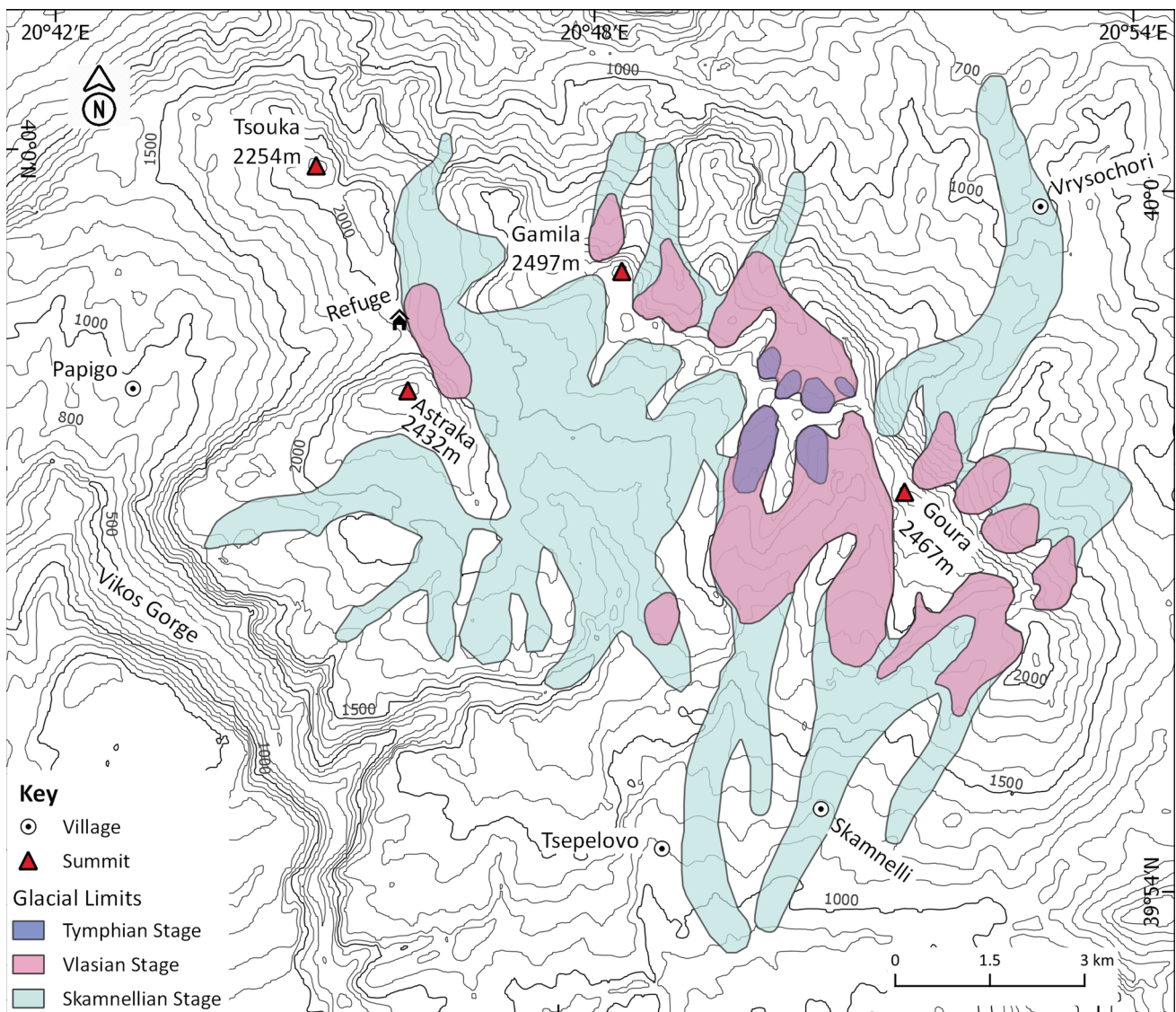
Mt Tymphi

Mt Tymphi is mainly formed of Palaeocene and Upper Eocene limestones. However, older Upper Jurassic/Senonian limestones and dolomites are also exposed on the cliffs of the northern escarpments of the highest peaks (Hughes and

Woodward 2017). Upper Eocene/Miocene flysch is generally restricted to the lower mountain slopes and was mostly situated outside the main areas of glacier erosion (IGME 1970). Combined glacial and karstic processes, on the other hand, have formed a classic glacio-karst system (Hughes et al. 2006e).

Numerous glacial and periglacial landscape features were recorded on Mount Tymphi including cirques, deep ice-scoured troughs, limestone bedrock pavements, rock glaciers, and extensive and well-preserved moraine complexes including lateral, terminal, and hummocky moraines. Sketch maps of the glacial geomorphology were published in Palmentola et al. (1990) and this pioneering work was then improved upon with more detailed mapping in Hughes (2004). An extensive dating program followed: secondary

calcites contained in the older and most extensive recorded glacial deposits were radiometrically dated by means of Uranium series, first by Woodward et al. (2004) then followed-up by Hughes (2004) and Hughes et al. (2006a). These data formed the basis for the definition of the glacial sequence on the Pindus Mountains (Hughes et al. 2005, 2006a). Correlating the results with cold-stage intervals recorded in the ca. 423 ka-long lacustrine pollen sequence at the nearby Lake Ioannina (Tzedakis 1994; Tzedakis et al. 2002), the glacial chronostratigraphy for the Pindus Mountains was defined. Three main glacial stages correlated with the marine isotope record have been identified (Hughes 2004; Hughes et al. 2005, 2006a):

Fig. 3 Glacial stages on Mt Tymphi (edited from Hughes et al. 2007)

- The Skamnellian Stage (MIS12; ca. 480–430 ka) equivalent to the Elsterian Stage of northern Europe.
- The Vlasian Stage (MIS 6; ca. 190–130 ka) equivalent to the late Saalian of northern Europe.
- The Tymphian Stage (MIS 5d–MIS 2; ca. 110–11.7 ka) equivalent to the Weichselian Stage of northern Europe.

These studies on Mt Tymphi provided abundant and clear evidence for extensive glacier formation during the first two Middle Pleistocene stages (MIS 12/MIS 6). As it can be seen in Fig. 3, extensive valley glaciers during the Skamnellian Stage extended down to altitudes of 850 m a.s.l. and 700 m a.s.l. on its southern and north/northeast slopes, respectively, with an average ELA of 1741 m a.s.l.. Aspect appears to have had insignificant effect on the overall distribution of the glaciers. Thus, factors such as shading and lee-slope accumulation also appear not to have been dominant controls on glacier development during these glaciations (Hughes et al. 2007). The moraines from this glaciation have deeply weathered soil profiles with profile development indices (PDIs) ranging from 51.8 to 61 (Hughes et al. 2006a). The PDIs were measured and scored following the methods of Harden (1982). In short, this index is used to quantitatively measure the degree of soil profile development taking as well into account its weathering degree. The higher the value of the PDI of the soil that covers the moraines is, the older the deposits are.

As the deposits from this glacial stage are traversed by mountain tracks and village roads around Tsepelovo, Skamnelli, and Vrysochori, good-quality exposures are commonly present in the lower altitude zone of the sediments. Such exposures in the tills show that the glacial sediments are dominated by limestone-derived sediments with a minor flysch component (Hughes et al. 2006e). They contain subrounded limestone boulders of a wide size range, cobbles, and gravels commonly dispersed in a fine-grained matrix rich in sands, silts, and clays (Woodward and Hughes 2011). Most interestingly, detailed sedimentological analyses of the diamicton sequences within these moraines, indicated that stacked diamicts separated by gravels related to melt out and glacial retreat record at least three phases of former glacial advance and retreat (Hughes et al. 2006e). Evidence of the later Vlasian Stage is confined to mid-valley positions (mean ELA 1862 m a.s.l.) with rather weathered soil profiles as the PDIs range from 29.8 to 38.3 (Hughes et al. 2006a).

As regards the Tymphian Stage—the last cold stage in Greece—the evidence implies a much more restricted glacier development. The youngest deposits formed in the highest cirques above 1800 m a.s.l. (mean ELA 2174 m a.s.l.; Hughes 2004) are well preserved, but are limited to rock glaciers and small moraines (Hughes et al. 2003). These deposits are well within the limits of the Vlasian

Stage deposits and show only very limited evidence of pedogenic weathering (PDIs of 7.8–9.0) (Hughes et al. 2006a). Therefore, they have been ascribed to the last cold stage, even though there are no radiometric or cosmogenic dating data (Hughes 2004; Hughes et al. 2006a, c). More marginal glacial conditions during these later cold stages appear to have forced glaciers to occupy locally-favourable topographic settings with northern and eastern aspects (Hughes et al. 2007).

Mt Smolikas

Mt Smolikas is the second tallest mountain of Greece at 2637 m a.s.l. and lies just 15 km to the north of Mt Tymphi. However, its ophiolitic geology means that it is less complex in form compared with neighbouring Mount Tymphi as it is a generally rounded mountain with fewer cirques and deep valleys cut in to it (Hughes 2004). Mt Smolikas is part of the Pindus ophiolite complex (Jones and Robertson 1997), part of a nappe which is tectonically overthrust onto the Eocene flysch of the Pindus Zone. Its ophiolites consist of serpentinites, harzburgites, and dunites which are traversed by pyroxinite and gabbro veins. Jurassic schists and limestones are also present locally, at the overthrust nappe of the ophiolitic complex (IGME 1987). Simple sketch maps of the glacial geomorphology of Smolikas were provided in the pioneering work of Boenzi et al. (1992) and this was followed up with more detailed mapping and sedimentological investigations in Hughes (2004).

Glacial geomorphological features are less well preserved than on Mt Tymphi and the glacial sequence in some cirque-valley systems is typically more fragmented (Hughes et al. 2006e). Evidence of a complete glacial sequence has been documented only on its northern slopes, while near its highest peaks well-developed cirques and glacial deposits within them have been recorded (Hughes et al. 2006d). Most importantly, four discrete phases of Pleistocene glacial activity are recorded on Mt Smolikas (Hughes et al. 2006c), implying that there is one more younger stage of glaciation here (Fig. 4; Table 2).

In particular, traces of vast glacier formation have so-far been documented only in the Vathylakkos valley on its northern slopes that has been correlated to the Skamnellian/Vlasian Stages (Hughes 2004; Hughes et al. 2006c). This deep ice-scoured valley is headed by typical glacial cirques near its tallest peaks (> 2600 m a.s.l.) and ends up in some thick diamicton deposits at an altitude of 1000 m a.s.l. near the village of Aghia Paraskevi (Fig. 4; Woodward and Hughes 2011). These deposits are traversed by a road revealing a 30 m-thick vertical section of ophiolite-derived unconsolidated sediments with a minor limestone component (Hughes et al. 2006e). A detailed sedimentological analysis of the diamicton sequences within these deposits revealed
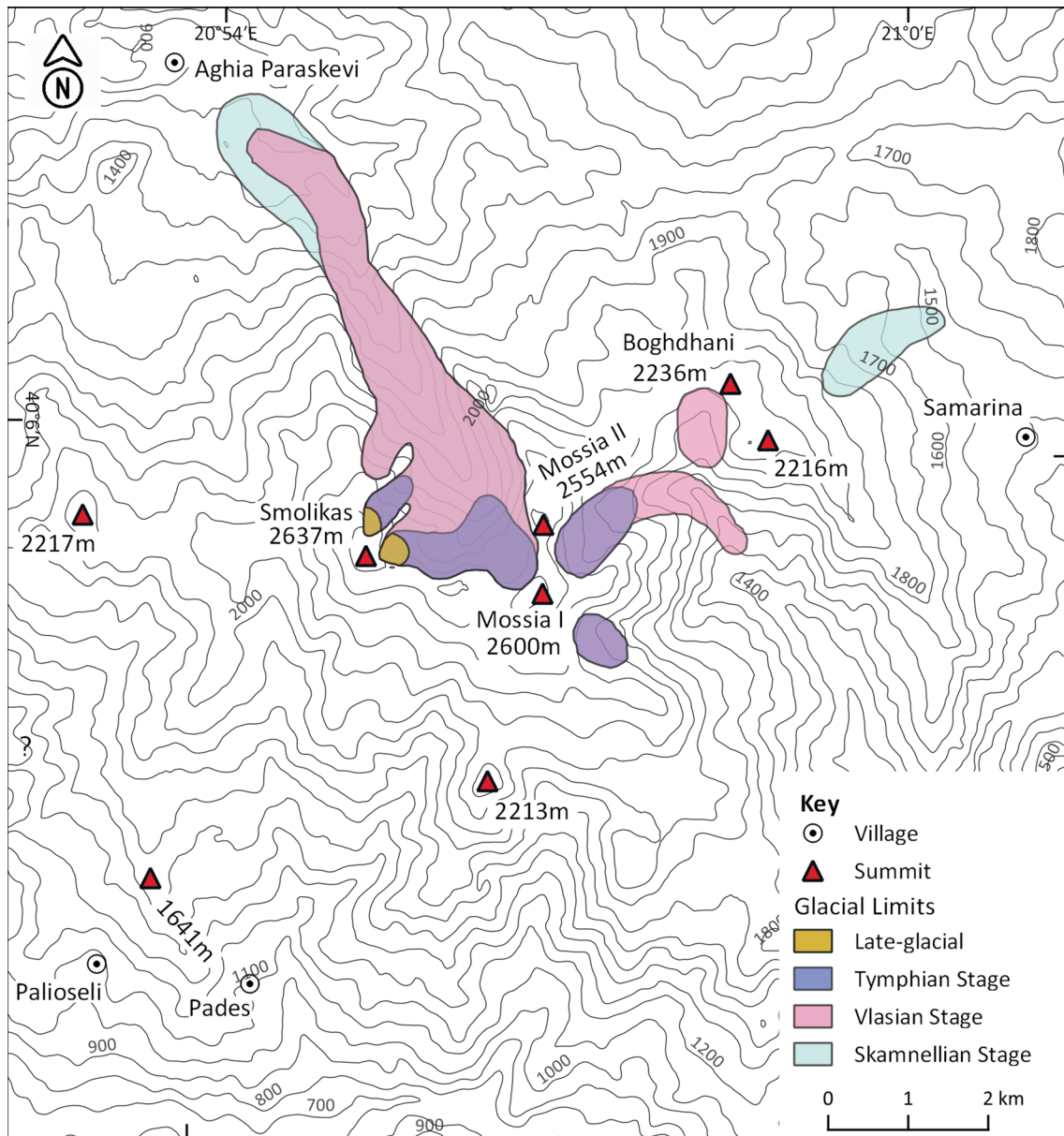
Fig. 4 Glacial stages and glacier extent on Mt Smolikas (edited from Hughes et al. 2007)

Table 2 Pleistocene glacial phases of Mt Smolikas

Phase	Age (correlations)	Orientation/mean ELA Altitude range of deposits
Late-glacial/Younger Dryas (Unit 4)	MIS 2; 12.9–11.7 ka	N/2372 m a.s.l 2300–2400 m a.s.l
Tymphian Stage (Unit 3)	MIS 5d–MIS 2; ca. 110–11.7 ka	N–NE/2241 m a.s.l 2000–2200 m a.s.l
Vlasian Stage (Unit 2)	MIS 6; ca. 190–130 ka	N/1997 m a.s.l 1100–1350 m a.s.l
Skamnellian Stage (Unit 1)	MIS12; ca. 480–430 ka	N/1680 m a.s.l 1000 m a.s.l

three stacked subglacial till facies separated by facies related to melt out. Moreover, the boundary between glaciotectonized units and undeformed original glacial deposits was considered as lithostratigraphical division between the different glacial units (Hughes et al. 2006e). Therefore, based on the stratigraphical sequence on Mt Tymphi, the lowest non-deformed unit (Unit 1—ELA 1680 m a.sl.) was ascribed by Hughes (2004) to the Skamnellian Stage (MIS 12), while the pair of glaciotectonized units deposited about 500 m up-valley (Unit 2—ELA 1997 m a.s.l.) were ascribed to at least two glacier advance/retreat cycles during the Vlasian Stage (MIS 6). The latter phase is also related with similar deposits that form clear ridges up-valley between 1100 and 1350 m a.s.l. (Hughes et al. 2006c). Elsewhere on Mt Smolikas, the glacial sequence is fragmentary due to the high erosion and numerous landslides of the ophiolitic bedrock. Therefore, stratigraphical correlation of low-to-mid-altitude deposits that could be Middle Pleistocene in age is difficult to establish. Moreover, it was originally assumed that there are no glacial erosional or depositional features on the southern slopes of Mt Smolikas (Hughes 2004; Hughes et al. 2006c). This was based on the lack of obvious cirques or troughs in topographic maps and the mapping of Hughes (2004, 2006c) generally agreed with the earlier observations of Boenzi et al. (1992).

The next two groups of moraines in the Vathylakkos valley (Fig. 4) occur at 2000–2150 m a.s.l. (Unit 3) and 2300–2400 m a.s.l. (Unit 4—mean ELA of 2372 m a.s.l.). These two suites of moraines are separated by hummocky moraines and perched boulders that were most probably deposited upon glacial retreat. Unit 3 deposits have been attributed to glacial activity during the Tymphian Stage (MIS 5d–MIS 2) and probably predate the LGM. Apart from the Vathylakos valley, glacier deposits within the N/NE cirques (2150–2200 m a.s.l.) below the summits of Mossia I & II (2600 m a.s.l. and 2554 m a.s.l., respectively) were also ascribed to stratigraphical Unit 3 based on their altitude and morphostratigraphical position (Hughes et al. 2006c). The mean ELA for Unit 3 glaciers was calculated at 2241 m a.s.l. by Hughes (2004).

Arguably, some of the most interesting features on Mt Smolikas are the high-altitude glacial deposits of stratigraphical Unit 4. These glacial landforms exceed in altitude the floors of the highest cirques on Mt Tymphi by 200 m and, therefore, could postdate the youngest moraines on Mount Tymphi (Tymphian Stage MIS 5d–MIS 2). It has been argued that they could have been formed after the local glacier maximum and the last cold stage—during the Late-glacial—and in particular that they might be Younger Dryas in age (Hughes 2004; Hughes et al. 2006c). This argument is well supported by more recent findings on Mt Olympus and Mt Chelmos (see next sections), but still needs to be confirmed by cosmogenic exposure dating. Historical satellite

imagery from late summer (September) appears to confirm that there are no permanent snowfields on Smolikas, unlike on Mount Olympus (Hughes 2018). Based on this evidence and snow melt modelling, Hughes (2018) argued that pronival ramparts that are present against the north-facing cliffs of Smolikas are also likely to be Late-glacial in age with no glacial or nival features dating to the Holocene. Again, this hypothesis requires further testing using cosmogenic exposure dating.

After these first advanced studies in northern Greece, the lack of further evidence from the last cold stage in Greece (MIS 5d–MIS 2; Hughes et al. 2006a) constituted an important gap in the glacial chronostratigraphy of the Pindus Mountains that led to further studies in Mt Olympus and the Peloponnese (see the next sections).

Mt Olympus (north Greece)

Mount Olympus is the highest mountain of Greece and the second highest of the Balkan peninsula reaching an elevation of 2918 m a.s.l. It is located in north Greece just 18 km west of the Aegean Sea shoreline and comprises a relatively small (surface area: 550 km^2) and isolated massif separated from adjacent lower mountains by shallow topographic depressions (Styllas et al. 2016). The lithology of the massif is characterized by a metamorphosed and deformed sequence of limestones of Triassic and Cretaceous-to-Eocene age, overlain by a late Eocene flysch, while high Pleistocene uplift rates up to 6 mm/year have been reported (Nance 2010). In the higher part of the mountain lies an extensive limestone plateau between 2200 and 2700 m a.s.l. surrounded by several peaks (Smith et al. 1997). Evidence of former glaciation is abundant: clearly shaped cirques and morainic deposits can be found at the head of its deep valleys both above and below the plateau. This glacial evidence was identified and reported in the first pioneering studies of the mountain (Cvijic 1917; Wiche 1956; Messerli 1967; Faugeres 1969).

The first detailed field mapping on Mount Olympus and the surrounding piedmont zone was carried out by Smith et al. (1997). In this study, they identified evidence of former extensive ice caps on the high-altitude plateaus of Mt Olympus as well as glacial deposits within a number of glacially scoured valleys headed by typical glacial cirques. Three discrete sedimentary packages (units 1–3) related to glacial activity in the uplands have been identified in the area—each capped by a distinctive soil. The lack of radiometric data directed Smith et al. (1997) towards a tentative correlation model for the timing of glacial phases based on the weathering of the soil profiles on those three sedimentary units. The quantification of weathering using pedogenic maturity indices allowed for the correlation with a poorly dated—for modern standards—sequence of alluvial sediments in the

nearby Larisa Basin by Demitrack (1986). The correlation of these sediments placed unit 1 before 200 ka (interpreted as deposition within MIS 8), and unit 2 within MIS 6. The sediments of unit 3, representing the last major glaciation of the massif which was restricted to valley heads, were placed within MIS4 to MIS2, (Smith et al. 1997). It should be noted that even though these ages are generally in agreement with the dated glacial deposits in other mountains, this archive cannot be considered reliable for regional correlation and comparisons due to both the poor chronological control of the Larisa Basin alluvial sequence and the difficulties of making valid comparisons of soil profile development when sites are located at different altitudes in contrasting geomorphological settings (Woodward and Hughes 2011). Therefore, this tentative model is not further considered in this paper.

The first radiometric data came soon after with the study of Manz (1998) that tried to improve the age control of the glacial deposits by dating boulder surfaces from the lower units using ^{36}Cl. This was one of the earliest attempts to apply cosmogenic exposure dating in the Mediterranean. The sampled boulders yielded ages ranging from 32 to 56 ka that appear to disagree with the findings from Northern Greece and Montenegro, which suggest that the most extensive glaciation phase took place during Middle Pleistone (Skamnellian Stage/MIS 12 and Vlasian Stage/MIS 6—Hughes et al. 2006a, 2010, 2011). However, the geomorphological context of the boulders sampled by Manz (1998) is unclear and similar ages have been found from moraines on Mount Chelmos where Pope et al. (2017) suggested that these deposits identify with a phase of glaciation belonging to MIS 3, within the Tymphian Stage but predating the global LGM. The absence of a reliable and internally consistent chronology for the Mount Olympus glacial record presented in these first studies limited its value as a basis for information retrieval in the palaeoclimatic context and prevented accurate correlations with the other sites (Woodward and Hughes 2011; Hughes and Woodward 2017; Pavlopoulos et al. 2018).

Interestingly, the most recent study of Styllas et al. (2018) on Mt Olympus brought up new evidence supporting several glaciation episodes during the Late-glacial and Holocene. In particular, a new chronology of glacial phases of Mt Olympus was proposed based on in situ produced ^{36}Cl cosmic ray exposure dating of moraine boulders. Samples were taken from boulders within two high-altitude cirques just below Olympus' highest peaks: the northeast facing and steeply inclined Throne of Zeus (TZ) cirque at 2580 m a.s.l. and the deeper, longer, and more enclosed northwest oriented Megala Kazania (MK) cirque at 2200 m a.s.l. (Fig. 5). Notably, the chronological order of the obtained ages is in good agreement with the stratigraphy of glacial landforms (Styllas et al. 2018).

A first phase (LG1) of glacial advance/stabilization is recorded in both cirques at 15.6 ± 2.0–14.2 ± 1.0 ka (recalculated timing). These glaciers started retreating by 14.09 ± 1.74 ka ago as dating of exposed bedrock within one of the dated moraines in the TZ cirque indicated. This phase tentatively correlates with the Oldest Dryas (17.5–14.7 ka; Rasmussen et al. 2006) and is characterized by cold and arid climate (Styllas et al. 2018). A set of clearly shaped moraines (MK-A) was mapped in the MK cirque below the LG-1 moraine complexes at an altitude of 2150 m a.s.l. and was ascribed to a glacial advance phase predating LG-1 and presumably near or before the LGM. Since this study was focused on the Late-glacial-to-Holocene glaciations, this moraine was not sampled. A second glacial phase (LG2) was attributed to 13.2 ± 2.0 ka–13.5 ± 2.3 ka, taking the mean of moraine boulders ages ranging from 14.6 to 12.5 ka. However, considering that taking a mean of scattered ages is not the best choice (Ivy-Ochs et al. 2007) and combined with the lack of any other evidence from palaeoclimate proxies or other glacial studies in the western Balkans for this period, this phase is not further considered in this paper. Instead, the respective boulder ages have been attributed to LG1 and LG3 phases (Table 3). The LG3 was characterized as a glacial retreat phase at 12.6 ± 1.6–12.0 ± 1.5 ka and is tentatively correlated to the Younger Dryas (12.9–11.7 ka; Rasmussen et al. 2014) under cold and dry climate conditions (Styllas et al. 2018).

As regards the Holocene, three distinct phases were recorded within the MK cirque. The first phase of glacial stagnation or re-advance is placed at 9.6 ± 1.2 ka (HOL1) which is strongly supported by identical ages of boulders coming from distinct moraines of the same stratigraphic order, while the second phase is placed at 2.6 ± 0.3–2.3 ± 0.3 ka (HOL2). Finally, the most recent glacier advance (HOL3) is dated to 0.64 ± 0.08 ka, at the beginning of the Little Ice Age, constrained by only one dated sample. However, glacier of snow/ice patch expansion would be expected during the Little Ice Age, since evidence for this has been identified at multiple sites further north in Montenegro (Hughes 2007, 2010).

It should be noted that due to the uncertainties in the cosmogenic exposure dating techniques that are related to the assumed production rates and the correction coefficients for erosion/snow cover, the age control of these glacial deposits is limited. Indicatively, for the reported ages of Styllas et al. (2018), the combined effect of the erosion/snow cover correction coefficients shifts backwards the raw calculated age of a sample by 8–15% whilst the analytical and production rate errors are within ± 10–15% of the final calculated age. Therefore, even though the above-mentioned glacial phases of Mt Olympus can be placed with confidence within the Late-glacial and the Holocene respectively, the reported ages should be viewed with caution and the precise timing of the
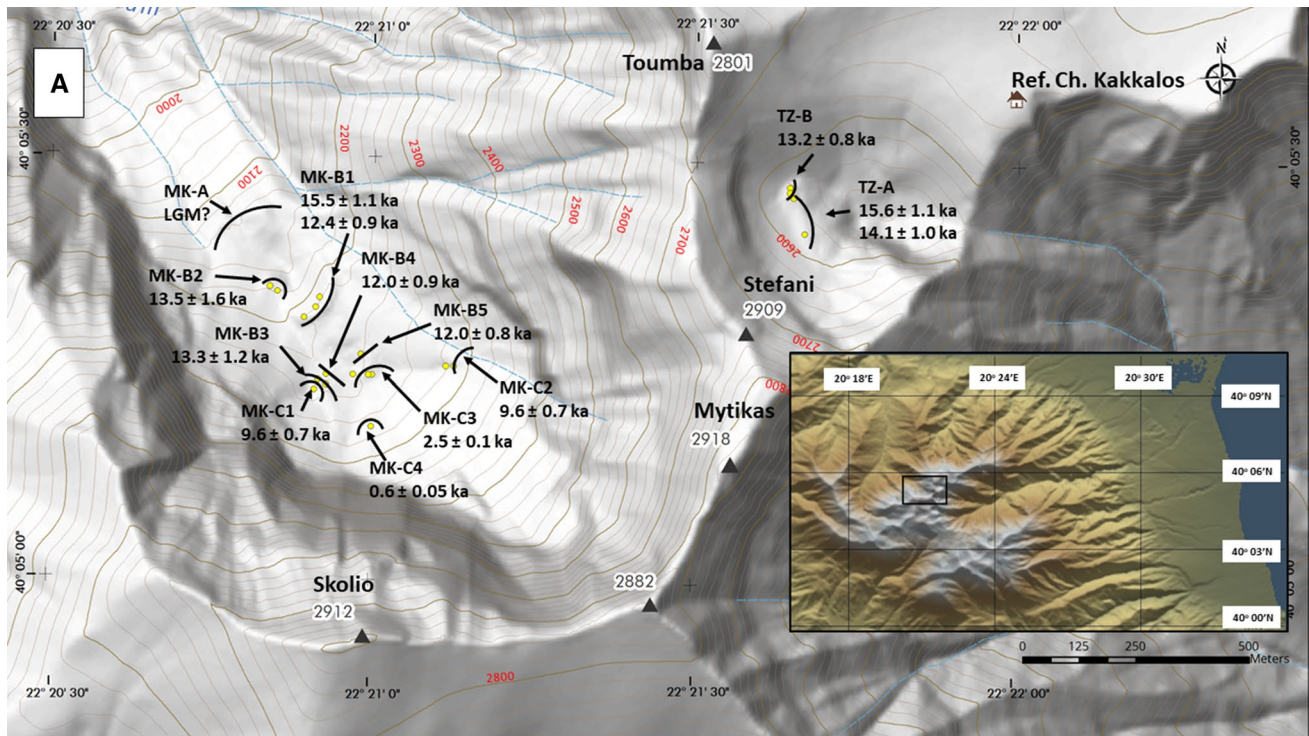
Fig. 5 Mean cosmogenic ^{36}Cl surface exposure ages of moraines in the Megala Kazania (MK) and Throne of Zeus (TZ) cirques on Mt Olympus (from Styllas et al. 2018)

glacier phases is likely to be subject to revision. The same is true of the earlier ages obtained by Manz (1998).

Peloponnese (south Greece) and the complex glaciations during the Tymphian Stage

The highest mountains in the Peloponnese (Fig. 1), Mt Taygetos (2407 m a.s.l.), Mt Chelmos (2355 m a.s.l.), Mt Ziria (2375 m a.s.l.), and Mt Erymanthos (2224 m a.s.l.), are dominated by limestone lithologies and hold abundant glacial evidence like cirques, glacial valleys, and moraines suggesting their multiple glaciation during the Quaternary.

Table 3 Late-glacial-to-Holocene glacial phases of Mt Olympus (adapted from Styllas et al. 2018)

Phase	Glacier behaviour	Age
Little Ice Age (HOL3)	Advance	0.64 ± 0.08 ka
Late Holocene (HOL2)	Advance	2.6 ± 0.3–2.3 ± 0.3 ka
Early Holocene (HOL1)	Stagnation/re-advance	9.6 ± 1.2 ka
Younger Dryas (LG3)	Retreat	12.6 ± 1.6–12.0 ± 1.5 ka
Oldest Dryas (LG1)	Advance/stabilization	15.6 ± 2.0–14.2 ± 1.0 ka

However, the geochronology and the palaeoclimatic context of this glacial evidence have been only partly explored so far (Pavlopoulos et al. 2018; Pope et al. 2017). In particular, Mt Chelmos is the only mountain of the Peloponnese that has to a certain extent been studied to an advanced level. The first pioneering studies on Mt Chelmos report cirques, moraines, perched boulders, and ice-moulded bedrock which are generally attributed to Quaternary glaciers (Philipson 1892; Maull 1921; Mistardis 1937a, b, c, 1946). Later on, Mastronuzzi et al. (1994) presented glacial features on Mt Chelmos that are attributed a Late Pleistocene age, although no ages were obtained. The first advanced studies on Mt Chelmos were conducted only years later by Pope et al. (2017) and Pavlopoulos et al. (2018).

Further south in the Peloponnese, glacial features are reported on Mt Taygetos by Maull (1921), Mistardis (1937a), Mastronuzzi et al. (1994), Pope (2010), and Kleman et al. (2016). On the eastern slopes of the massif, there is an impressive set of moraines and glacial boulders within a steep cirque at an altitude of only 1850 m a.s.l. (Fig. 6). Pope (2010) argued that glacial meltwater is likely to have been closely related to alluvial fan development in the Sparta fans situated downslope (Pope and Wilkinson, 2006). Even though in the study of Mastronuzzi et al. (1994), it is claimed that Chelmos and Taygetos are the only mountains in the Peloponnese where glacial traces can be recognized,

Mistardis (1937a) reports glacial cirques and moraines on Mt Erymanthos, while recent observations from Mt Ziria, just a few km to the east of Mt Chelmos, suggest that this massif has also been glaciated in the past (Pope et al. 2017).

Advanced studies on Mt Chelmos

Mt Chelmos rises to 2355 m a.s.l., at a distance of only 25 km from the coastline, reflecting the intense tectonic uplift rates that range from 0.3 mm/y in Corinth (Armijo et al. 1996) to 2.9–3.5 mm/year during the Holocene (Pirazzoli et al. 2004). Mt Chelmos is formed by a geological sequence of pelagic limestones and radiolarites of Mesozoic age, Upper Triassic–Upper Eocene carbonate formations, and Tertiary clastic sequences like flysch (Pope et al. 2017; Pavlopoulos et al. 2018).

The first advanced systematic study on Mt Chelmos was conducted by Pope et al. (2017), and included detailed geomorphologic mapping of glacial evidence and a dating program of the younger moraine deposits (Fig. 7; Table 4). The most extensive glacial phase along with its unequivocal glacial traces (Stratigraphical Unit 1) remains undated, but has been correlated with the Skamnellian/Vlasian Stages of northern Greece (MIS12/MIS6). This unit could represent more than one glaciation episodes, but it was not possible to distinguish multiple moraine units that correspond to both stages. During this glacial phase (Phase I), Mt Chelmos was glaciated by a plateau ice field with valley glaciers characterized by a mean ELA of 1967 m a.s.l. radiating out of it (Pope et al. 2017). Deposits from these glaciers were found down to 1180 m a.s.l. in the northeast, while Pavlopoulos et al. (2018) recorded heavily eroded diamicton deposits buried within the Lagadha alluvial fan at an altitude of 950 m a.s.l.

(Fig. 7). These non-stratified deposits could be interpreted as till deposited by a former thin and long glacier draining the central ice field, reaching similar altitudes with the respective Middle Pleistocene glaciers on Mt Tymphi.

The younger high-altitude moraines at the head of the valleys were formed during Late Pleistocene glacial phases by smaller valley and cirque glaciers. Glacial boulders from these moraines were dated using ^{36}Cl terrestrial cosmogenic nuclide exposure dating (Pope et al. 2017). The yielded ages suggest that these moraines are the result of glacier advance/stabilization during two phases in Late Pleistocene: Phase II at 39.9 ± 3.0–30.4 ± 2.2 ka (Stratigraphical Unit 2b—mean ELA 2046 m a.s.l.) characterized by cirque and valley glaciers and Phase III at 12.6 ± 0.9–10.2 ± 0.7 ka (Stratigraphical Unit 3) during which small glaciers were confined within the existing cirques.

At the global LGM, glaciers were present, but exposure ages of 22.9 ± 1.6–21.2 ± 1.6 ka from a suite of recessional moraines (Stratigraphical Unit 2c—mean ELA 2046 m a.s.l.) in the highest parts of the Epano Kambos valley in the central part of the massif are assumed to indicate glacier retreat at this time. This is consistent with evidence from Mt Tymphi in northern Greece of arid and cold climate conditions around the global LGM (Hughes et al. 2013). The ages from these moraines combined with the older ages from the Unit 2b moraines suggest that ice is likely to have occupied the cirques of Mount Chelmos from MIS 3 to 2 and oscillated in response to varying climatic conditions. The most recent phase of glaciation associated with Stratigraphical Unit 3 (mean ELA—2174 m a.s.l.) is recorded by clear cirque moraines that are present in the highest parts of some, though not all, of the glaciated valleys (see Fig. 9).

Fig. 6 Set of terminal moraines at Gouves (alt. 1850 m) on Mt Taygetos (Photo: Aris Leontaritis 2018)
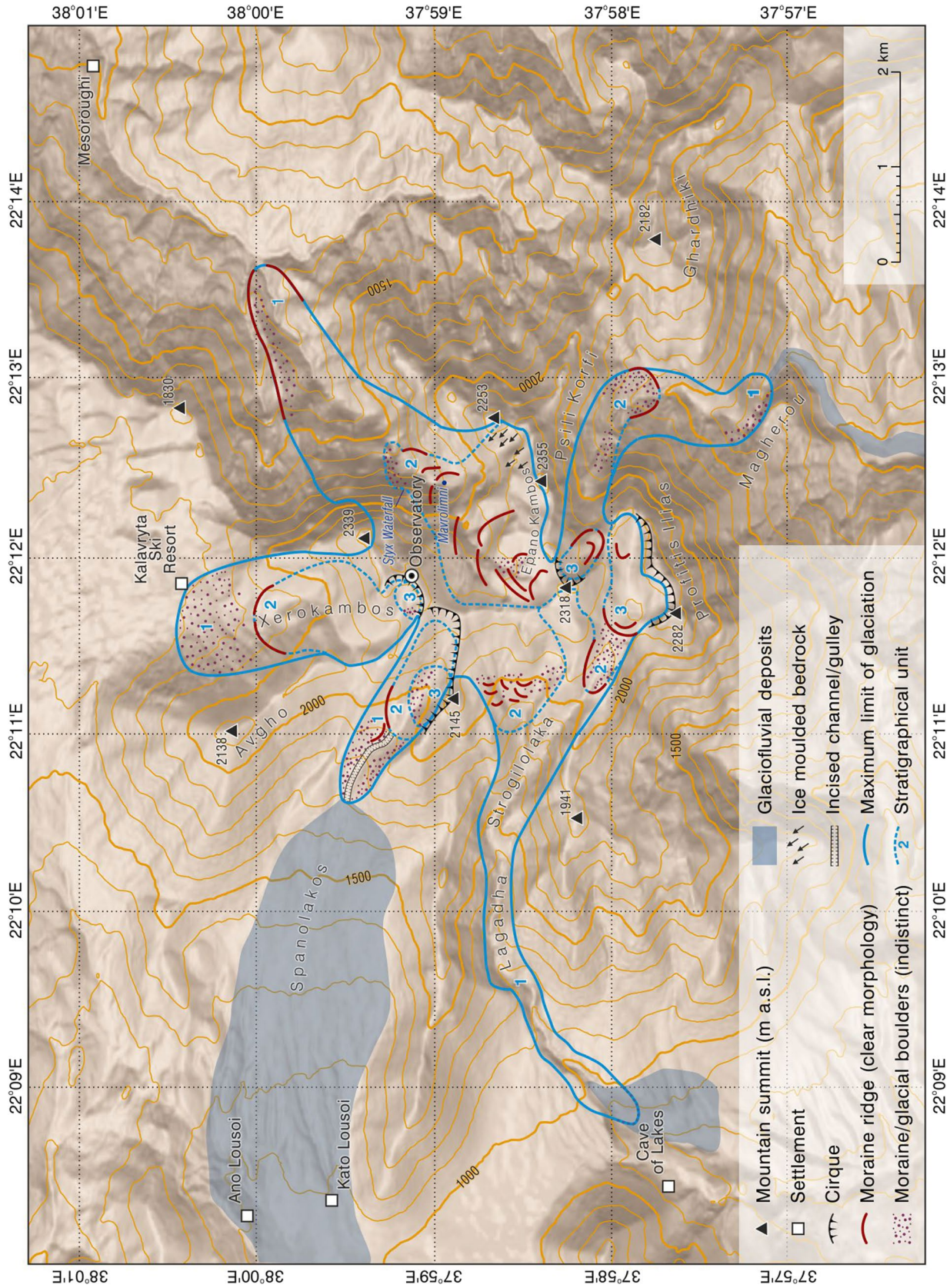
Fig. 7 Glacial geomorphological map of Mt Chelmos (modified from Pope et al. 2017). Some morphostratigraphical units are diachronous, like for example Unit 2 moraines that differ in age in different valleys (see Table 4)

Table 4 Glacial Stratigraphical units of Mt Chelmos (adapted from Pavlopoulos et al. 2018)

Stratigraphical unit	Altitude range mean ELA	Age ([1]OSL Dating, [2] 36Cl dating)	Glacial Stage (corresponding MIS)
3	2100 m a.s.l ELA–2174 m a.s.l	12.6 ± 0.9–10.2 ± 0.7 ka[2]	MIS 2–Younger Dryas
2c retreat phase	2200 m a.s.l ELA–2046 m a.s.l	22.9 ± 1.6–21.2 ± 1.6 ka[2]	MIS 2–Global LGM–Tymphian Stage
2b	1600–2100 m a.s.l ELA–2046 m a.s.l	39.9 ± 3.0–30.4 ± 2.2 ka[2]	MIS 3–Tymphian Stage
2a	1850–2050 m a.s.l n/a	89 ± 9–86 ± 7 ka[1]	MIS 5b–Tymphian Stage
1	950–1450 m a.s.l ELA–1967 m a.s.l	Correlation with Middle Pleistocene glacial phases	MIS 12–Skamnellian Stage MIS 6–Vlasian Stage

This last phase probably correlates with the Younger Dryas (12.9–11.7 ka; Rasmussen et al. 2014).

The latest study on Mt Chelmos by Pavlopoulos et al. (2018) provided further evidence from the dating of a ter-mino-lateral moraine in the Spanolakos valley using the OSL method (Fig. 7). This moraine had initially been correlated by Pope et al. (2017) with the Kato Kambos unit (Strati-graphical Unit 2b) on grounds of altitude and its formation had, therefore, been attributed to the glacial advance/sta-bilization phase at 40–30 ka. However, Pavlopoulos et al. (2018) argued that the OSL dating of fine-material samples from the lower external part of this moraine, yielding ages of 89 ± 9–86 ± 7 ka, which indicates that this could also rep-resent another glacier advance/stabilization phase (Unit 2a; Table 4) during the complex Tymphian Stage (MIS 5d–MIS 2).

It should be noted that the unit subdivisions marked in Fig. 7 are based on morphostratigraphical position of groups of moraines, and in some valleys, there are not enough ages to pin down exactly which moraines can be ascribed to strati-graphical units 2a, 2b, and 2c. However, the morphostratig-raphy is not always straight-forward, and in these units, subdivisions are likely to be revised as more ages become available. In any case, these two studies on Mt Chelmos have undoubtedly given new perspective to the nature of glacia-tions during the Tymphian Stage in the mountains of Greece.

Central Greece (the Mountains of Sterea Hellas and the Agrafa mountains)

Traces of former glaciers on the mountains of central Greece that are dominated by limestone lithologies were already identified by the first pioneer researchers in the beginning of the twentieth century. In Sterea Hellas just 70 km north of Mt Chelmos, traces of extensive glacial valleys and till as well as high-altitude well-preserved

Fig. 8 Frontal moraines and glacio-karst depression within a glacial cirque at 2250 m a.s.l. on Mt Parnassos, in central Greece (Photo: Aris Leontaritis 2019)

Fig. 9 Geomorphology of the Agrafa Mountains in the southern Pindus range bares numerous glacial and periglacial features like this characteristic glacially scoured U-shaped valley under the Hatzi peak (2038 m a.s.l.) with evident moraines and glacial sediments (Photo: Aris Leontaritis 2018)

moraines within numerous typical cirques were reported on Mt Parnassos (2457 m a.s.l.—Renz 1910; Maull 1921; Mistardis 1937a; Pechoux 1970) and Mt Vardousia (2495 m a.s.l.—Maull 1921; Mistardis 1937a) and to a lesser extent on Mt Gkiona (2504 m a.s.l.—Mistardis 1937a; Pechoux 1970) and Mt Tymphrestos (2312 m a.s.l.—Klebelsberg 1932). Indeed, the claim of former glacial evidence on these high mountains in the southern part of central Greece can easily be confirmed both on the field (e.g., Fig. 8) and on satellite imagery.

While it has been claimed that evidence of glaciation in Greece is present only in mountains that exceed 2200 m a.s.l. in altitude (Boenzi and Palmentola 1997), pioneering studies and recent field observations (Leontaritis, unpublished data) in the Agrafa Mountains (1900–2184 m a.s.l.—Hunt and Sugden 1964) and further south in Evritania (Mt Chelidona 1974 m a.s.l., Mt Kaliakouda 2099 m a.s.l.—Mistardis 1937a) show that the geographical and altitudinal extent of former glaciers in Greece has been underestimated (Fig. 9). While the glacial sedimentary records in the mountains of central Greece constitute a potentially important archive of former glacial episodes, it has not yet been studied. Moreover, the dating of the glacial landforms found in the above-mentioned mountains is of great importance for understanding the missing links between Northern Greece and the Peloponnese (Pavlopoulos et al. 2018).

The Glacial History of Greece: overview and discussion

The glacial phases in the mountains of Greece according to the so-far published studies are summarized in Table 5. It should be noted that due to the uncertainties in the cosmogenic exposure dating techniques, the age control of younger glacial deposits is to a certain extent limited. Therefore, even though certain glacial phases can be placed with confidence within the Late-glacial or Holocene, the reported ages should be viewed with caution and the precise timing of the glacier phases is likely to be subject to revision.

Middle Pleistocene glaciations (Skamnellian–Vlasian Stages)

Unlikely the Alps (Hughes et al. 2013) and eastern Mediterranean mountains (Turkey, Lebanon; Sarıkaya and Çiner 2017) where glaciers reached their maximum extent around the LGM, the most extensive Middle Pleistocene glacial phases in the mountains of Greece took place during MIS 12 (Skamnellian Stage) and MIS 6 (Vlasian Stage). This has been well established by radiometric data from Mt Tymfi in north-western Greece (Woodward et al. 2004; Hughes 2004; Hughes et al. 2006a). Later studies in the mountains of Montenegro and more specifically in the Orjen, Durmitor, Sinjajevina, and Moraća massifs confirmed that the largest glaciations there also date from the Middle Pleistocene (Hughes et al. 2010, 2011). Similar glacial deposits in terms of extent and altitude reach were also mapped in Mt Chelmos (Pope et al. 2017) and Mt Smolikas (Hughes 2004; Hughes et al. 2006c), and have been attributed to the

Table 5 Overview table of the glacial history of Greece

Glacial evidence on the mountains of Greece

Glacial stage	Geographical position	Dating data ELA	Marine isotope stage (age)	Type of evidence	Reference study
Holocene	Mt Olympus HOL3	^{36}Cl n/a	MIS 1 (0.64 ka)	Glacial boulder	Styllas et al. (2018)
	Mt Olympus HOL2	^{36}Cl n/a	MIS 1 (2.6–2.3 ka)	Moraines and glacial boulders	Styllas et al. (2018)
	Mt Olympus HOL1	^{36}Cl n/a	MIS 1 (9.6 ka)	Moraines and glacial boulders	Styllas et al. (2018)
Late-glacial	Mt Olympus LG2	^{36}Cl n/a	Younger Dryas (12.6–12.0 ka)	Retreat moraines and glacial boulders	Styllas et al. (2018)
	Mt Chelmos	^{36}Cl 2174 m	Younger Dryas (12.6–10.2 ka)	Moraines and glacial boulders	Pope et al. (2017)
	Mt Smolikas	n/a 2372 m	Younger Dryas (13–11 ka)	Moraines	Hughes et al. (2006c)
	Mt Olympus LG1	^{36}Cl >2300 m	Oldest Dryas (15.6–14.2 ka)	Moraines and glacial boulders	Styllas et al. (2018)
Tymphian Stage	Mt Chelmos	^{36}Cl 2046 m	MIS 2–LGM (23–21 ka)	Retreat moraines and glacial boulders	Pope et al. (2017)
	Mt Chelmos	^{36}Cl 2046 m	MIS 3–Local GM (40–30 ka)	Moraines and glacial boulders	Pope et al. (2017)
	Mt Olympus	n/a n/a	Pre-LGM	Moraine ridge	Styllas et al. (2018)
	Mt Chelmos	OSL n/a	MIS 5b (89–86 ka)	Moraine ridge	Pavlopoulos et al. (2018)
	Mt Tymphi	n/a 2174 m	MIS 5d–MIS 2 (111–11.5 ka)	Rock glaciers small moraines	Hughes et al. (2006a)
	Mt Smolikas	n/a 2241 m	MIS 5d–MIS 2 (111–11.5 ka)	Moraines	Hughes (2004)
Vlasian Stage	Mt Tymphi	U-series 1862 m	MIS6 (190–126 ka)	Moraines, till, secondary calcites	Hughes et al. (2006a)
	Mt Smolikas	n/a 1997 m		Moraines, till	Hughes (2004)
Skamnellian Stage	Mt Tymphi/N. Greece	U-series 1741 m	MIS 12 (480–430 ka)	Moraines, till secondary calcites	Hughes et al. (2006a) Present paper
	Mt Smolikas/N. Greece	n/a 1680 m		Moraines, till	Hughes (2004)
	Mt Chelmos/Peloponnese	n/a 1967 m		Moraines, till	Pope et al. (2017)

Middle Pleistocene, although without obtaining any radiometric dates. Interestingly, evidence of vast glacier formation is evident in numerous mountains higher than 1900 m a.s.l. throughout mainland Greece which can rather safely be ascribed to these Middle Pleistocene glacial phases. The evidence from Mt Chelmos implies that during the Skamnellian Stage, the massif was glaciated by a plateau ice field with valley glaciers radiating from a central ice dome. The same ice configuration is very likely to have occurred over Mt Tymphi in NW Greece as well as over the mountains of Montenegro (Hughes et al. 2010, 2011). However, the so-far published evidence from Mt Smolikas is controversial, since it suggests that only its northern slopes were glaciated during Middle Pleistocene (Hughes et al. 2006c), a fact that has been attributed to its ophiolitic lithology (Hughes et al. 2007). Moreover, there is still an open question regarding the extent of Middle Pleistocene glacial phases on Mt Olympus.

In the palaeovegetation/palaeoclimatic record from Tenaghi Philippon (Fig. 10), a close correspondence between abundances of tree populations and ice volume has been suggested, as the subsequent aridity and cooling of ice accumulation would lead to tree population reductions (Tzedakis et al. 2003). Based on the extremely low abundance of arboreal pollen (AP), MIS 12 is considered to be the most extreme climatic glacial interval of the last ~500 ka (Tzedakis et al. 2003), followed by MIS 6 and MIS 2. Pollen assemblages from Lake Ohrid in-between 487–424 ka BP evidence a two-step reduction of AP abundance, implying
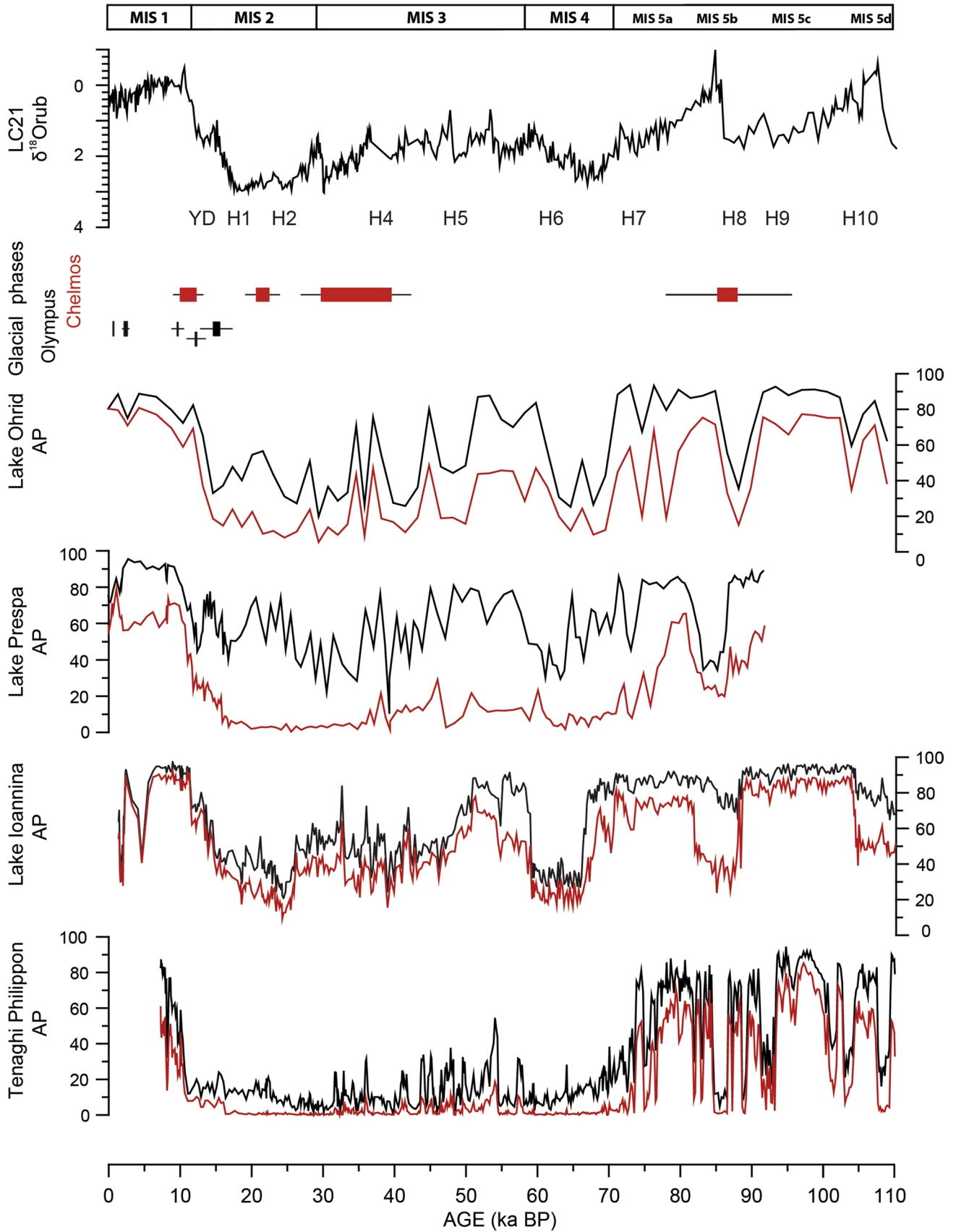
Fig. 10 Selected regional pollen records plotted against age (ka), in correlation to planktonic foraminiferal $\delta^{18}O$ in the LC21 marine sediment core from the Aegean Sea (Grant et al. 2012). Arboreal Pollen (AP) in black and AP excluding Pinus in red from: Tenaghi Philippon (data from Wulf et al. 2018), Lake Ioannina (AP excluding Pinus and Juniperus: Tzedakis et al. 2002), Lake Ohrid (Sadori et al. 2016; Wagner et al. 2019), and Lake Prespa (Panagiotopoulos et al. 2014). See Fig. 2 for location of sites

that the MIS 12 glacial phase has been cold but not very dry (Sadori et al. 2016). Similarly, during the long glacial phase corresponding to MIS 6, low AP abundances, but also interesting vegetation variability in the palaeo-archives of the southern Balkans is evidenced (Tzedakis et al. 2003; Roucoux et al. 2011; Sadori et al. 2016). Arboreal pollen abundance of the early part of MIS 6 in Lake Ioannina is high, in relation to the late part, and shows pronounced oscillations, implying cool and wet conditions (Roucoux et al. 2011). In Lake Ohrid, the second part of MIS 6 appears to be the driest phase of the last 500 ka (Sadori et al. 2016), while pollen-based palaeoclimatic reconstructions point to cold and dry conditions in the area (Sinopoli et al. 2019).

Recently, the analysis of the time proxy series of Lake Ohrid for the last 1.36 Ma and model data has shown that winter precipitation appears increased during periods of low Northern Hemisphere winter insolation due to orbital forcing on changes in precipitation variability (Wagner et al. 2019). Therefore, during periods like MIS 12 and MIS 6, favourable climatic conditions for the formation of glaciers must have prevailed. However, this correlation does not apply during colder and drier glacial periods with increased global ice volume (Wagner et al. 2019) such as the later parts of these two severe stages. The extensive MIS 12 and MIS 6 glaciers were, therefore, most probably formed during the early and relatively wet parts of these severe cold stages, as reduced precipitation during the later arid parts would have inhibited glacier build-up (Hughes et al. 2003). Hughes et al. (2006d) also argued that the maximum extent of glaciers during the Vlasian Stage (MIS6/190–130 ka) might have occurred in an interval of cold, yet more moist conditions, prior to limit of the pollen record of Lake Ioannina at 133 ka that indicates very arid climatic conditions at the end of MIS 6 (Tzedakis et al. 2002). This evidence underlines that winter precipitation is a crucial factor for the glaciers expansion as precipitation strongly controls the mass balance of glaciers (Ohmura et al. 1992).

Tymphian Stage glaciations (pre-LGM-to-LGM and Late-Glacial)

Much more restricted glacier development occurred during Late Pleistocene and in particular during the last glacial cycle and the Tymphian Stage (MIS 5d–MIS 2).

Early Tymphian Stage to the global Last Glacial Maximum (LGM; 27–23 ka)

Evidence for a possible glaciation phase in Mt Chelmos during the early Tymphian Stage was presented by Pavlopoulos et al. (2018). The OSL dating of samples from morainic deposits at an altitude of 1900–2050 m a.s.l. in the Spanolakos valley yielded burial ages of 89–86 ka that could indicate another phase in glacial evolution in the Peloponnese during MIS5b. This is the only glacial evidence in Greece and the Western Balkans for this period and further evidence is needed to test this further. The issue of glacial activity in the Mediterranean during the cold sub-stages of MIS 5 (5d and 5b) is an intriguing one (Woodward et al. 2004).

The study of Pope et al. (2017) on Mt Chelmos showed that at the global LGM (27–23 ka; Hughes and Gibbard 2015), glaciers were present but exposure ages of 23–21 ka from a suite of recessional moraines is assumed to indicate glacier retreat at this time, earlier than the retreat of Northern Hemisphere mountain glaciers at ~19 ka (Clark et al. 2009). This is in consistence with evidence from Mt Tymphi where the presence of small glaciers during the Tymphian Stage at high altitudes combined with many rock glaciers has been interpreted as the result of arid and cold climate conditions around the global LGM (Hughes et al. 2003). Kuhlemann et al. (2013) have also argued that arid climatic conditions in Western Balkans prevailed during the LGM. However, it is possible that the rock glaciers of Greece date to the Late-glacial, and this was advocated by Palmentola and Stamatopoulos (2006). Interestingly though, in the same study of Pope et al. (2017), a limited glacial advance phase was dated at 40–30 ka, implying that ice is likely to have occupied the cirques of Mount Chelmos from MIS 3 to 2 and oscillated in response to varying climatic conditions, especially in response to millennial-scale shifts between cold/dry and cool/wet conditions in Greece (see discussion in Hughes et al. 2006d). The shift of this local glacier maximum on Mt Chelmos prior to the global LGM, is in accordance with evidence from the other mountains across the Mediterranean like northern Spain (Serrano et al. 2012a, b; Oliva et al. 2019), the Italian Apennines (Giraudi and Frezzotti 1997), and Turkey (Sarıkaya et al. 2014). Interestingly, cosmogenic dates from the western and central Taurus Range in Turkey suggest similar pre-LGM glacier advance phases: at 35 ± 2.5–28.1 ± 2.6 ka (^{36}Cl) on Mt Akdağ (Sarıkaya et al. 2014) at 46.0 ± 7–29.8 ± 2.3 ka (^{36}Cl) on Mount Bolkar (Çiner and Sarıkaya 2017) and at 29.7 ± 2.9 ka (^{10}Be, ^{26}Al) on the nearby Dedegöl Mountains (Köse et al. 2019).

Similarly, the geomorphological studies on Mt Smolikas (Hughes et al. 2006c) and Mt Olympus (Styllas et al. 2018) suggest that well-formed moraines (Stratigraphical Unit 3 at 2000–2200 m a.s.l. on Smolikas; moraine MK-A at 2150 m a.s.l. on Olympus) can be ascribed to a glacial advance phase

before the LGM but lack any cosmogenic dating data. In any case at this point, it is not possible to compare the glacial evidence from Mt Chelmos with those from Mt Olympus and the Pindus mountains, as the glaciation sequence for the LGM and the local glacier maximum in northern Greece remains undated.

Examining the pollen records of the southern Balkan Peninsula, several abrupt vegetation successions indicating major changes in moisture availability and temperature correlated to the succession of Greenland cold events have been identified during the Early Last Glacial, corresponding to the later facies of the MIS 5 (Tzedakis 1999; Tzedakis et al. 2003; Panagiotopoulos et al. 2014; Milner et al. 2016; Sinopoli et al. 2018), while this vegetation pattern of rapid expansion and reduction of forest populations continues throughout the Last Glacial (Fig. 10). A scheme connecting the tree population abundance with climatic favourable conditions for glacier formation has been proposed by Hughes et al. (2006d) based on the pollen record of Lake Ioannina (Tzedakis et al. 2002).These intervals are characterized by large differences between total arboreal pollen frequencies and arboreal frequencies excluding the tolerant of cold conditions *Pinus* and *Juniperus* species, reflecting to moist yet cold conditions (Hughes et al. 2006d). Such intervals are recognized at 31–35 ka, 37–39 ka, and 83–88 ka. The former two periods could be correlated with a possible pre-LGM local Glacial Maximum while the latter with a glacial phase during the MIS5b stadial similarly to the respective glacial phases on Mt Chelmos (Table 5). The MIS 5b stadial is clearly recorded in the presented pollen records (Fig. 10) whereas the pre-LGM period shows considerable variability in AP abundances among the different sites.

Some further insights into the timing of Late Pleistocene glaciations were inferred from radiometric dates obtained from fluvial sediments deposited downstream of the glaciated headwaters of the Voidomatis catchment on Mt Tymphi which provide some constraint on the upstream glacial chronology (Hughes and Woodward, 2008). Hamlin et al. (2000) recognized at least four separate alluvial units. Secondary carbonates within three of them yielded maximum uranium-series ages of 113 ± 6 ka, 80 ± 7 ka, and 28.2 ± 7 ka–24.3 ± 2.0 ka (Lewin et al. 1991; Hamlin et al. 2000; Woodward et al. 2008) correlating with deposition during MIS 6, MIS 5b, and MIS 2 (closely to the LGM at 22-20 ka) respectively. The sand and silt matrix of these alluvial units is dominated by limestone-rich fines, which are derived from glacial erosion in the catchment headwaters (Lewin et al. 1991; Woodward et al. 1992, 1995). The uranium-series ages thus suggest that large glaciers and active moraine complexes were present in the headwaters of this river system during these periods (Woodward et al. 2004).

The Late-glacial (17.5–11.7 ka)

The late Tymphian stage was characterized by two cold periods that favoured glacial advance: the Oldest and the Younger Dryas at 17.5–14.7 ka (Rasmussen et al. 2006) and 12.9–11.7 ka (Rasmussen et al. 2014), respectively. These two cold periods have long been recognized to form the beginning and end of the Late-glacial interval and are recognized in the oxygen isotope record of Greenland cores and correlate with GS-2.1a and GS-1 stadials in the GRIP ice core (Björck et al. 1998; Rasmussen et al. 2006), while Oldest Dryas can also be correlated with Heinrich Event 1 (17.5–16 ka; Cacho et al. 1999; Bond et al. 1993).

In Greece, glacial deposits from the late Tymphian stage have so-far been dated only on Mt Chelmos and Mt Olympus at 2100 m a.s.l. and 2200 m a.s.l., respectively. In particular, a limited glacial advance phase has been dated on Mt Chelmos at 12.6–10.2 ka that can be correlated with Younger Dryas, whereas in Olympus, a similar advance/stabilization of glaciers has been ascribed to the Oldest Dryas (Phase LG1 at 15.6–14.2 ka). The morphological features of glacial deposits on Mt Olympus that were dated to Younger Dryas though suggest a glacial retreat phase and unfavourable conditions for glacial advance (Phase LG3 at 12.6–12.0 ka; Styllas et al. 2018). These findings further support the assumptions of Hughes et al. (2006c) that have correlated the high-altitude (2300–2400 m a.s.l.) glacial deposits mapped on Mt Smolikas (Hughes 2004) to the moraine complexes found above 2200 m a.s.l. in the Megala Kazania cirque in Mt Olympus, ascribing their formation to the Late-glacial. In any case, future work on Late Pleistocene glacial deposits in the mountains of northwest Greece focusing on the Tymphian Stage is clearly needed to compare the studies in the Peloponnese, Mt Olympus, and northwest Greece in an effort to compose a robust chronographical map of Late Pleistocene glaciation phases in Greece.

A number of studies in western Balkans provide further evidence for these Late-glacial phases. A similar glaciation to the LG1 glacial phase in Olympus occurred in Mt Pelister, situated immediately east of Lake Prespa in The Republic of North Macedonia, at 15.24 ± 0.85 ka (^{10}Be Ages; Ribolini et al. 2017) that can also be correlated with the Gschnitz stadial of the Alps (Ivy-Ochs et al. 2006) and the Fontari Stadial at 15 ka in the Italian Apennines (Giraudi and Frezzotti 1997). In the pollen record of Lake Prespa, this interval exhibits amplified AP frequencies, mainly as a result of the increase of *Pinus* (Panagiotopoulos et al. 2014), in contrast to Lakes Ioannina and Ohrid (Fig. 10), implying that local climatic conditions may have favoured the expansion of glaciers according to the scheme proposed by Hughes et al. (2006d) described above. Similarly, glacial advance has been dated to 17–14 ka in the south Carpathians (Retezat Mountains;

Reuther et al. 2007) and to 19–14 ka in the Rila Mountains in Bulgaria, although the latter has been interpreted as a late LGM phase (Kuhleman et al. 2013). In the Šara Range in Kosovo, two phases of glacial advance have been dated with [10]Be to 19–14 ka and 14–12 ka (Kuhlemann et al. 2009). As regards the former phase, the oldest age points to a moraine formation in the course of the LGM, whereas the others could potentially represent recessional moraines (Hughes et al. 2013). On the other hand, the younger, high-altitude moraines (2020–2300 m a.s.l.) were ascribed to the Younger Dryas (Kuhlemann et al. 2009). Evidence for Late-glacial glacier advance phases has also been identified in several mountains in Turkey (Sarıkaya and Çiner 2017).

The Younger Dryas phase is strongly supported by the cosmogenic [36]Cl ages from the Galicica Mountains between Lakes Ohrid and Prespa in The Republic of North Macedonia, where five limestone boulders from an end moraine were dated with [10]Be to 12.8–11.3 ka (Gromig et al. 2018). Minimum ages obtained by U-series dating of secondary calcite cements in moraines in the Orjen massif, Montenegro, show that valley glaciers had retreated from end moraine positions by 17 ka. U-series ages from secondary calcite cements in cirque moraines in the same valley though show that the last phase of glaciation occurred before 8–9 ka, probably during the Younger Dryas (Hughes et al. 2010). Similar findings have also been found in the Durmitor massif (Hughes and Woodward 2008, their Fig. 5; Hughes et al. 2011). Further northwest, in Bosnia and Herzegovina, Žebre et al. (2019) dated 20 moraine boulders that yielded ages spanning from Oldest Dryas in Velež Mountain (14.9 ± 1.1 ka) to Younger Dryas in Crvanj Mountain (11.9 ± 0.9 ka), while Çiner et al. (2019) report Younger Dryas (within error) ages from the Svinjača (13.2 ± 1.8 ka) and Glavice (13.5 ± 1.8 ka) areas. A Younger Dryas glacial advance phase is also consistent with evidence from the Italian Maritime Alps (Federici et al. 2012), the Italian Apennines (MT Aquila Stadial—Giraudi and Frezzotti 1997), and western Taurus range in Turkey (Sarıkaya and Çiner 2017).

Late Pleistocene pollen records

As regards Late Pleistocene in general [early Tymphian Stage to LGM and the Late-glacial, a close examination of arboreal pollen (AP) and AP excluding *Pinus* frequencies from existing archives], Fig. 10 shows that the duration and independent characteristics of vegetation patterns vary significantly implying differences connected with local microclimates, topography, and elevation. For example, the comparison of the Tenaghi Philippon record at low elevation (Müller et al. 2011; Milner et al. 2016; Wulf et al. 2018) with the intermediate to higher altitude ones of Lakes

Ioannina, Prespa, and Ohrid (Tzedakis et al. 2003; Panagiotopoulos et al. 2014; Sadori et al. 2016; Wagner et al. 2019) showcases the variability of trees response to Last Glacial climatic oscillations like the Heinrich events. Still, the palaeovegetation and palaeoclimatic records from Lake Ioannina, Lake Ohrid and Lake Prespa are in agreement with the onset of the recorded glacial episodes just before the threshold of AP percentages reduction. The catchments of these lakes include mountainous areas with significant glacial deposits like the Pindus Mountain ridge, Mt Pelister, and the Galicia Mountains, respectively, adding up into their value as independent palaeoarchieve for discussion. The diversification of the planktonic foraminiferal $\delta^{18}O$ palaeoclimatic records, in LC21 and the Arboreal Pollen (AP) excluding Pinus in Tenaghi Philippon can be attributed to both to the low altitude and to the fact that they are open systems and in direct correlation with the Aegean atmospheric and sea circulation. This particular climatic system influences the local climate by increasing precipitation and modifying the wind regime with prevailing southern winds. Unfortunately, such a high resolution and independently dated archive is not appealable yet in southern Greece in order be used as a comparison for Mt Chelmos, as Kopais record suffers several dating uncertainties (Tzedakis 1999). At the same time, no dating data from the mountains of northern Greece that could be correlated with the Ioannina, Prespa, and the Ohrid record are available for neither for the early Tymphian Stage and the LGM or the Late-glacial.

Holocene glaciations

As regards the Holocene, Mt Olympus is the only mountain to hold such evidence in Greece. Glacial deposits were recently dated by Styllas et al. (2018), suggesting three discrete phases of glacial advance. Local topography seems to have played a crucial role for the viability of these late glaciers as the deposits are found in a high-altitude cirque with NW aspect and high walls (up to 600 m) that provide extended shading, while windblown snow from the surrounding ridges (2900 m a.s.l.) is another factor that could have contributed in the formation of glaciers during climatically unfavourable conditions (Styllas et al. 2018).

The first phase of glacial stagnation or short re-advance is placed at 9.6 ka (HOL1) during a general early Holocene phase of warming and glacier retreat just before the onset of very humid and warm conditions in the north Aegean Sea (Styllas et al. 2018). The second Late Holocene phase (HOL2) of glacial advance at 2.6–2.3 ka under wet conditions and solar insolation minima is correlated with North Atlantic's Bond 2 event (Bond et al. 2001) and the Homeric solar Minimum (Wirth and Sessions 2016). The most recent glacier advance (HOL3) is dated to 0.64 ka, at the beginning

of the Little Ice Age. Whilst this is constrained by only one age, glacier or snow/ice patch expansion would be expected during the Little Ice Age, since evidence for this has been identified at multiple sites further north in Montenegro (Hughes 2007, 2010).

Unlike on Mount Olympus, historical satellite imagery from late summer appears to confirm that there are no permanent snowfields on Smolikas. Based on this evidence and snow melt modelling, it has been argued that on Mt Smolikas, there are no glacial or nival features dating to the Holocene.

ELAs, Palaeoatmospheric circulation, and precipitation patterns

The Skamnellian stage glaciers (MIS 12) had an average ELA of 1741 m a.s.l. on Mt Tymphi and 1680 m a.s.l. on Mt Smolikas in northwest Greece (Hughes 2004), whereas on Mt Chelmos in the Peloponnese, the largest Middle Pleistocene glaciation was characterized by ELAs of 1967 m a.sl. (Pope et al. 2017). This difference of 220–280 m is in consistence with a warmer and drier climate in the Peloponnese compared to northern Greece as these two locations are separated by more than 2° of latitude (Pope et al. 2017).

However, the ELAs for the Late Pleistocene glaciers show an interesting and somehow unexpected trend. As regards the pre-LGM to LGM period, the only available data from dated glacial deposits come from Mt Chelmos where the glaciers had an average ELA of 2046 m a.s.l. (Pope et al. 2017). Surprisingly, the glaciers that have been attributed to the same period in northern Greece based on the morphostratigraphy of the respective glacial deposits had a higher mean ELA of 2174 m a.s.l. and 2241 m a.s.l. on Mt Tymphi and Mt Smolikas, respectively (Hughes 2004).

As regards the Late-glacial, there is a similar trend from north to south: the assumed Younger Dryas glaciers on Mt Smolikas had an average ELA of 2372 m a.s.l. (Hughes 2004; no cosmogenic dating data and, therefore,, likely to be subject to revision), on Mt Olympus, the Late-glacial moraines had an ELA higher than 2300 m a.s.l. (the lowest moraines lying at 2250 m a.s.l. and the cirque walls at 2500 m a.s.l.; Styllas et al. 2018), while on Mt Chelmos, the Younger Dryas palaeoglaciers appear to have been considerably lower at 2174 m a.s.l. (Pope et al. 2017). Some 70 km north of Mt Smolikas, on Mt Pelister in The Republic of North Macedonia, Oldest Dryas glaciers had an ELA of 2250 m a.s.l. (Ribolini et al. 2017) which is still higher compared with Mt Chelmos, while in the Galicica mountains above the nearby Lake Ohrid in the Republic of North Macedonia, the Younger Dryas glaciers had a slightly lower ELA of 2130 m a.s.l. (Gromig et al. 2018).

It should be noted that it has been argued that Late-glacial glaciers were absent on Mt Tymphi (Hughes et al. 2006c),

but ongoing research might revise this assumption. As the morphostratigraphic correlations for Late Pleistocene glaciers in northern Greece are anyway tentative, it might be proved that the considered LGM glaciers of Mt Tymphi and Mt Smolikas are for example Late-glacial in age and similarly that the highest unit on Mt Smolikas is Holocene in age. In any case, even if the Late Pleistocene ELAs in northwest Greece (Mt Tymphi and Mt Smolikas) are considered in this comparison within a wider Late Pleistocene timing framework, the fact that the Peloponnese glaciers had similar or even lower ELAs than the glaciers in northwest Greece and the Republic of North Macedonia during the LGM and especially during the Late-Glacial can be explained by wetter conditions in the former.

Examining the precipitation map of Greece today (Fig. 11), it is evident that moisture supply is strongly associated with westerlies and hints at a west–east track of atmospheric depressions through the Mediterranean. The Pindus Mountains extend from the NW to the SE causing orographic precipitation to the westerly depressions and, as a result, rain shadow to eastern mainland Greece where Mt Olympus is located. If we accept that westerlies were the main moisture carrier during Late Pleistocene, then the higher ELA of Mt Olympus glaciers can be attributed to the drier climatic conditions related to the rain shadow caused by the Pindus mountain range. A good indication of the impact of westerlies on the western Balkans climate is the fact that the Pleistocene glaciers on Mt Orjen in Montenegro were c.500–600 m lower than in the Peloponnese and in The Republic of North Macedonia, a situation that could have been forced only by considerably higher precipitation in Montenegro that today exceeds 5000 mm per year (Gromig et al. 2018). However, as Mt Chelmos today receives less moisture than northwest Greece (Fig. 11) and given their latitude difference, the ELAs of its Late Pleistocene glaciers are plausible only if cold-stage depressions during this period had a more southerly track than today (Pope et al. 2017).

Further insights into the Late Pleistocene precipitation regime of this region can be inferred by palaeoatmospheric circulation patterns reconstruction for the Mediterranean basin based on the recent analysis of the time proxy series from Lake Ohrid for the last 1.36 Ma and model data by Wagner et al. (2019). More specifically, the reconstruction of the geographical expansion of geopotential height anomalies associated with precipitation maxima in Lake Ohrid (Fig. 12) showed pronounced troughs in the central Mediterranean area and an increase in rainfall during the winter half-year in western Balkans (Wagner et al. 2019), which is crucial for glaciers formation in this area. Enhanced winter precipitation in the Mediterranean mid-latitudes is a result of local cyclogenesis combined with the southward shift in the atmospheric circulation cells in the Northern

Fig. 11 Annual precipitation in Greece (source: Climatic Atlas of Greece—https://climatlas. hnms.gr). 1. Pindus Mountains, 2. Mt Olympus, and 3. Mt Chelmos
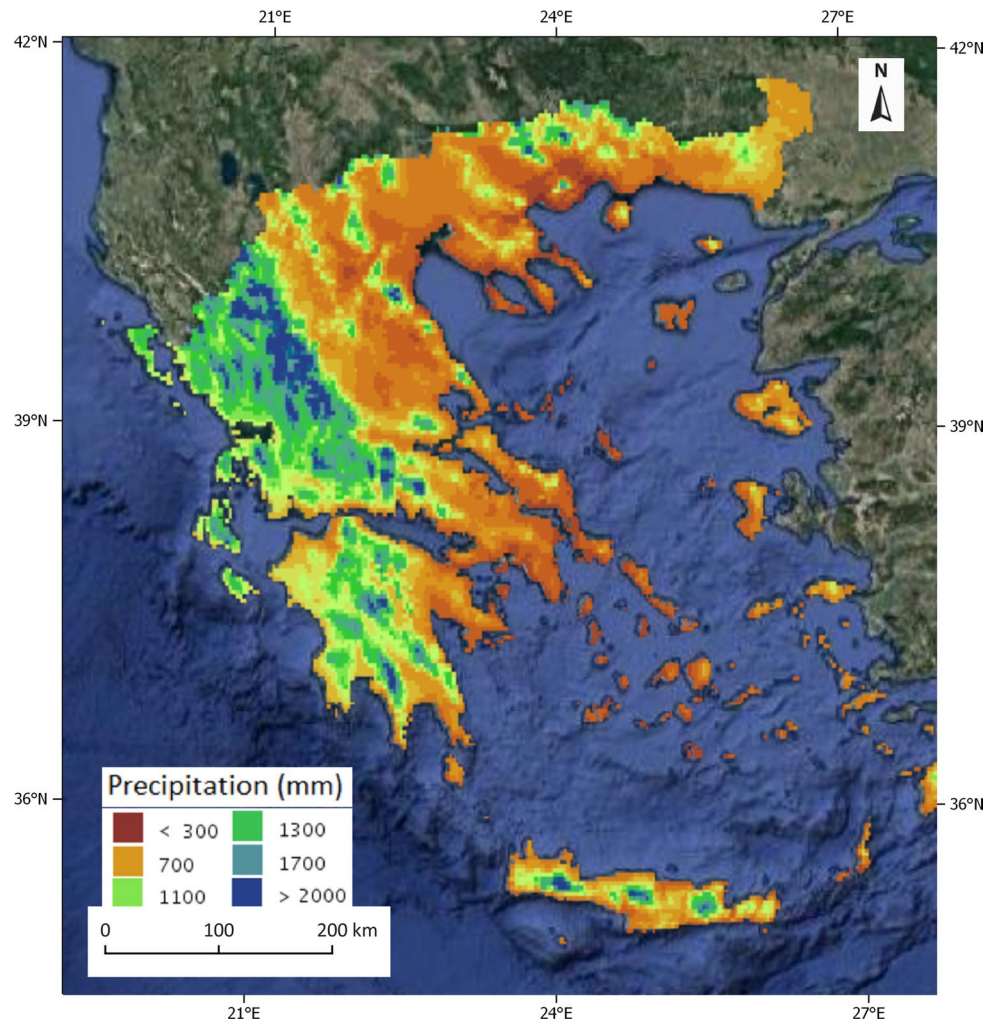

Hemisphere during winter (Wagner et al. 2019) which, in turn, favours a more southerly trajectory for storm tracks across the North Atlantic and into the Mediterranean (Kutzbach et al. 2014). Moreover, the local cyclogenesis in central Mediterranean during precipitation maxima (Fig. 12) forces moisture supply to the mountains of Greece into an SW–NE track which implies significantly enhanced precipitation in the Peloponnese compared to northern Greece and The Republic of North Macedonia as it can also be observed in similar cyclogenesis events today. On the other hand, the precipitation regime in the coastal mountains of Montenegro would not be affected. This is also in consistence with oxygen isotope data from speleothems in the Central Alps (Luetscher et al. 2015) which indicate that major glacier advances during the LGM had a primary moisture source from southerly advection, pointing to the Mediterranean Sea and the subtropical area as source regions for high precipitation rates in the Alps (Monegato et al. 2017). The presented glacial evidence and the respective ELAs are in accordance

with this hypothesis, while at the same time, it underlines the significance of precipitation in the formation of glaciers.

Conclusions

This review paper provides insight into our current understanding of glaciations in the mountains of Greece. The ice cover during the largest Middle Pleistocene glaciations—the Skamnellian (MIS 12) and Vlasian Stages (MIS 6)—was more extensive than previously thought. Interestingly, evidence of vast glacier formation is evident in numerous mountains higher than 1900 m a.s.l. throughout mainland Greece which can rather safely be ascribed to these Middle Pleistocene glacial phases. New evidence from Mt Chelmos indicates that extensive ice field/ice caps formed on mountains throughout the Balkans with outlet glaciers forming on all slope orientations during the most extensive glacial phases. However, the so-far evidence from Smolikas
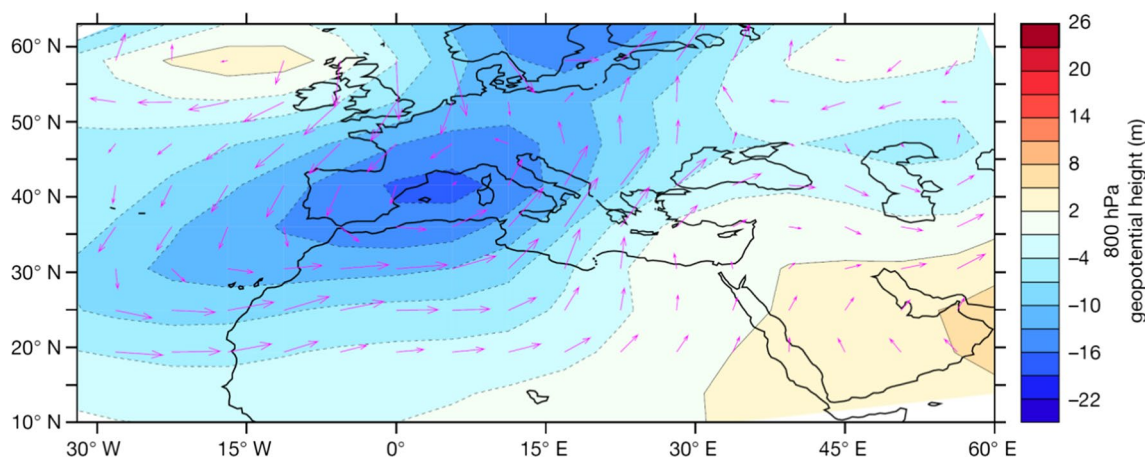
Fig. 12 Composite anomalies of September–November, 800 hPa geopotential height (m, shading), and wind (m s^{-1}, vectors) associated with precipitation maxima in Lake Ohrid (from Wagner et al. 2019)

is contradictive with glacial deposits identified only on its northern slopes. Further work is needed to understand the full glacial extent on Smolikas as well as the timing of its glacial sequence.

Recently, the analysis of time proxy series for the last 1.36 Ma and model data showed that increased winter precipitation, a crucial factor for the expansion of glaciers, corresponds with periods of low Northern Hemisphere winter insolation providing very favourable conditions for the formation of extensive ice fields which is in accordance with the glacial record in Greece. The palaeovegetation/palaeoclimatic record of the southern Balkans indicate cold and wet climate conditions during the early parts of MIS 12 and MIS 6 followed by cold and arid conditions, indicating glacier build-up during the early and relatively wet parts of these severe cold stages.

Ice extent was considerably smaller during the Tymphian Stage (MIS 5d–MIS2). This has been confirmed by cosmogenic exposure ages in recent studies on Mt Olympus and Mt Chelmos, and is accordance with evidence from a number of studies in the mountains of western Balkans, the Italian Apennines, and the Maritime Alps. However, whereas in the Alps and in Turkey, it is proven that glaciers reached their maximum extent during the LGM and their re-advance phases during the Late-Glacial and especially during the Younger Dryas (Egesen stadial) are relatively well established, the response of climate and consequently of glaciers in Greece during these severe climatic events remains poorly elucidated as the Late Pleistocene glacial record in the mountains of Greece is fragmentary and, in some cases, controversial.

A close examination of pollen frequencies from the existing archives shows that the duration and independent characteristics of vegetation patterns vary significantly during the Tymphian Stage implying differences connected with local microclimates, topography, and elevation. Still, the palaeovegetation and palaeoclimatic records from Lake Ioannina, Lake Ohrid, and Lake Prespa are in agreement with the onset of the recorded glacial episodes just before the threshold of AP percentages reduction. Unfortunately, such a high-resolution and independently dated archive is not appealable yet in southern Greece in order be used as a comparison for Mt Chelmos, while at the same time, no dating data from the mountains of northern Greece that could be correlated with the Ioannina, Prespa, and the Ohrid record are available for the Tymphian Stage. The comparison of Late Pleistocene ELAs across the Balkans though indicates a wetter climate in southern Greece that can be attributed to the palaeoatmospheric circulation mechanisms and precipitation regime during this period. Enhanced winter precipitation in southern Greece is a result of a more southerly trajectory for storm tracks across the Mediterranean, while at the same time, the local cyclogenesis in central Mediterranean forced moisture supply into an SW–NE track.

As regards the Holocene, very small glaciers formed in some north-oriented deep cirques on Mt Olympus where they survived because of strong local topoclimatic controls. Unlike on Mount Olympus, historical satellite imagery from late summer appears to confirm that there are no permanent snowfields on Smolikas. Based on this evidence and snow melt modelling, it has been argued that on Mt Smolikas, there are no glacial or nival features dating to the Holocene. Again, this hypothesis requires further testing using cosmogenic exposure dating.

It should be noted that even though important information has been added in the last 2 decades, there is need for further research in Greece and the wider Balkans to establish the timing and extent of glaciations. As regards

Greece in particular, still open questions are the extent of glaciation phases during Middle Pleistocene and the LGM on Mt Olympus. Moreover, Late Pleistocene glacial deposits in the northwest Pindus Mountains remain undated and it is, therefore, impossible to correlate them with the findings of the studies in the Peloponnese (pre-LGM and Late-glacial) and Mt Olympus (Late-glacial) to compose a robust chronographical map of Late Pleistocene glaciation phases in the mountains of Greece.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

Armijo R, Meyer BG, King GP, Rigo A, Papanastassiou D (1996) Quaternary evolution of the Corinth Rift and its implications for the Late Cenozoic evolution of the Aegean. Geophys J Int 126:11–53. https://doi.org/10.1111/j.1365-246X.1996.tb05264.x

Bassiouka A (2011) The demographic identity of mountainous areas of Greece. Master thesis, Post-Graduate Program: Environment and Development of Mountainous Areas, National Technical University of Athens, Athens **(in Greek)**

Boenzi F, Palmentola G (1997) Glacial features and snow-line trend during the last glacial age in the Southern Apennines (Italy) and on Albanian and Greek mountains. Z Geomorphol N F Suppl 41:21–29

Boenzi F, Palmentola G, Sanso P, Tromba F (1992) Le Tracce Glaciali Del Massiccio Dello Smolikas (Catena Del Pindo—Grecia). Riv Geogr Ital 99:379–393

Bond G, Broecker W, Johnsen S, McManus J, Labeyrie L, Jouzel J, Bonani G (1993) Correlations between climate records from North Atlantic sediments and Greenland Ice. Nature 365:143–147. https://doi.org/10.1038/365143a0

Bond G, Kromer B, Beer J, Muscheler R, Evans MN, Showers W, Hoffmann S, Lotti-Bond R, Hajdas I, Bonani G (2001) Persistent solar influence on North Atlantic climate during the Holocene. Science 294:2130–2136

Bourcart J (1922) Les confins albanais administres par la France, Paris, p 104

Cacho I, Grimalt JO, Pelejero C, Canals M, Sierro FJ, Flores JA, Shackleton NJ (1999) Dansgaard-Oeschger and Heinrich event imprints in Alboran Sea palaeotemperatures. Paleoceanography 14:698–705. https://doi.org/10.1029/1999PA900044

Çiner A, Sarıkaya MA (2017) Cosmogenic ^{36}Cl Geochronology of late Quaternary glaciers on the Bolkar Mountains, south central Turkey. In: Hughes P, Woodward J (eds) Quaternary glaciation in the Mediterranean Mountains. Geological Society of London Special Publication, p 433. 10.1144/SP433.3

Çiner A, Stepišnik U, Sarıkaya MA, Žebre M, Yıldırım C (2019) Last Glacial Maximum and Younger Dryas piedmont glaciations in Blidinje, the Dinaric Mountains (Bosnia and Herzegovina): insights from 36Cl cosmogenic dating. Mediterr Geosci Rev 1:25–43. https://doi.org/10.1007/s42990-019-0003-4

Clark PU, Dyke AS, Shakun JD, Carlson AE, Clark J, Wohlfarth B, Mitrovica JX, Hostetler SW, McCabe AM (2009) The last glacial maximum. Science 325:710–714. https://doi.org/10.1126/science.1172873

Cvijic J (1917) L'epoque glaciaire dans la peninsule balkanique. Ann Geogr 26:189–218

Faugeres L (1969) Problems created by the geomorphology of Olympus, Greece: relief, formation, and traces of Quaternary cold periods with discussion. Association Francaise pour l'Etude du Quaternaire 6:105–127

Federici PR, Granger DE, Ribolini A, Spagnolo M, Pappalardo M, Cyr AJ (2012) Last Glacial Maximum and the Gschnitz stadial in the Maritime Alps according to ^{10}Be cosmogenic dating. Boreas 41:277–291. https://doi.org/10.1111/j.1502-3885.2011.00233.x

Florineth D, Schlüchter C (2000) Alpine evidence for atmospheric circulation patterns in Europe during the Last Glacial Maximum. Quat Res 54:295–308. https://doi.org/10.1006/qres.2000.2169

Giraudi C, Frezzotti M (1997) Late Pleistocene glacial events in the Central Apennines, Italy. Quat Res 48:280–290. https://doi.org/10.1006/qres.1997.1928

Grant KM, Rohling EJ, Bar-Matthews M, Ayalon A, Medina-Elizalde M, Bronk Ramsey C, Satow C, Roberts AP (2012) Rapid coupling between ice volume and polar temperature over the past 150,000 years. Nature 491:744–747. https://doi.org/10.1038/nature11593

Gromig R, Mechernich S, Ribolini A, Wagner B, Zanchetta G, Isola I, Bini M, Dunai TJ (2018) Evidence for a Younger Dryas deglaciation in the Galicica Mountains (FYROM) from cosmogenic ^{36}Cl. Quat Int 464:352–363. https://doi.org/10.1016/j.quaint.2017.07.013

Hamlin RHB, Woodward JC, Black S, Macklin MG (2000) Sediment fingerprinting as a tool for interpreting long-term river activity: the Voidomatis basin, Northwest Greece. In: Foster IDL (ed) Tracers in geomorphology. Wiley, Chichester, pp 473–501

Harden JW (1982) A quantitative index of soil development from field descriptions: examples from a chronosequence in central California. Geoderma 28:1–28. https://doi.org/10.1016/0016-7061(82)90037-4

van Hinsbergen DJJ, Edwards MA, Govers R (2009) Geodynamics of collision and collapse at the Africa–Arabia–Eurasia subduction zone—an introduction. Geol Soc Lond Spec Publ 311:1–7. https://doi.org/10.1144/SP311.1

Hughes PD (2004) Quaternary glaciation in the Pindus Mountains, northwest Greece. PhD thesis, University of Cambridge

Hughes PD (2007) Recent behaviour of the Debeli Namet glacier, Durmitor, Montenegro. Earth Surf Proc Land 10:1593–1602. https://doi.org/10.1002/esp.1537

Hughes PD (2010) Little Ice Age glaciers in Balkans: low altitude glaciation enabled by cooler temperatures and local topoclimatic controls. Earth Surf Proc Land 35:229–241. https://doi.org/10.1002/esp.1916

Hughes PD (2018) Little ice age glaciers and climate in the Mediterranean mountains: a new analysis. Cuad Invest Geogr 44:15–46

Hughes PD, Gibbard PL (2015) A stratigraphical basis for the Last Glacial Maximum (LGM). Quat Int 383:174–185. https://doi.org/10.1016/j.quaint.2014.06.006

Hughes PD, Woodward JC (2008) Timing of glaciation in the Mediterranean mountains during the last cold stage. J Quat Sci 23:575–588. https://doi.org/10.1002/jqs.1212

Hughes PD, Woodward JC (2017) Quaternary glaciation in the Mediterranean mountains: a new synthesis. In: Hughes PD,

Woodward JC (eds) Quaternary glaciation in the Mediterranean Mountains, vol 433. Geol. Soc. London Special Publications, pp 1–23. 10.1144/SP433.14

Hughes PD, Gibbard PL, Woodward JC (2003) Relict rock glaciers as indicators of Mediterranean palaeoclimate during the Last Glacial Maximum (Late Würmian) of northwest Greece. J Quat Sci 18:431–440. https://doi.org/10.1002/jqs.764

Hughes PD, Gibbard PL, Woodward JC (2005) Quaternary glacial records in mountain regions: a formal stratigraphical approach. Episodes 28:85–92

Hughes PD, Woodward JC, Gibbard PL, Macklin MG, Gilmour MA, Smith GR (2006a) The glacial history of the Pindus Mountains, Greece. J Geol 114:413–434. https://doi.org/10.1086/504177

Hughes PD, Woodward JC, Gibbard PL (2006b) Quaternary glacial history of the Mediterranean mountains. Prog Phys Geogr 30:334–364. https://doi.org/10.1191/0309133306pp481ra

Hughes PD, Woodward JC, Gibbard PL (2006c) The last glaciers of Greece. Zeitscrift Geomorphol 50:37–46

Hughes PD, Woodward JC, Gibbard PL (2006d) Late Pleistocene glaciers and climate in the Mediterranean. Glob Planet Change 50:83–98. https://doi.org/10.1016/j.gloplacha.2005.07.005

Hughes PD, Gibbard PL, Woodward JC (2006e) Middle Pleistocene glacier behaviour in the Mediterranean: sedimentological evidence from the Pindus Mountains, Greece. J Geol Soc Lond 163:857–867. https://doi.org/10.1144/0016-76492005-131

Hughes PD, Gibbard PL, Woodward JC (2007) Geological controls on Pleistocene glaciations and cirque form in Greece. Geomorphology 88:242–253. https://doi.org/10.1016/j.geomorph.2006.11.008

Hughes PD, Woodward JC, van Calsteren PC, Thomas LE, Adamson KR (2010) Pleistocene ice caps on the coastal mountains of the Adriatic Sea: palaeoclimatic and wider palaeoenvironmental implications. Quat Sci Rev 29:3690–3708. https://doi.org/10.1016/j.quascirev.2010.06.032

Hughes PD, Woodward JC, van Calsteren PC, Thomas LE (2011) The glacial history of the Dinaric Alps, Montenegro. Quat Sci Rev 30:3393–3412. https://doi.org/10.1016/j.quascirev.2011.08.016

Hughes PD, Gibbard PL, Ehlers J (2013) Timing of glaciation during the last glacial cycle: evaluating the concept of a global 'Last Glacial Maximum' (LGM). Earth Sci Rev 125:171–198. https://doi.org/10.1016/j.earscirev.2013.07.003

IGME (Institute of Geology and Mineral Exploration) (1970) 1:50,000 Geological map of Greece. Tsepelovon Sheet. Institute of Geological and Mineral Exploration, Athens

IGME (Institute of Geology and Mineral Exploration) (1987) 1:50,000 Geological map of Greece. Konitsa Sheet. Institute of Geological and Mineral Exploration, Athens

Ivy-Ochs S, Kerschner H, Kubik PW, Schlüchter C (2006) Glacier response in the European Alps to Heinrich Event 1 cooling: the Gschnitz stadial. J Quat Sci 21:115–130. https://doi.org/10.1002/jqs.955

Ivy-Ochs S, Kerschner H, Schlüchter C (2007) Cosmogenic nuclides and the dating of Lateglacial and Early Holocene glacier variations: the Alpine perspective. Quat Int 164–165:53–63. https://doi.org/10.1016/j.quaint.2006.12.008

Jolivet L, Faccenna C (2000) Mediterranean extension and the Africa-Eurasia collision. Tectonics 19:1095–1106. https://doi.org/10.1029/2000TC900018

Jones G, Robertson AHF (1997) Tectono-stratigraphy and evolution of the Mezozoic Pindus ophiolite and related units, northwestern Greece. J Geol Soc Lond 148:267–288. https://doi.org/10.1144/gsjgs.148.2.0267

King G, Sturdy D, Bailey G (1997) The tectonic background to the Epirus Landscape. In: Bailey GN (ed) Klithi: palaeolithic settlement and quaternary landscapes in northwest Greece. Klithi

in its local and regional setting, vol 2. MacDonald Institute for Archaeological Research, Cambridge, pp 541–558

Klebelsberg RV (1932) Der Tymphrestos im Aetolischen Pindos. Jahrb Geol Bundesanst 82:17–30

Kleman J, Borgström I, Skelton A, Hall A (2016) Landscape evolution and landform inheritance in tectonically active regions: the case of the Southwestern Peloponnese, Greece. Zeitschrift für Geomorphologie 60:171–193. https://doi.org/10.1127/zfg/2016/0283

Köse O, Sarıkaya MA, Çiner A, Candaş A (2019) Late Quaternary glaciations and cosmogenic ^{36}Cl geochronology of Mount Dedegöl, south-west Turkey. J Quat Sci 34:51–63

Kuhlemann J, Rohling EJ, Krumrei I, Kubik P, Ivy-Ochs S, Kucera M (2008) Regional synthesis of Mediterranean atmospheric circulation during the last glacial maximum. Science 321:1338–1340. https://doi.org/10.1126/science.1157638

Kuhlemann J, Milivojevic M, Krumrei I, Kubik PW (2009) Last glaciations of the Sara range (Balkan peninsula): increasing dryness from the LGM to the Holocene. Austrian J Earth Sci 102:146–158

Kuhlemann J, Gachev E, Gikov A, Nedkov S, Krumrei I, Kubik P (2013) Glaciation in the Rila mountains (Bulgaria) during the Last Glacial Maximum. Quat Int 293:51–62. https://doi.org/10.1016/j.quaint.2012.06.027

Kutzbach JE, Chen G, Cheng H, Edwards R, Liu Z (2014) Potential role of winter rainfall in explaining increased moisture in the Mediterranean and Middle East during periods of maximum orbitally-forced insolation seasonality. Climate Dyn 42:1079–1095. https://doi.org/10.1007/s00382-013-1692-1

Lewin J, Macklin MG, Woodward JC (1991) Late Quaternary fluvial sedimentation in the Voidomatis Basin, Epirus, northwest Greece. Quat Res 35:103–115. https://doi.org/10.1016/0033-5894(91)90098-P

Lionello P, Malanotte-Rizzoli P, Boscolo R (2006) Mediterranean climate variability. Elsevier, Amsterdam

Louis H (1926) Glazialmorphologishche Beobachtungen im albanischen Epirus. Erde 1926:398–409

Luetscher M, Boch R, Sodemann H, Spötl C, Cheng H, Edwards RL, Friscia S, Hof F, Müller W (2015) North Atlantic storm track changes during the Last Glacial Maximum recorded by Alpine speleothems. Nat Commun 6(6344):1–6. https://doi.org/10.1038/ncomms7344

Manz LA (1998) Cosmogenic ^{36}Cl chronology for deposits of presumed Pleistocene age on the Eastern Piedmont of Mount Olympus, Pieria, Greece. Unpublished MSc thesis, Ohio University

Mastronuzzi G, Sanso P, Stamatopoloulos L (1994) Glacial landforms of the Peloponnisos (Greece). Riv Geogr Ital 101:77–86

Maull O (1921) Beiträge zur Morphologie des Peloponnes und des sdlichen Mittelgriechenlands. Geogr Abhandlungen X(3):179–302

Messerli B (1967) Die Eiszeitliche und die gegenwartige Vergletscherung im Mittelmeeraum. Geogr Helv 22:105–228

Milner AM, Roucoux KH, Collier REL, Müller UC, Pross J, Tzedakis PC (2016) Vegetation responses to abrupt climatic changes during the Last Interglacial Complex (Marine Isotope Stage 5) at Tenaghi Philippon, NE Greece. Quat Sci Rev 154:169–181. https://doi.org/10.1016/j.quascirev.2016.10.016

Mistardis G (1935) Geomorphological research in northeastern Epirus (in Greek). Athens, pp 1–33

Mistardis G (1937a) Sur la morphologie des parties superieures des hautes montagnes de la Grece. Reprinted from the bulletin of the first Panhellenic mountaineering Conference in Athens, pp 35–41

Mistardis G (1937b) Traces de glaciation dans la partie montagneuse du nord du Peloponese. Zeitschrift für Gletscher Kunde XXV:122–129

Mistardis G (1937c) Recherche geomorphologique dans la partie superieure des monts Aroania (Chelmos). Reprinted from the bulletin of the first Panhellenic mountaineering Conference in Athens, pp 94–103

Mistardis G (1946) Aroania (Chelmos). "To Vouno"—Greek Mountaineering Club edition (in Greek), pp 37–64

Monegato G, Scardia G, Hajdas I, Rizzini F, Piccin A (2017) The Alpine LGM in the boreal ice-sheets game. Sci Rep 7:2078. https://doi.org/10.1038/s41598-017-02148-7

Müller UC, Pross J, Tzedakis PC, Gamble C, Kotthoff U, Schmiedl G, Wulf S, Christanis K (2011) The role of climate in the spread of modern humans into Europe. Quat Sci Rev 30:273–279. https://doi.org/10.1016/j.quascirev.2010.11.016

Nance RD (2010) Neogene-Recent extension on the eastern flank of Mount Olympus, Greece. Tectonophysics 488:282–292. https://doi.org/10.1016/j.tecto.2009.05.011

Niculescu C (1915) Sur les traces de glaciation dans le massif Smolica chaıne du Pinde meridional. Bulletin de la Section Scientifique de l'Academie Roumaine 3:146–151

Oerlemans J (2005) Extracting a climate signal from 169 glacier records. Science 308:675–677. https://doi.org/10.1126/science.1107046

Ohmura A, Boetcher M (2018) Climate on the equilibrium line altitudes of glaciers: theoretical background behind Ahlmann's P/T diagram. J Glaciol 64:489–505

Ohmura A, Kasser P, Funk M (1992) Climate at the equilibrium line of glaciers. J Glaciol 38:397–411. https://doi.org/10.3189/S0022143000002276

Oliva M, Palacios D, Fernández-Fernández JM, Rodríguez-Rodríguez L, Garcia Ruiz J-M, Andrés N, Carrasco RM, Pedrazza J, Perez Alberti A, Valcarel M, Hughes PD (2019) Late Quaternary glacial phases in the Iberian Peninsula. Earth Sci Rev 192:564–600. https://doi.org/10.1016/j.earscirev.2019.03.015

Palmentola G, Stamatopoulos L (2006) Preliminary data about sporadic permafrost on Peristeri and Tzoumerka massifs (Pindos chain, Northwestern Greece). Rev Geom 8:17–23

Palmentola G, Boenzi F, Mastronuzzi G, Tromba F (1990) Osservazioni sulle trace glaciali del M. Timfi, Catena del Pindo (Grecia). Geografia Fisica e Dinamica Quaternaria 13:165–170

Panagiotopoulos K, Böhm A, Leng MJ, Wagner B, Schäbitz F (2014) Climate variability over the last 92 ka in SW Balkans from analysis of sediments from Lake Prespa. Climate Past 10:643–660. https://doi.org/10.5194/cp-10-643-2014

Pavlopoulos K, Leontaritis A, Athanassas CD, Petrakou C, Vandarakis D, Nikolakopoulos K, Stamatopoulos L, Theodorakopoulou K (2018) Last glacial geomorphologic records in Mt Chelmos, North Peloponnesus, Greece. J Mt Sci 15:948–965. https://doi.org/10.1007/s11629-017-4563-0

Pechoux PE (1970) Traces d'activité glaciaire dans les montagnes de Grèce central. Rev Geogr Alp 58:211–224. https://doi.org/10.3406/rga.1970.3465

Philipson A (1892) Der Peloponnes. Versuch einer Landeskunde auf geologischer Grundlage. Friedlaender & Sohn, Berlin, p 382

Pirazzoli PA, Stiros SC, Fontugne M, Arnold M (2004) Holocene and Quaternary uplift in the central part of the southern coast of the Corinth Gulf (Greece). Mar Geol 212:35–44. https://doi.org/10.1016/j.margeo.2004.09.006

Pope RJ (2010) Linking high altitude glacier melting to Late Quaternary sedimentation in environmentally sensitive range-front alluvial fans in the Sparta Basin, southern Greece. Geophemera 108:17–23. https://geomorphology.org.uk/sites/default/files/Geophemera%20108.pdf

Pope RJ, Wilkinson KN (2006) Reconciling the roles of climate and tectonics in Late Quaternary fan development on the Spartan

piedmont, Greece. Geol Soc Spec Publ 251:133–152. https://doi.org/10.1144/GSL.SP.2005.251.01.10

Pope RJ, Hughes PD, Skourtsos E (2017) Glacial history of Mount Chelmos, Peloponnesus, Greece. In: Hughes PD, Woodward JC (eds) Quaternary glaciation in the Mediterranean mountains, vol 433. Geol. Soc. London, Special Publications, pp 211–236. 10.1144/SP433.11

Rasmussen SO, Andersen KK, Svensson AM, Steffensen JP, Vinther BM, Clausen HB, Siggaard-Andersen M-L, Johnsen SJ, Larsen LB, Dahl- Jensen D, Bigler M, Roethlisberger R, Fischer H, Goto-Azuma K, Hansson ME, Ruth U (2006) A new Greenland ice core chronology for the last glacial termination. J Geophys Res. https://doi.org/10.1029/2005JD006079

Rasmussen SO, Bigler M, Blockley SP, Blunier T, Buchardt SL, Clausen HB, Cvijanovic I, Dahl-Jensen D, Johnsen SJ, Fischer H, Gkinis V, Guillevic M, Hoek WZ, Lowe JJ, Pedro JB, Popp T, Seierstad IK, Steffensen JP, Svensson AM, Vallelonga P, Vinther BM, Walker MJC, Wheatley JJ, Winstrup M (2014) A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. Quat Sci Rev 106:14–28. https://doi.org/10.1016/j.quascirev.2014.09.007

Regato P, Salman R (2008) Mediterranean Mountains in a changing world. Guidelines for developing action plans. International Union for Conservation of Nature and Natural Resources, Gland

Renz C (1910) Stratigraphische Untersuchungen im griechischen Mesozoikum und Paläozoikum. Wien, p 131

Reuther AU, Urdea P, Geiger C, Ivy-Ochs S, Niller H-P, Kubik PW, Heine K (2007) Late Pleistocene glacial chronology of the Pietrele Valley, Retezat Mountains, Southern Carpathians constrained by [10]Be exposure ages and pedological investigations. Quat Int 164–165:151–169. https://doi.org/10.1016/j.quaint.2006.10.011

Ribolini A, Bini M, Isola I, Spagnolo M, Zanchetta G, Pellitero R, Mechernich S, Gromig R, Dunai T, Wagner B, Milevski I (2017) An Oldest Dryas glacier expansion on Mount Pelister (Former Yugoslavian Republic of Macedonia) according to 10Be cosmogenic dating. J Geol Soc Lond 175:100–110. https://doi.org/10.1144/jgs2017-038

Roucoux KH, Tzedakis PC, Lawson IT, Margari V (2011) Vegetation history of the penultimate glacial period (Marine isotope stage 6) at Ioannina, north-west Greece. J Quat Sci 26:616–626. https://doi.org/10.1002/jqs.1483

Sadori L, Koutsodendris A, Masi A, Bertini A, Combourieu-Nebout N, Francke A, Kouli K, Joannin S, Mercuri AM, Panagiotopoulos K, Peyron O, Torri P, Wagner B, Zanchetta G, Donders TH (2016) Pollen-based paleoenvironmental and paleoclimatic change at Lake Ohrid (SE Europe) during the past 500 ka. Biogeosciences 13:1423–1437. https://doi.org/10.5194/bgd-12-15461-2015

Sarıkaya MA, Çiner A (2017) The late Quaternary glaciation in the Eastern Mediterranean. In: Hughes P, Woodward J (eds) Quaternary glaciation in the Mediterranean mountains. Geological Society of London Special Publication. p 433. 10.1144/SP433.4

Sarıkaya MA, Ciner A, Haybat H, Zreda M (2014) An early advance of glaciers on Mount Akdagˇ, SW Turkey, before the global Last Glacial Maximum; insights from cosmogenic nuclides and glacier modelling. Quat Sci Rev 88:96–109. https://doi.org/10.1016/j.quascirev.2014.01.016

Serrano E, González-Trueba JJ, González-García M (2012) Mountain glaciation and paleoclimate reconstruction in the Picos de Europa (Iberian Peninsula, SW Europe). Quat Res 78:303–314. https://doi.org/10.1016/j.yqres.2012.05.016

Serrano E, González-Trueba JJ, Pellitero R, González-García M, Gómez-Lende M (2012) Quaternary glacial evolution in the

Central Cantabrian Mountains (Northern Spain). Geomorphology 196:65–82. https://doi.org/10.1016/j.geomorph.2012.05.001

Sinopoli G, Masi A, Regattieri E, Wagner B, Francke A, Peyron O, Sadori L (2018) Palynology of the Last Interglacial Complex at Lake Ohrid: palaeoenvironmental and palaeoclimatic inferences. Quat Sci Rev 180:177–192. https://doi.org/10.1016/j.quascirev.2017.11.013

Sinopoli G, Peyron O, Masi A, Holtvoeth J, Francke A, Wagner B, Sadori L (2019) Pollen-based temperature and precipitation changes in the Ohrid Basin (western Balkans) between 160 and 70 ka. Climate Past 15:53–71. https://doi.org/10.5194/cp-15-53-2019

Smith GW, Nance RD, Genes AN (1997) Quaternary glacial history of Mount Olympus, Greece. Geol Soc Am Bull 109:809–824

Smith GR, Woodward JC, Heywood DI, Gibbard PL (1998) Mapping glaciated karst terrain in a Mediterranean mountain environment using SPOT and TM data. In: Burt PJA, Power CH, Zukowski PM (eds) RSS98: developing international connections, (proceedings of the remote sensing society's annual meeting), Greenwich, September 1998, pp 457–463

Styllas MN, Schimmelpfennig I, Ghilardi M, Benedetti L (2016) Geomorphologic and paleoclimatic evidence of Holocene glaciation on Mount Olympus, Greece. Holocene 26:709–721. https://doi.org/10.1177/0959683615618259

Styllas MN, Schimmelpfennig I, Benedetti L, Ghilardi M, Aumaître G, Bourlès D, Keddadouche K (2018) Late-glacial and Holocene history of the northeast Mediterranean mountain glaciers—new insights from in situ-produced ^{36}Cl-based cosmic ray exposure dating of paleo-glacier deposits on Mount Olympus, Greece. Quat Sci Rev 193:244–265. https://doi.org/10.1016/j.quascirev.2018.06.020

Tzedakis PC (1994) Vegetation change through glacial-interglacial cycles: a long pollen sequence perspective. Philos Trans R Soc Lond 345:403–432. https://doi.org/10.1098/rstb.1994.0118

Tzedakis PC (1999) The last climatic cycle at Kopais, central Greece. J Geol Soc 156:425–434. https://doi.org/10.1144/gsjgs.156.2.0425

Tzedakis PC, Lawson IT, Frogley MR, Hewitt GM, Preece RC (2002) Buffered tree population changes in a Quaternary refugium: evolutionary implications. Science 297:2044–2047. https://doi.org/10.1126/science.1080630

Tzedakis PC, McManus JF, Hooghiemstra H, Oppo DW, Wijmstra TA (2003) Comparison of changes in vegetation in northeast Greece with records of climate variability on orbital and suborbital frequencies over the last 450 000 years. Earth Planet Sci Lett 212:197–212. https://doi.org/10.1016/S0012-821X(03)00233-4

Tzedakis PC, Frogley MR, Lawson IT, Preece RC, Cacho I, de Abreu L (2004) Ecological thresholds and patterns of millennialscale climate variability: the response of vegetation in Greece during the last glacial period. Geology 32:109–112. https://doi.org/10.1130/G20118.1

Vogiatzakis IN (2012) Mediterranean mountain environments. Wiley-Blackwell, Oxford

Wagner B, Vogel H, Francke A et al (2019) Mediterranean winter rainfall in phase with African monsoons during the past 1.36 million years. Nature 573:256–260. https://doi.org/10.1038/s41586-019-1529-0

Wiche K (1956) Beitrag zur Morphologie des Thessalischen Olymp. Geographischer Jahresberichtus Osterreich 26:25–40

Wirth SB, Sessions AL (2016) Plant-wax D/H ratios in the southern European Alps record multiple aspects of climate variability. Quat Sci Rev 148:176–181. https://doi.org/10.1016/j.quascirev.2016.07.020

Woodward JC (2009) The physical geography of the mediterranean. Oxford University Press, Oxford

Woodward JC, Hughes PD (2011) Glaciation in Greece: a new record of cold stage environments in the Mediterranean. In: Ehlers J, Gibbard PL, Hughes PD (eds) Quaternary glaciations—extent and chronology. A closer look. Elsevier, Amsterdam, pp 175–198. 10.1016/B978-0-444-53447-7.00015-5

Woodward JC, Lewin J, Macklin MG (1992) Alluvial sediment sources in a glaciated catchment: the Voidomatis basin, northwest Greece. Earth Surf Process Landf 16:205–216. https://doi.org/10.1002/esp.3290170302

Woodward JC, Lewin J, Macklin MG (1995) Glaciation, river behaviour and Palaeolithic settlement of upland northwest Greece. In: Lewin J, Macklin MG, Woodward JC (eds) Mediterranean quaternary river environments. Balkema, Rotterdam, pp 115–129

Woodward JC, Macklin MG, Smith GR (2004) Pleistocene glaciation in the mountains of Greece. In: Ehlers J, Gibbard PL (eds) Quaternary glaciations —extent and chronology. Part I: Europe. Elsevier, Amsterdam, pp 155–73. https://doi.org/10.1016/S1571-0866(04)80066-6

Woodward JC, Hamlin RHB, Macklin MG, Hughes PD, Lewin J (2008) Glacial activity and catchment dynamics in northwest Greece: long-term river behaviour and the slackwater sediment record for the last glacial to interglacial transition. Geomorphology 101:44–67. https://doi.org/10.1016/j.geomorph.2008.05.018

Wulf S, Hardiman MJ, Staff RA, Koutsodendris A, Appelt O, Blockley SPE, Lowe JJ, Manning CJ, Ottolini L, Schmitt AK, Smith VC, Tomlinson EL, Vakhrameeva P, Knipping M, Kotthoff U, Milner AM, Müller UC, Christanis K, Kalaitzidis S, Tzedakis PC, Schmiedl G, Pross J (2018) The marine isotope stage 1–5 cryptotephra record of Tenaghi Philippon, Greece: towards a detailed tephrostratigraphic framework for the Eastern Mediterranean region. Quat Sci Rev 186:236–262. https://doi.org/10.1016/j.quascirev.2018.03.011

Žebre M, Sarıkaya MA, Stepišnik U, Yıldırım C, Çiner A (2019) First ^{36}Cl cosmogenic moraine geochronology of the Dinaric mountain karst: velež and Crvanj Mountains of Bosnia and Herzegovina. Quat Sci Rev 208:54–75. https://doi.org/10.1016/j.quascirev.2019.02.002