Quaternary glaciation in the Mediterranean mountains: a new synthesis

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Abstract: The Mediterranean mountains were repeatedly glaciated during the Pleistocene. Glaciers were present in most of the major mountains areas from Morocco in the west to the Black Sea coast of Turkey in the east. Some mountains supported extensive ice caps and ice fields with valley glaciers tens of kilometres long. Other massifs sustained only small-scale ice masses, although this was the exception rather than the norm. Glaciers still exist today and there is evidence that small glaciers were a common sight in many regions during the Little Ice Age. The Mediterranean mountains are important for palaeoclimate research because of their position in the mid-latitudes and sensitivity to changes in the climate regimes of adjacent areas including the North Atlantic. These mountains are also important areas of biodiversity and long-term biological change through the Quaternary ice age. All of this provided challenges and opportunities for Palaeolithic societies. This paper reviews the history of the study of glaciation in the Mediterranean mountains from pioneer nineteenth century observations through to the detailed geomorphological mapping and advanced geochronological datasets of recent times. We also review the current state of knowledge to frame the contributions presented in this volume. Lastly, this new synthesis then identifies outstanding research problems and assesses the prospects for new studies of glaciation in the Mediterranean mountains.

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The mountains surrounding the Mediterranean Sea were repeatedly glaciated during the Quaternary. Glacial processes have been important agents of long-term landscape modification and classic glacial scenery has been documented across this region. As in other parts of the world, the influence of these glaciers was not confined to the uplands because meltwaters carried large volumes of outwash sediment through the downstream reaches of river basins – this glacial signal can be traced to the Mediterranean coast and offshore. The geomorphological and sedimentological record of glaciation in these mountains is now providing valuable information on past climates because the viability of glaciers is closely related to atmospheric air temperatures and moisture supply. The glacial record can be compared with modern climate data to generate information on the nature of winter moisture supply (as snow) and summer temperatures during Pleistocene cold stages. These data usefully complement the rich body of proxy climate data that has been retrieved from other Mediterranean archives, including lake basins, speleothems and the marine sedimentary record (Woodward 2009).

The Mediterranean region is situated in an important position for understanding Quaternary climate change in the northern hemisphere. Lying immediately to the east of the North Atlantic Ocean and aligned along the low mid-latitudes, the Mediterranean basin is an important corridor for westerly atmospheric circulation between the Sahara Desert and the Alps. Today, moisture-bearing atmospheric depressions – generated both in the North Atlantic Ocean and in the Mediterranean basin itself – are able to penetrate eastwards to central Asia. This situation may have been more marked during Pleistocene cold stages at those times when both the oceanic and atmospheric polar fronts were much further south than today, with the former positioned off Iberia in the North Atlantic Ocean (Ruddiman & McIntyre 1981; Roucoux et al. 2005).

The mountains of the Mediterranean represent dynamic landscape systems that are highly responsive to climate change (Tzedakis et al. 2004; Regato & Salman 2008; Woodward 2009; Vogiatzakis 2012). There is now a large body of evidence showing that the mountainous peninsulas of southern Europe, as well as the mountains of North Africa, hosted biotic refugia during Pleistocene cold stages (Tzedakis 1993; Hewitt 2000). It is mainly from these refugia in southern Europe that plants and animals colonized central and northern Europe during interglacials. The presence of glaciers in these
refugial centres during Pleistocene cold stages has important implications for moisture supply as well as temperature; large glaciers in the uplands would have limited the availability of ‘temperate’ refugial sites in topographically sheltered sites such as valley floors. Moreover, the association of glaciated Mediterranean uplands and their meltwater rivers with zones of Palaeolithic human activity and migration routes (Woodward et al. 1995; Gamble 1999; Gibert et al. 2003) highlights the importance of understanding environmental conditions in Mediterranean mountain catchments during Pleistocene cold stages.

This introduction provides a critical review of current knowledge of glaciation in the Mediterranean mountains from Morocco to Turkey. The aims of this introduction are to: (1) provide the background to the history of glacial research in the Mediterranean mountains; (2) introduce the papers in this volume; (3) examine the current state of knowledge regarding Pleistocene glaciation in the Mediterranean mountains; (4) review the recent and current extent of glaciers in the Mediterranean mountains; and (5) set out a new agenda by discussing progress, problems and prospects for the study of glaciations in the Mediterranean mountains.

The glacial pioneers

There is a long history of glacial research in the Mediterranean mountains. Some of the earliest papers on this topic are listed by country and region in Table 1. By the end of the nineteenth century nearly all the Mediterranean mountain ranges were known to have been glaciated in the Pleistocene (Table 1). These early glacial studies involved some of the key figures in geographical research (Table 1). These early glacial studies involved some of the key figures in geographical research in the early twentieth century, including Jovan Cvijić and Albrecht Penck in the lead up to the First World War and Emmanuel de Martonne in the 1920s (Ehlers et al. 2016). Jovan Cvijić was one of the first geographers to appreciate the extent of glaciation in southeast Europe and worked extensively in the Balkans in the late nineteenth and early twentieth centuries (Cvijić 1899, 1900, 1917 and references cited therein). Albrecht Penck – better known for his classic glacial work in the Alps – was another of the Mediterranean glacial pioneers; he worked in the Pyrenees and the Dinaric Alps (Penck 1885, 1900). Much of the glacial geomorphological research in the early twentieth century was influenced by the geopolitical framework at that time. In northern Albania, for example, geological investigations were dominated by Austrian researchers such as Karl Roth von Telegd and Ernst Nowack (Roth von Telegd 1923; Nowack 1929). In southern Albania and northwest Greece, studies were dominated by Italian researchers (Almagià 1918; Sestini 1933). The French scholar Emmanuel de Martonne was a widely travelled geographer who undertook glacial research across the Mediterranean and beyond, from Morocco (Martonne 1924) to Romania (Martonne 1907, 1922). Other key figures who worked across the Mediterranean were: Klebelsberg, who worked in Spain, Italy and Greece (e.g. Klebelsberg 1928, 1930, 1931, 1932a, 1932b, 1933–1934); Suter, who worked in Italy (e.g. Suter 1932, 1934); and Louis, who worked extensively in the Balkans and Turkey (e.g. Louis 1926, 1944). Glacial research in the Mediterranean was particularly active in the inter-war period between 1920 and 1940 (see reviews in Messerli 1967; Hughes 2012; Ehlers et al. 2016). Glacial geomorphological research in the region once again flourished after the Second World War, especially in the 1950s, 1960s and early 1970s, with notable research in Morocco (e.g. Mensching 1953, 1960; Wiche 1953), Montenegro (Liedtke 1962) and Greece (e.g. Hagedorn 1969), all published in German.

As is clear from the Foreword to this volume, the most intrepid and geographically wide-ranging researcher in the two decades after the Second World War was the remarkable Swiss scholar Bruno Messerli, who produced important papers on the glacial geomorphology of the Sierra Nevada in Spain (Messerli 1965a), Mount Erciyes in Turkey (Messerli 1964, 1965b), the mountains of the Lebanon (Messerli 1966) and even the Tibesti Mountains in Chad (Messerli 1972). Bruno Messerli’s classic review of glaciation (Messerli 1967), based on 364 cited publications, was the first to illustrate the full scope of Pleistocene glacial activity across the entire Mediterranean region. Messerli’s research, however, was followed by a period of relative stagnation in the development of ideas and fresh approaches that lasted for almost three decades. One reason for this very limited progress was the difficulty involved in dating glacial deposits and landforms – a problem not restricted to the Mediterranean mountains in this period. Mediterranean glacial research lost momentum because most of the glaciated areas had been identified and the extent – if not the age – of glaciation was relatively well known. In addition, international research in key parts of the Mediterranean was hampered by political tensions, such as the Balkan conflicts of the 1990s. The past decade, however, has witnessed a dramatic expansion in the number and sophistication of Pleistocene glacial studies. There is little doubt that this reflects the wider availability of geochronological techniques for dating glacial landforms, especially uranium series and cosmogenic exposure dating. Table 1 presents a summary of some of the first papers reporting dates for the glacial records of the mountain ranges across the Mediterranean.
Table 1. Summary of the history of glacial research in the Mediterranean mountains, listing some of the earliest publications on glaciation and glacial geochronology for each region

| Location               | Earliest known publication on glaciation | Some of the first publications related to the dating of glaciation | Dating methods applied (see text for sources) | Current state of research using the hierarchy of Hughes et al. (2006a) |
|------------------------|------------------------------------------|------------------------------------------------------------------|-----------------------------------------------|--------------------------------------------------|
| Portugal               | Cabral (1884)                            | Janssen & Woldringh (1981), Vidal Romani *et al.* (1999), Vieira *et al.* (2001) | $^{14}$C, cosmogenic, TL                       | Mapping/advanced                                  |
| Spain                  | Prado (1860)                             | Vidal Romani *et al.* (1999)                                      | Cosmogenic                                    | Advanced                                         |
| Pyrenees (France, Spain)| Penck (1885)                             | Sorriaux (1981), Jalut *et al.* (1982), Mardones & Jalut (1983) | Uranium series, $^{14}$C                      | Advanced                                         |
| Pyrenees (Andorra)     | Blade (1875)                             | Turu (2002)                                                       | $^{14}$C                                       | Advanced                                         |
| Maritime Alps          | De Lorenzo (1895)                        | Ponel *et al.* (2001), Federici *et al.* (2008)                   | $^{14}$C, cosmogenic                           | Advanced                                         |
| Corsica                | Pumpelly (1859)                          | Hewitt (2001)                                                    | Cosmogenic                                    | Advanced                                         |
| Italian Apennines      | De Lorenzo (1895)                        | Frezzotti & Giraudi (1992)                                       | Tephrochronology, $^{39}$Ar/$^{87}$Ar, $^{14}$C | Advanced                                         |
| Sicily                 | Maier (1936)                             |                                                                  |                                               | Pioneer/mapping                                  |
| Slovenia               | Brückner (1890)                          | Bavec *et al.* (2004)                                            | OSL                                           | Mapping/advanced                                  |
| Croatia                | Penck (1900)                             |                                                                  | $^{14}$C, uranium series                      | Advanced                                         |
| Bosnia                 | Cvijić (1899, 1900, 1917)                | Marjanac *et al.* (2001), Marjanac (2012)                        | $^{14}$C                                       | Mapping                                          |
| Montenegro             | Cvijić (1899, 1900, 1917)                |                                                                  | Uranium series                                | Advanced                                         |
| Albania                | Almagià (1918)                           |                                                                 | Uranium series, cosmogenic                     | Pioneer/mapping                                  |
| Mainland Greece        | Cvijić (1900, 1917)                      | Woodward *et al.* (2004)                                         |                                               | Advanced                                         |
| Crete                  | Creutzburg (1928)                        |                                                                  |                                               | Pioneer/mapping                                  |
| Turkey                 | Ainsworth (1842)                         | Akçar *et al.* (2007)                                            | Cosmogenic                                    | Advanced                                         |
| Lebanon                | Diener (1886)                            | Moulin *et al.* (2011)                                           | Cosmogenic                                    | Mapping                                          |
| Algeria                | Raclus (1885, p. 207, fig. 67),          |                                                                  |                                               | Pioneer                                          |
|                       | Barbier & Cailleux (1950)                |                                                                  |                                               |                                                  |
| Morocco                | Hooker & Ball (1878)                    | Hughes *et al.* (2011a)                                          | Cosmogenic                                    | Mapping/advanced                                  |

$^{14}$C, radiocarbon dating; OSL, optically stimulated luminescence; TL, thermoluminescence.
A new phase of glacial research

The timing of glaciations in the Mediterranean mountains has been constrained using a range of approaches. Examples presented in this volume include cosmogenic nuclide exposure dating of boulders and bedrock surfaces (Akcăr et al. 2015; Çiner & Sarıkaya 2015; Federici et al. 2016; Palacios et al. 2016; Pope et al. 2015; Sarıkaya & Çiner 2015; Turu et al. 2016), radiocarbon dating of basal glacial lake deposits (Giraudi & Giaccio 2015; Serrano et al. 2016; Turu et al. 2016), Ar/Ar dating of tephras in mountain basins (Giraudi & Giaccio 2015), optically stimulated luminescence dating of glacio-fluvial outwash deposits (Serrano et al. 2016; Turu et al. 2016) and uranium series dating of secondary carbonate cements (Adamson et al. 2016; Serrano et al. 2016) in glacial and glacio-fluvial deposits.

Ten years ago we published a review article on the Quaternary glacial history of the Mediterranean mountains (Hughes et al. 2006a). In reviewing the history of glacial research in this region up to that time, we identified three distinct stages in the development of this field of research:

1. A pioneer phase characterized by the initial descriptive observations of glacial landforms in a particular region;
2. A mapping phase when the distribution of glacial landforms and sediments was first depicted on sophisticated geomorphological maps; and
3. An advanced phase characterized by a detailed understanding of the geochronology of glacial sequences using radiometric dating alongside detailed sedimentological and stratigraphic analyses.

Most areas of the Mediterranean had undergone pioneer phase research by 2006 – this had typically taken place in the late nineteenth or early twentieth centuries. The results of this phase were comprehensively reviewed in Messerli’s landmark paper (Messerli 1967) and we have summarized our own literature search in Table 1. However, as noted earlier, the last few decades of the twentieth century were characterized by rather limited progress, notwithstanding some new mapping efforts in Italy, France and Spain in particular. There has been a marked increase in research activity into Quaternary glaciation across the Mediterranean region in the decade since we published our review paper. This research is now flourishing in many countries and many more regions have moved from the mapping to the advanced phase. In some places, the shift to the mapping phase was accompanied by the introduction of geochronological dating. A key advance of the last decade has been the widespread application of cosmogenic exposure dating in most parts of the Mediterranean. Many hundreds of dates are now available for glacial sediments and landforms. As a result, it is now possible to identify a fourth meta-analysis phase because researchers are able to explore patterns in the large number of dates now available to better understand the regional patterns of glacial advance and retreat and their wider palaeoenvironmental significance (e.g. Hughes & Woodward 2008; Woodward & Hughes 2011; Sarıkaya & Çiner 2015).

Structure and key themes of this volume

We will now examine the key themes explored by the papers in this volume beginning in North Africa and moving clockwise around the Mediterranean. North Africa is represented by Hannah et al. (2016), who provide new insights into the origin of extensive plateau ice fields above 3500 m in the Tazaghart and Iouzagner areas of the Moroccan High Atlas. This is the first time that Pleistocene plateau ice fields have been described from North Africa. This paper also presents evidence for late Holocene niche glaciers in the High Atlas that were present during the Little Ice Age and, possibly, as recently as the mid-twentieth century.

The Iberian Peninsula is represented by three papers: two from Spain and one from Andorra. For northern Spain, Serrano et al. (2016) provide a new synthesis of the glacial history of the Cantabrian Mountains, including the Picos de Europa (Torrecerredo, 2648 m a.s.l.). They highlight the early maximum extent of glaciers during the last glacial cycle. Further south, Palacios et al. (2016) explore the nature and extent of glacier advances after the global Last Glacial Maximum (LGM) and present exposure ages from moraines dating to the Older Dryas. This interval was characterized by glacier advances or phases of glacier stability across central and northern Europe, but it has, until now, rarely been documented in the Mediterranean mountains. Turu et al. (2016) set out detailed evidence from an ice-marginal palaeolake sediment record in Andorra for a much larger marine isotope stage (MIS) 4 advance compared with that of MIS 2. Comparison with other areas of the Pyrenees highlights the asynchronous records of glacier fluctuations in different parts of these mountains and raises important questions about the underlying causes.

The glacial history of Italy is represented by two papers from contrasting areas: one from the Maritime Alps, where glaciers were contiguous with the main Alpine ice sheet, and one from the Apennines, where discrete glaciers formed on numerous mountains. For the former area, Federici et al.
provide detailed evidence of Late Pleistocene glaciation from the LGM to the Little Ice Age, with moraine positions dated using exposure dating (for the older features) and lichenometry for the late Holocene moraines. Giraud & Giaccio (2015) provide a much longer record of multiple glaciations in Italy from proglacial palaeolake basins in the Apennines. These are especially interesting because they preserve a record of glaciation that is commonly missing in the moraine record. Giraud & Giaccio (2015) report evidence of major Middle Pleistocene glaciations during MIS 14, 12, 10, 8 and 6. They also highlight the importance of tectonic processes (uplift and/or subsidence) in altering the relative positions of glacial features in the landscape.

Across the Adriatic, current knowledge of glaciations in Slovenia is reviewed by Ferk et al. (2015). As in Italy, two styles of glaciation have been recognized: one connected to the main Alpine ice sheet and one associated with more localized glaciation in the northern Dinaric Alps. Further south, in Montenegro, Adamson et al. (2016) report new evidence of glacier–fluvial interaction in the Bay of Kotor. Here, a large alluvial fan formed directly below a major outlet glacier of the former Orjen ice cap. The fan is Middle Pleistocene in age and closely related to the largest glaciation of this region that took place during MIS 12 (Adamson et al. 2014). Much further south on the Balkan Peninsula, Pope et al. (2015) report geochronological evidence from Mt Chelmos in the Peloponnesus, where a large ice cap, similar to that found on Mt Orjen, formed during the Middle Pleistocene. However, Pope et al. (2015) focus attention on the timing of the Late Pleistocene glaciation and provide evidence for an earlier glacier maximum dating to MIS 3, which was followed by glacier retreat to the high cirques in MIS 2. They present the first dates confirming the presence of Younger Dryas glaciers in Greece. Bathrellos et al. (2015) have compiled a database on the characteristics of cirques in the mountains of Greece. They discuss the potential effects of tectonism on these and other glacial landforms. This paper highlights some of the problems associated with the reconstruction of equilibrium line altitudes (ELAs) in areas of very active tectonics and assesses their usefulness for wider regional comparisons.

Turkey continues to be a very active area of Pleistocene glacial research. It is comprehensively represented here by three papers that include new regional syntheses and valley-scale case studies. Akgar et al. (2015) focus on a case study from Uludag in the far northwest in which they present a suite of 10Be exposure ages for one of the best-dated records in the Mediterranean mountains. Ciner & Sarkaya (2015) present the first glacial cosmogenic exposure age geochronology from the Bolkar Mountains of south-central Turkey with 30 new 36Cl exposure ages. The paper by Sarkaya & Ciner (2015) reviews the glaciations of southern Turkey and neighbouring countries, including Lebanon. Recent research by the teams associated with these papers has established the glacial geomorphology of the mountains of Turkey as one the best-dated records of its kind in the world.

Quaternary glaciation of the Mediterranean mountains: the current state of knowledge

Atlas Mountains

The Atlas Mountains were extensively glaciated during the Pleistocene. The glacial record in the Atlas Mountains is important for understanding the palaeoclimate of the Mediterranean during Pleistocene cold stages because they are the most southerly of all the Mediterranean mountains and lie between the North Atlantic Ocean, the Sahara Desert – the largest desert on Earth – and the Mediterranean Sea. The history of glacier research in this region is summarized in Hughes et al. (2004, 2011a), Messerli (1967) and Hannah et al. (2016) in this volume.

The most detailed studies of glaciation are from the Marrakech High Atlas, which culminate at Jebel Toubkal, the highest summit in North Africa (4167 m a.s.l.). There has been a long history of research in this area – for reviews of the earliest papers, see Dresch (1941) and Messerli (1967). A series of more recent studies has presented detailed geomorphological maps and cosmogenic ages for the landforms of this area (Hughes et al. 2011a, 2014; Hannah et al. 2016 in this volume).

Early research mentions significant glaciation in other parts of the High Atlas, such as on Irhil McGoun (4071 m a.s.l.) in the NE High Atlas (Wiche 1953) (Fig. 1), but no further research has been reported. Evidence of glaciation has also been reported in the Djurdjura (2308 m a.s.l.) and Aurès (2328 m a.s.l.) mountains of Algeria (Barbier & Cailleux 1950 and Ballais 1981, 1983, respectively). Despite the relatively low altitude and low latitude of the Djurdjura Mountains, the presence of glaciers in this area was noted as early as the nineteenth century by Raclus, who also provided a sketch map of the “Ancient glaciers of the Haizer Mountains” (part of the Djurdjura Mountains) (Raclus 1885, p. 207, fig. 67). However, most areas of the Atlas Mountains and adjacent chains in NW Africa have never been studied for evidence of Pleistocene glaciation. In this sense, large areas of the Atlas Mountains have not yet even attained...
pioneer phase status in the glacial geomorphological research hierarchy defined by Hughes et al. (2006a).

Iberia and Pyrenees

The Pleistocene glaciers of Iberia were strongly influenced by their proximity to the North Atlantic Ocean (Fig. 2) and the pattern of Pleistocene snowlines reflects the moisture supply over this peninsula. Some of the lowest glaciers were present in the north and west of the peninsula. For example, a large ice cap (c. 66 km$^2$) formed over the relatively low-lying Serra da Estrela (1991 m a.s.l.) in Portugal (Fig. 2) (Vieira 2008). The last ice cap on the Serra da Estrela appears to be Late Pleistocene in age based on $^{14}$C ages from lakes and bogs within the glacial limits as well as thermoluminescence dating of outwash (Janssen & Woldringh 1981; Van der Knaap & Van Leeuwen 1997; Vieira et al. 2001).

There has been a dramatic increase in the number of publications on Pleistocene glacial records from the mountains of Spain over the past 10 years, most of which present new geochronological data. The major and ongoing debate in this region relates to the timing of the maximum extent of glaciation during the last glacial cycle. Essentially, there have been two viewpoints: one where researchers find an early local glacier maximum, predating the global LGM by several to tens of millennia, and another where researchers argue that the largest glacier advance is broadly synchronous with the global LGM. This issue may have arisen due to the spatial complexity of climate and topography, with glaciers behaving rather differently depending on their location. In the Pyrenees, for example, the evidence from Andorra shows that the largest glaciers occurred in MIS 4, whereas the MIS 2 glaciers were the largest in the eastern Pyrenees (e.g. Delmas et al. 2011). There is a good deal of evidence in the Cantabrian Mountains of northern Spain that puts the largest glaciation of the last glacial cycle in MIS 3 or 4 (Jiménez-Sánchez & Farias 2002; Serrano et al. 2012, 2013, 2015, 2016). By contrast, the moraines damming Lago de Sanabria in the Sanabria National Park have been dated to MIS 2 (Rodríguez-Rodríguez et al. 2014) and were associated with an outlet glacier draining a large ice cap (Cowton et al. 2009). In the central and southern mountains of Spain, such as the Gredos (Palacios et al. 2011), Sierra de Guadarrama (Palacios et al. 2012) and Sierra Nevada (Gómez-Ortiz et al. 2012), all the current evidence points to the largest advance having taken place during MIS 2. In some cases the maximum glaciation was close in time to the global LGM (e.g. in the Gredos and Guadarrama), whereas in other areas it clearly predated it (e.g. the Sierra Nevada), although it was still within MIS 2. Domínguez-Villar et al. (2013) have argued that the MIS 2 advance in central Spain predated the global LGM by several thousand years.
The distribution of Pleistocene glaciation in the Mediterranean mountains and the associated equilibrium line altitudes (ELAs) at the maximum recorded phase of glaciation. This was inspired by a similar figure published by Messerli (1967, Karte 1) although it is updated and revised based on the most recent data available. It is known that the timing of glaciations varied across the Mediterranean mountains with some glaciers reaching their maximum extent in the Middle Pleistocene (Italy, Croatia, Montenegro, Greece), whilst other areas contain evidence of only Late Pleistocene glaciers (e.g. Turkey). The ELA isopleth map for the entire region is diachronous but provides an indication of Pleistocene glacier distributions. Even for the last glacial cycle glaciers reached their maximum extents at different times (Hughes & Woodward 2008; Hughes et al. 2013) and a synchronous ELA isopleth map for the entire region is likely to be unrealistic. A synchronous ELA isopleth map is only possible for well-dated moraines in narrow time intervals such as the global LGM (Hughes & Gibbard 2015) or the Younger Dryas (Renssen et al. 2015), when glaciers expanded in many areas. The legend lists key locations featured in this volume.
The deglacial (post-LGM) history of the Spanish mountains is now well constrained, with Palacios et al. (2016) revealing evidence for an Older Dryas advance. This occurred at a similar time to other advances across the Mediterranean associated with Heinrich Event I. However, evidence of a glacial advance associated with the Younger Dryas has so far proved elusive in Iberia and is not clearly recorded in the moraine succession, although it has been suggested for some mountains (e.g. Palacios et al. 2012), but not others (e.g. Palacios et al. 2011). The Younger Dryas has not been identified in moraine records in the Cantabrian Mountains, but it is well represented in lake sediment records. This is surprising given the proximity to the North Atlantic Ocean, where this climatic event is usually very clearly imprinted. Another potential explanation is the limited dating control for the moraine successions in the Cantabrian Mountains. The Late-glacial is often associated with rock glaciers in Spain (cf. Pellitero et al. 2011; Serrano et al. 2013). In the Sierra Nevada, rock glaciers continued to form until well into the Holocene, with some yielding exposure ages of c. 7 ka (Gómez-Ortiz et al. 2012). If rock glaciers were more important than glaciers in Spain during the Younger Dryas, this would have important palaeoclimatic significance, especially for establishing the track of moisture-bearing depressions at this time.

Real glaciers (rather than rock glaciers) have been confirmed in other parts of the Mediterranean mountains during the Younger Dryas through cosmogenic exposure dating of moraines. Examples are found in Morocco (Hughes et al. 2011a), in the Maritime Alps (Federici et al. 2008, 2016) and in Greece (Pope et al. 2015). The presence of glaciers (rather than rock glaciers) in these areas during the Younger Dryas suggests an excess of snow accumulation over the supply of debris. Rock glaciers are commonly indicative of dry and cold conditions (cf. Humlum 1998; Hughes et al. 2003), with some still active today in the highest Mediterranean mountains (Ribolini & Fabre 2006; Akçar & Schlüchter 2005). Older moraines are also present in many of these mountain areas, although the age of these glacial deposits has not yet been established (e.g. Gómez-Ortiz et al. 2012; Palacios et al. 2012).

The possibility cannot be ruled out that these glaciations date to early in the last glacial cycle or to one or more of the Middle Pleistocene cold stages. Middle Pleistocene glaciations have been confirmed in the glacial geomorphological record in only a few parts of Iberia and the Pyrenees. They have been identified beyond the limits of the last glaciation in the Pyrenees, an observation that was first made over half a century ago (Barrère 1963). The age and succession of the Middle Pleistocene glaciations in the Pyrenees is still unclear, however, and field evidence is patchy, with only a few radiometric ages published in recent years (e.g. Delmas et al. 2011). This is partly related to the fact that, in contrast to the situation in Greece, for example, the maximum extents of the glaciers of the last glacial cycle in the Pyrenees were close to the extent of the largest recorded Middle Pleistocene glaciations. The evidence is also patchy in Iberia, with limited evidence for large Middle Pleistocene glaciations. The most striking evidence is from the relatively low-lying Sierra de Quiexa and Serra do Gerês in the NW of the peninsula, where cosmogenic exposure ages place the largest glaciations firmly within the Middle Pleistocene, with a glacial chronological record dating to at least 250 ka (Fernandez Mosquera et al. 2000; Vidal Romani et al. 2015). This is based on a rather limited sample size (six samples using $^{21}$Ne with replicates on just two samples using $^{10}$Be) and more research is required to test this finding. There is also evidence of a major glaciation during the Middle Pleistocene in the Cantabrian Mountains of northern Spain, recently dated by uranium series (Villa et al. 2013). Earlier research in this region had hinted at the presence of major Middle Pleistocene glaciations (Gale & Hoare 1997) although, at present, the actual geomorphological evidence for moraines of this age is as limited as the geochronological control.

Maritime Alps and Apennines

The glaciers of the Maritime Alps appear to show patterns of advance and retreat that are similar to other parts of the Alps. Recent cosmogenic exposure dating by Federici et al. (2008, 2012) has helped constrain the timings of advances, revealing a classic Alpine succession of LGM, Gschnitz (equivalent in time to Heinrich Event I) and Egesen (Younger Dryas) moraines. This work is further refined in this volume by Federici et al. (2016), who present more ages from moraines to reinforce the view that the classic Alpine succession is evident in the Maritime Alps.

Western Balkans: Slovenia to Greece

The Pleistocene glaciers of Slovenia can be divided into those belonging to the main Alpine chain, which were contiguous with the main Alpine ice sheet, and those in the south of the country that formed separate ice masses in the Dinaric Alps. Small glaciers are present today in the mountains of Slovenia (Colucci 2016; Del Gobbo et al. 2016), including on the highest peak of Triglav (2864 m) and nearby Skuta (2532 m). The glacier on Triglav has decreased in size over the past 100 years, covering an area <0.01 km$^2$ since 2003 (Triglav Čekada et al. 2012;
Hughes 2014). The glacial record of Slovenia is still poorly dated – as noted in the review by Ferk et al. (2015) in this volume – although a few ages were presented over a decade ago in Bavec et al. (2004) from the glaciated Soča valley.

Lying immediately to the south of Slovenia, the Dinaric Alps of Croatia have been studied by several researchers. These can be divided into studies that focus on the Late Pleistocene geomorphological record, which is well preserved on mountains such as Velebit (Belj 1985; Bognar et al. 1991; Velić et al. 2011, Bočić et al. 2012) and Risnjak (Bogner and Prugovečki 1997). Other researchers also recognize much larger Middle Pleistocene glaciations that even reached offshore (Marjanac & Marjanac 2004, 2016; Marjanac 2012). The latter studies highlight the rich body of sedimentological evidence exposed at the present coast, including sites such as Novigrad More, where glacial deposits are visible in section. Erratics have been identified on the islands of Krk and Rab. Uranium series ages from secondary carbonates show that these deposits are Middle Pleistocene in age, with the oldest and most extensive glaciations correlating with the largest glaciations recorded further south in Montenegro and Greece. The full extent of glaciation in this area (Fig. 2) remains unresolved, however, and more basic field research is required to fully understand the extent of glaciation.

Evidence for large Pleistocene ice caps in Montenegro has been identified on the coastal mountains at Orjen (Hughes et al. 2010) and Lovćen (Žebre & Stepišnik 2014) and on interior mountains such as Durmitor (Djurović 2009; Hughes et al. 2011b), Kuć–Žijovo (Petrović 2014) and Prokletije (Milivojević et al. 2008). The Pleistocene ELAs of these glaciers, especially those on the coast, were some of the lowest in the Mediterranean mountains (Fig. 2), indicating high levels of precipitation during cold stages with a similar pattern to that observed today. The glaciated mountains of Slovenia, Croatia and Montenegro include some of the best examples of glacio-karst landscapes known in the Mediterranean region (Gams 1969; Lewin & Woodward 2009).

Large Pleistocene ice fields covered many parts of the Pindus Mountains in Greece, as well as on Mt Olympus in the northeast. The chronology of the Greek glacial sequence was established in Woodward et al. (2004) and Hughes et al. (2006b), with the largest glaciations dating to MIS 12 and 6 (Fig. 3), with much more restricted glacier development during the last glacial cycle, including the widespread occurrence of rock glaciers (Hughes

Fig. 3. Exposure in Middle Pleistocene moraine showing limestone-rich till on the southern slopes of Mt Tymphi near the village of Tsepelovo in the Pindus Mountains of NW Greece. Photograph taken by Jamie Woodward.
The restricted nature of the Late Pleistocene glaciation in Greece is confirmed by Pope et al. (2015) in this volume. These researchers applied cosmogenic exposure dating to show that Late Pleistocene glaciers on Mt Chelmos in the Peloponnese were restricted to the highest valley areas above 2000 m a.s.l. Further dating is required on the most extensive glacial deposits on Mt Chelmos and the surrounding areas to more clearly establish the patterns of glaciation in different cold stages in southern Greece. The patterns of glaciation in Greece reveal a strong west–east gradient in ELAs (Fig. 2). This implies that, like today, moisture was strongly associated with westerlies and hints at a west–east track of atmospheric depressions through the Mediterranean. However, questions remain over the extent and timing of glaciations on Mt Olympus (Smith et al. 1997, 2006) because there are anomalously low interpretations of ELAs in this area compared with the rest of Greece.

**Turkey and the Near East**

The last decade has seen a large number of studies published in this region (Akcıar et al. 2007, 2008, 2014; Sarkaya et al. 2008, 2009, 2014; Zahno et al. 2009, 2010; Zreda et al. 2011; Reber et al. 2014; Çiner et al. 2015). These are either 10Be or 36Cl exposure age studies. As reviewed by Sarkaya & Çiner (2015) and Akcıar et al. (2015) in this volume, all of these data indicate Late Pleistocene glaciation in Turkey.

In marked contrast with the records in Greece, Italy and the western Mediterranean, there is currently no published evidence of older Middle Pleistocene glaciations anywhere in Turkey. This suggests that the climatic controls on glaciation in Turkey during cold stages were not the same as those for most other mountain areas of the Mediterranean. Although ELA patterns do indicate a westerly source for moisture during the last cold stage in western Turkey (Fig. 2), the absence of an earlier glacier record may be related to the relative influence of the westerly atmospheric circulation as the primary source of moisture in different cold stages. If further research confirms that the Middle Pleistocene glaciers were smaller than the Late Pleistocene glaciers in Turkey, it may be because the climate was drier in the severe Middle Pleistocene cold stages in this region. For example, MIS 12 was one of the most severe glacial stages of the Pleistocene, with tree pollen absent from Tenaghi Philippou in NE Greece (Tzedakis et al. 2003). In NW Greece, the largest glacier advances were facilitated by some of the coldest summer temperatures of the Pleistocene (Hughes et al. 2007). However, unlike in NW Greece, the absence of similar large Middle Pleistocene glaciers in Turkey suggests that much colder summer temperatures were unable to offset the arid climate. This may suggest that westerly sourced depressions were unable to penetrate with significant effects into the far eastern Mediterranean during the Middle Pleistocene cold stages. A further consideration is the relative influence of the Indian monsoon v. climate systems from the North Atlantic, which are both known to affect the climate in Turkey and the Near East (Bar-Matthews et al. 2000, 2003). In the Holocene, for example, dry winters in Turkey were often associated with cold and wet winters in the European Alps (Jones et al. 2006). Thus, although these effects are not yet understood for the Pleistocene, it is likely that the climate in the eastern Mediterranean can be governed by rather different controls than that in the west. Establishing the magnitude and significance of effects on glacier behaviour across the Mediterranean mountains during different cold stages poses a challenge for future research. It should now be possible to use climate and glacier models to test some of these ideas.

**Mediterranean islands: Crete, Sicily and Corsica**

The Mediterranean islands contain some of the highest mountains in the region and many of these were glaciated in the Pleistocene. Corsica, for example, where the highest peak of Monte Cinto reaches 2706 m a.s.l., was extensively glaciated and some glaciers were up to 14 km long during the last cold stage (Conchon 1978, 1986). The first cosmogenic ages from moraines in Corsica were presented by Hewitt (2001). This pioneering study was followed by a larger dataset published in Kuhlemann et al. (2008), who applied 10Be analyses to show that the most extensive glacial phase of the last cold stage took place in MIS 2. On Sardinia, where the highest peak reaches 1834 m a.s.l. at Punta La Marmora, there is no evidence for significant glaciation. Nivation hollows appear to have been present in the Pleistocene (Messerli 1967), although the age of these features is unknown.

Mt Etna (3329 m a.s.l.) on Sicily is by far the highest mountain on the Mediterranean islands and one of the highest mountains in the entire region, yet clear evidence of glaciation has been buried by lava flows or obliterated by explosive volcanic activity, perhaps most recently in the Lateglacial (Albert et al. 2013). However, this volcano would have certainly been glaciated. Neri et al. (1994) and Neri (2002) estimated a Pleistocene snowline of c. 2500 m a.s.l. and Carveni et al. (2012) have identified morphological evidence of a glacial valley on the NE flank of Etna.

In Crete, the southernmost of the large Mediterranean islands, evidence of glaciation is limited and, in some areas, strongly contested (Hughes &
Woodward 2009). Perhaps the clearest evidence of former glaciation is on Mt Ida (or Mt Psiloritis, 2456 m a.s.l.), the highest mountain in Crete. Here, Fabre & Maire (1983) recognized a cirque with moraines at an altitude of c. 1945 m. Further west, in the White Mountains, Poser (1957), Bonnefont (1972) and Boenzi et al. (1982) did not find any evidence of glaciation. However, Bathrellos et al. (2015) in this volume and in an earlier paper (Bathrellos et al. 2014) report cirques in the White Mountains. Nemec & Postma (1993) have also argued that the White Mountains were glaciated during the Pleistocene and stated that ‘there is much compelling geomorphic indication of probable cirque glaciers or an ice cap with glaciers’ (Nemec & Postma 1993, pp. 237–238). They studied a series of alluvial fans in southern Crete and have argued that they were formed by large fluvial discharges associated with ice cap wastage in the White Mountains. They dated these fans to the Middle Pleistocene using uranium series techniques. Hempel (1991) recognized deposits in the White Mountains and on Mt Ida that he called ‘fluvial–nival’, which he ascribed to the Saalian glaciations on the basis of uranium series dating. Comprehensive field observations from the highest parts of the mountains of Crete are needed to fully test these ideas (Hughes & Woodward 2009; Hughes 2012). Establishing the true nature of the glacial record at this latitude in the eastern Mediterranean is important to better understand the pattern of glaciations across the entire Mediterranean region.

**Modern and Little Ice Age glaciers**

A small number of glaciers still survive in southern Europe. These are documented in Grunewald & Scheithauer (2010) and their locations are shown in Figure 4. The majority of modern glaciers in the Mediterranean mountains are restricted to the highest peaks over 3000 m a.s.l. in the Pyrenees and eastern Turkey. However, in wetter areas such as the western Balkans, small niche glaciers survive on mountains where the peaks are as low as 2400–2700 m a.s.l. (Hughes 2009). There are no modern glaciers in the Atlas Mountains, which represent the southernmost of the Mediterranean mountains. However, perennial snow fields did exist in the twentieth century and there is evidence for small niche glaciers, such as that below the cliffs of Tazaghart. This feature is discussed in detail in Hannah et al. (2016) and is thought to have formed during the Little Ice Age.

The Little Ice Age is known to have been a period of global glacier expansion beginning in the thirteenth century (or earlier) and reaching a maximum in the seventeenth to nineteenth centuries (Solomina et al. 2016). Hughes (2014) has identified many sites around the Mediterranean where glaciers were present during the Little Ice Age (Fig. 3). These include southern Spain, where the Corral Veleta glacier was present as late as the 1920s (Messerli 1967). Today, this feature is a buried ice patch and is technically permafrost – the most southerly known permafrost in Europe (Gómez et al. 2001). In northern Spain, west of the Pyrenees, ice patches still exist, although these are not dynamic ice masses and therefore technically not glaciers. However, true glaciers were present in several parts of Spain during the Little Ice Age (González Trueba et al. 2008).

Just over 20 glaciers survive today in the Pyrenees, whereas glaciers were present on 15 massifs in over 100 cirques during the Little Ice Age (see Grove & Gellatly 1995; González Trueba et al. 2008; Hughes & Woodward 2009). Some small glaciers also survive in the Maritime Alps, the southernmost outposts of the Alps, where 15 small glaciers were present at the end of the twentieth century (Federici & Pappalardo 1995). Further east in Slovenia, two glaciers have been reported in the Julian Alps below the peaks of Triglav (2864 m a.s.l.) (Triglav Čekada et al. 2012) and Skuta (2532 m a.s.l.) (Pavšek 2004), with two small glaciers also present on the slopes of Canin (2587 m a.s.l.) just over the border in Italy (Triglav Čekada et al. 2014). To the south in Montenegro, a small glacier still exists in the Durmitor Massif (Hughes 2007, 2008; Djurovic 2012) (Fig. 5). Several small glaciers survive in Albania (Hughes 2009), although the year-on-year status of these glaciers appears to change fairly rapidly (Gachev & Stoyanov 2012). Many more small niche glaciers existed throughout the Balkans in the Little Ice Age (Hughes 2010). There are no modern glaciers in Greece. Hughes et al. (2006c) argued that the last glaciers in the mountains of Greece were likely to be Younger Dryas in age. However, Smith et al. (1997) suggested that cirque moraines on Mt Olympus, the highest mountain in Greece, were Holocene ‘Neoglacial’ in age. Recent research by Styllas et al. (2016) has confirmed the presence of permanent snow fields in the northern cirque of Megali Kazania on Mt Olympus and these researchers use this evidence to argue that Holocene glaciers formed in this cirque. The presence of Holocene glaciers on Mt Olympus is plausible given the recent findings from Montenegro and Albania, although there is currently no unequivocal evidence for Holocene glaciers in Greece. Turkey has the largest number of modern glaciers in the Mediterranean region – at least 38 have been identified. The largest glaciers are found in southeast Turkey on mountains such as Cilo Sat (4135 m a.s.l.) (Hughes 2014). Turkish glaciers covered a total area of c. 22.9 km² in 1980.
Fig. 4. Locations of modern or Little Ice Age glaciers in the Mediterranean mountains based on Hughes (2014).
Kurter & Sungur 1980). The ELA of glaciers in the 1950s was between 3100 and 4200 m a.s.l., with the lowest glaciers present on the northern slopes of the Pontic Mountains, the highest in the eastern interior close to the border with Iran.

The state of the glaciers in all these areas is always changing and the total number of true glaciers is liable to change. This is not always towards fewer or smaller glaciers despite the trend towards a warmer climate. For example, the Triglav glacier in Slovenia expanded slightly in the early part of this century as a result of heavy snowfall in successive winters. In most areas, however, there has been a clear trend towards glacier retreat and extinction. This is highlighted by the fact that there were hundreds of small glaciers present in the Balkans in the Little Ice Age, yet there were fewer than 10 identified as active in the twentieth century (Hughes 2010). The extent of Little Ice Age glaciers is simply unknown in many areas and it is likely that many more sites of former Little Ice Age glaciers will become apparent. Thus small glaciers were present from the Atlas Mountains in the west to the Taurus Mountains in the east even during the late Holocene (Fig. 3).

Mediterranean glaciation: progress, problems and prospects

One outcome of the dramatic increase in published work on the glaciations of the Mediterranean mountains in the last decade is the emergence of important new questions. Although the pioneer phase had been attained in many regions by the time of Messerli’s classic 1967 review, it is only recently that the mapping and advanced phases have become established. The mapping and advanced phases have often occurred simultaneously because the creation of dating frameworks also requires accurate geomorphological base maps. However, it is apparent that the recent focus on rigorous mapping and dating has been concentrated in relatively few regions of the Mediterranean mountains and especially in Iberia/the Pyrenees and Turkey. There have been numerous studies in the last decade or so in the western Balkans, but large areas remain unstudied, including most of Bosnia and parts of Greece. In Italy, only a few areas have seen both mapping and dating applied to the glacial successions (Giraudi & Frezzotti 1997; Kotarba et al. 2001; Federici et al. 2008, 2012, 2016; Giraudi et al. 2011; Giraudi...
2012; Giraudi & Giaccio 2015). In Morocco, the mapping and advanced phases are only just beginning and here too this work is restricted to a relatively small area around the SW High Atlas. Areas that remain untouched beyond the most basic pioneer observations include Algeria, Bosnia, large areas of Albania and most of Lebanon. Some new dating of glacial moraines in Lebanon has been presented by Moulin et al. (2011) and is reviewed in this volume by Sarıkaya & Çınier (2015). However, detailed studies in this area are lacking and this is likely to remain the case for some time given the political instability in the region.

A full evaluation of the glacial history of the Mediterranean mountains is still hampered by the fact that large swathes remain undated. Even where mountains have many dates from glacial terrains, these are often focused on well-preserved Late Pleistocene moraines because they offer the best opportunities for cosmogenic exposure dating. Conversely, where other methods have been applied to older moraines, such as uranium series dating in the western Balkans, there has been only limited progress in dating the Late Pleistocene moraine successions. This is likely to change given the recent success of \(^{36}\text{Cl}\) dating on limestone terrains in Greece (Pope et al. 2015). Several different dating techniques need to be applied to fully understand the complexity and timespan of glacial successions in the Mediterranean mountains. For example, \(^{36}\text{Cl}\) dating in limestone terrains is appropriate for dating surfaces up to about 30–40 ka. Beyond this age range, surface weathering means that the technique becomes both inaccurate and imprecise. Conversely, uranium series dating of cemented moraines allows for ‘old’ Middle Pleistocene glacial sediments to be identified and bracketed in time, but the minimum ages generated by this approach mean that it lacks the precision needed to tie down the timing of glacier advances. Thus \(^{36}\text{Cl}\) exposure age dating is probably the best approach for dating Late Pleistocene moraines in the case of limestone terrains, whereas the technique is not viable for older Middle Pleistocene moraines and uranium series dating provides the best approach in these areas. These approaches should be used in tandem for successions that span both the Middle and Late Pleistocene. Similar issues can be identified with a range of other dating techniques, including radiocarbon and optically stimulated luminescence, and the future study of Mediterranean glaciations should strive to apply multiple techniques simultaneously.

This has now been achieved in many studies of the Pleistocene fluvial record in the Mediterranean (Lewin et al. 1991; Hamlin et al. 2000; Rowan et al. 2000; Schulte et al. 2008; Woodward et al. 2008; Macklin & Woodward 2009). This is the ideal approach, but resource constraints and the availability of suitable samples often provide obstacles to achieving this ambition.

Figure 2 illustrates the distribution of Quaternary glaciers in the Mediterranean mountains. This map is diachronous because some of these glaciers and associated snowlines are Late Pleistocene in age (e.g. in Turkey), whereas others are Middle Pleistocene in age (e.g. in Greece and Montenegro). Other glacier maxima that occurred within the same glacial cycle may have done so at different times (Hughes & Woodward 2008). Nonetheless, the pattern of glaciation and the lowest Pleistocene ELAs shown in this map reveal important insights into the key controls on glaciations: precipitation patterns and summer air temperatures. In general, glaciers had lower ELAs in places where the climate was wetter or colder. Pleistocene glacier equilibrium line distributions followed a similar pattern to today’s distribution of precipitation. This is significant because it highlights the role of the mid-latitude westerlies on glacier formation during Pleistocene cold stages because the wettest areas both today and during the Pleistocene include the western parts of Iberia, Italy, Greece and Turkey – areas which receive their precipitation predominantly from westerly derived depressions. In Iberia, these depressions are sourced in the Atlantic Ocean. The Mediterranean mountains that border areas of major modern cyclogenesis – such as the Alboran Sea, Gulf of Genoa, the Adriatic Sea and Aegean Sea – are characterized by some of the lowest glaciers of the Pleistocene.

The generalization of Figure 2 belies the fact that glacier behaviour was very different spatially and temporally across the Mediterranean mountains. Existing evidence of the glaciations across the Mediterranean reveals both similarities and contrasts. For example, the large Middle Pleistocene glaciations of the western Balkans are not matched in Turkey or in North Africa. This may be an artefact of the dating technique used, with the oldest moraines in some especially seismically and geomorphologically active areas being beyond the resolution of cosmogenic exposure dating. In other situations the contrasts appear to be real, such as the absence of Middle Pleistocene glaciations in Turkey even though they are clearly present in Greece. Explaining this pattern represents a key challenge for any pan-Mediterranean palaeoclimate modelling based on the glacier record.

The problem of tectonics and its effects on the landscape cannot be ignored in the Mediterranean glacial record. The Mediterranean mountains lie in a zone of ongoing and intense tectonic activity and their very existence is a product of this setting (cf. Roberts & Stewart 1994; Faure Walker et al. 2012). Rates of uplift and subsistence vary dramatically across the region, however (Mather 2009) so
that, as we go further back in time, the position of the land surface relative to the Earth’s geoid becomes distorted. This effect is compounded by the fact that sea-levels have also changed dramatically during the glacial and interglacial cycles of the Quaternary. In this volume, Giraudi & Giaccio (2015) and Bathrellos et al. (2015) attempt to address the issue of tectonics. Hughes (2004, pp. 226–227) argued that tectonic uplift in the Pindus Mountains of Greece is countered by lowered relative sea-levels during cold stages so that the effects of uplift on mountain altitudes have been insignificant for the last 300,000 years or so. By contrast, Smith et al. (2006) estimated that uplift-corrected palaeo-ELAs on Mt Olympus were as low as 500–600 m a.s.l. This is >1000 m lower than the uncorrected ELAs reconstructed for the Pindus Mountains in the west. Such dramatic uplift corrections complicate comparisons across wide areas (hence the question mark for Mt Olympus in Fig. 2). In this volume, Pope et al. (2015) confront this problem, although for the Late Pleistocene at least they consider the uplift question of negligible significance for reconstructing palaeo-ELAs. It can be argued that this is even the case in an area subject to the most intense tectonism in Greece, close to the Gulf of Corinth (cf. Roberts & Stewart 1994; Pirazzoli et al. 2004). For Middle Pleistocene glacier reconstructions this issue is potentially even more problematic. Despite the problems in accounting for tectonic uplift, Hughes (2004) and Hughes et al. (2006d) argued that changes in uplift and relative sea-level do not affect any extrapolation of temperature to different altitudes if it is assumed that the uplift between extrapolated points has been relatively uniform. At the cirque valley scale this may be a reasonable assumption, although Giraudi & Giaccio (2015) highlight the possibility of significant tectonic distortions even at this scale. The importance of such local tectonic differences for glacier reconstructions is open to debate, largely because of difficulties in establishing the significance of the impact. However, the tectonic issue cannot be ignored when comparing reconstructed ELAs over hundreds of kilometres across and between massifs, especially for the older Middle Pleistocene glaciations. For Late Pleistocene glaciations the tectonic factor is not likely to be climatically significant so that the ELAs are likely to be comparable across mountain chains and even across the entire Mediterranean region. Even for the Middle Pleistocene, the effects of uplift are countered by the fact that cold stage sea-levels were >120 m lower than today (see discussion in Pope et al. 2015). Although tectonics is clearly fundamental in shaping the Mediterranean mountains in the longer term (i.e. over the whole Cenozoic), climate is arguably the main driver of geomorphological change over the timescales of the Middle and Late Pleistocene. A similar conclusion was reached from the study of fluvial records across several sites in the Mediterranean region by Macklin et al. (2002). This should therefore encourage future mapping, dating and reconstruction of these glacier records to refine and fully test the distribution illustrated in Figure 2, with the goal of providing a temporally dynamic series of ELA maps for the Mediterranean mountains.

Mediterranean glaciers had significant impacts on downstream fluvial regimes and sediment supply (Lewin et al. 1991; Woodward et al. 2008). Several studies have identified the impacts of glaciation recorded in downstream fluvial sediments (Woodward et al. 1992, 1994, 1995, 2008; Lewis et al. 2009), including their role in filling polje basins in classic karst terrains (Adamson et al. 2014, 2016). Changes in glacial meltwater flux can have significant impacts on lake levels (Wilson et al. 2015), especially in limestone areas where large volumes of meltwater are transferred via subterranean karst conduits (Woodward et al. 2008; Adamson et al. 2014; Wilson et al. 2015). From their study of the marine sediment record offshore of southern France, Bonneau et al. (2014) have shown that turbidity current activity was greater during the last glacial than in the Holocene. They were also able to show how the flux of fine-grained sediment from glaciated mountain catchments to offshore basins decreased significantly following glacier retreat. Linking the onshore and offshore records of Pleistocene glacial activity is a key objective for future research. The mountains of the Mediterranean are known to have hosted refugia for temperate flora and fauna during glacial stages (Tzedakis 1993, Hewitt 2000) and it is likely that glaciers were a significant influence on the geography of refugia due to their physical presence and influence on microclimates, while also sustaining some refugia through the supply of meltwater. The interactions between glaciers and Pleistocene refugia in the Mediterranean uplands is worthy of more systematic research.

Conclusions

Our understanding of the Pleistocene glaciations of the Mediterranean mountains has improved dramatically over the last decade. This has largely resulted from the widespread application of geochronological techniques to date moraines and associated sediments and landforms as well as studies of the coarse- and fine-grained outwash deposited in downstream fluvial systems. This volume presents a large body of new work from some of the leading researchers in the study of Mediterranean glaciations and signposts key opportunities for future
Much of this future activity will be driven by the key themes of timing and palaeoclimate as well as attempts to link the terrestrial and offshore records. Dating methods are now more widely available and many researchers have recognized the importance of building robust geochronologies for glaciation across the region. This will provide a platform for the development of temporally and spatially dynamic palaeoclimatic simulations for multiple glacial phases across the Mediterranean mountains.

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