

# Timing of glaciation in the Mediterranean mountains during the last cold stage

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**ABSTRACT:** Recent research in the mountains of the Mediterranean has attempted to establish the timing of the maximum extent of glaciers during the last cold stage. Several dating methods have been utilised and new dating frameworks have emerged in key areas. In several places, multiple dating techniques (radiocarbon, optically stimulated luminescence, U-series) applied to glacial and associated sediments suggest that local glacier maxima preceded the *global* Last Glacial Maximum (LGM, ca. 18 <sup>14</sup>C ka BP/ 21 cal. ka BP) by at least several thousand years. Studies in Spain, the Pyrenees, the Maritime Alps and Turkey utilising cosmogenic isotope analyses (<sup>10</sup>Be and <sup>36</sup>Cl), have yielded glacial geochronologies with maxima that correlate closely with the marine isotope record of ice volume and the global LGM. In some cases, the use of different geochronological techniques has led to conflicting evidence for the timing of the local last glacier maxima in the same area. From a palaeoclimate perspective, glacier–climate reconstructions for the *local* last glacier maxima in the mountains of central Italy, northern Greece and western Turkey indicate that climate was wet and cold. In Italy and Greece the local glacier maxima preceded the driest part of the last cold stage – as indicated by palaeoecological records – by several thousand years. For western Turkey, however, recent cosmogenic exposure ages combined with glacier modelling suggest a local last glacier maximum characterised by cold and wet conditions coinciding with the global LGM. The available evidence indicates that a dichotomy is emerging, not only in our understanding of the timing of glaciation across the Mediterranean, but also in the palaeoclimatic interpretations derived from glacial and palaeoecological records. Copyright © 2008 John Wiley & Sons, Ltd.



**KEYWORDS:** Mediterranean; glaciers; glaciation; Late Pleistocene; geochronology; dating.

## Introduction

The nature of cold-stage climates in the Mediterranean region has been the focus of much research in recent decades, with particular emphasis on the last cold stage (Marine Isotope Stage (MIS) 5d-2; Alpine chronostratigraphy – Würmian Stage). Long lacustrine sequences from tectonic and volcanic basins and speleothem records have provided much of the terrestrial evidence for former environmental conditions (Tzedakis *et al.*, 1997; Allen *et al.*, 1999; Bar Matthews *et al.*, 1999). However, the timing of glacial activity in the Mediterranean mountains during the last cold stage has proved difficult to establish (Hughes *et al.*, 2006a). Progress has been made using radiocarbon dating of lacustrine deposits within former glacier limits (e.g. González-Sampériz *et al.*, 2006) and uranium series dating of fluvial deposits in valleys downstream of former glaciation (e.g. Lewin *et al.*, 1991; Woodward *et al.*, 2008). It is only very recently, however, that well-dated records have been

obtained from the glacial sediments and landforms themselves. In addition, recent developments in cosmogenic isotope analyses have led to some of the first publications of exposure ages for glacial features in the Mediterranean (e.g. Akçar *et al.*, 2007).

This paper reviews the available glacial geochronological data from the Mediterranean mountains for the last cold stage, including the Younger Dryas, and examines the evidence for glacier advances in conjunction with other records of regional and global climate change. This paper forms part of the INQUA Mountain Glacier Research Project 'Timing and Nature of Mountain Glacier Advances, from 5e to YD'. We examine the timing of glacier development across the Mediterranean and consider regional glacier dynamics in relation to the Last Glacial Maximum. This global stratigraphical event is abbreviated LGM in this paper and occurred at ca. 18 <sup>14</sup>C ka BP or ca. 21 cal. ka BP (cf. CLIMAP Project Members, 1976; Martinson *et al.*, 1987; COHMAP Members, 1988; Yokoyama *et al.*, 2000).

Middle Pleistocene glacier activity has been recognised in several Mediterranean mountain areas, including north-west Spain, the Pyrenees, the Italian Apennines and the Pindus Mountains of Greece (Fernandez Mosquera *et al.*, 2000; Kotarba

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*et al.*, 2001; Peña *et al.*, 2004; Woodward *et al.*, 2004; Hughes *et al.*, 2006b). In all of these areas the Late Pleistocene glaciations appear to have been significantly smaller than during the Middle Pleistocene cold stages. In some places, such as western and northeastern Turkey, evidence of glacial deposits older than the Late Pleistocene has not yet been found (Akçar *et al.*, 2008; Sarıkaya *et al.*, 2008). Attempts to establish the timing of glacier activity during the last cold stage in the Mediterranean mountains have involved a range of techniques including radiocarbon, luminescence (thermoluminescence and optically stimulated luminescence (OSL)) and cosmogenic nuclide analyses. The timing of glaciation during the last glacial cycle has also been inferred from the dating of related sediments, such as those in fluvial sequences downstream of glaciated areas. The geochronology of glaciation during the last cold stage is reviewed below with reference to individual mountain areas surrounding the Mediterranean Sea. These glaciers were small compared to the glaciers in the Alps and elsewhere in Europe during the Late Pleistocene, but their small surface areas and southerly latitude made them especially sensitive to climate change. The European Alps are beyond the scope of this paper, but we include the Maritime Alps because of their very close proximity to the Mediterranean littoral at the Côte d'Azur (Fig. 1).

## Glacial geochronology

### Iberia: Spain and Portugal

Until recently, there was limited geochronological control on the timing of Pleistocene glaciations in Spain and Portugal. Dating frameworks now exist for glacial sediments and landforms in the mountains of northwest Iberia, central Spain and the Cantabrian Mountains (Fig. 1).

Jiménez-Sánchez and Farias (2002) provided the first numerical age determinations (using radiocarbon dating) to establish the chronology of glacial phases in the Redes Natural Park of the Cantabrian Mountains. The most extensive glacial phase here was characterised by an ice field with outlet glaciers extending up to 5 km in length, descending to ca. 950 m above sea level (a.s.l.) with snowlines at ca. 1550 m a.s.l. A radiocarbon date of  $28.99 \pm 0.23$   $^{14}\text{C}$  ka BP ( $34.177 \pm 0.516$  cal. ka BP) was obtained for this glacial phase from a core retrieved from ice-dammed lacustrine deposits that formed when drainage was blocked by a lateral moraine. This provides a minimum age for the presence of glacier ice. Furthermore, radiometric dating of proglacial deposits, interpreted as being synchronous with the local last glacier maximum in the nearby Comella basin of the Picos de Europa, yielded an age of  $40.48 \pm 0.82$   $^{14}\text{C}$  ka BP. These dates, from the Redes Natural Park and the Picos de Europa, imply that the maximum phase of glaciation during the last glacial stage took place much earlier than the global LGM.

In central Spain, Palacios *et al.* (2007) have reported  $^{36}\text{Cl}$  exposure ages for glacial landforms in the Sierra de Gredos and Sierra de Guadarrama. These dates place the local glacier maximum in these mountains at ca. 21 ka – around the time of the global LGM. No earlier glacial formations were found in this area, in contrast to the record from northwest Iberia discussed below.

In the Serra da Estrela, the highest mountains of Portugal (1991 m a.s.l.) (Fig. 1), glaciation during the last cold stage was characterised by a plateau ice cap which fed diffluent glaciers, the longest of which was 13 km (Daveau, 1971). Thermo-

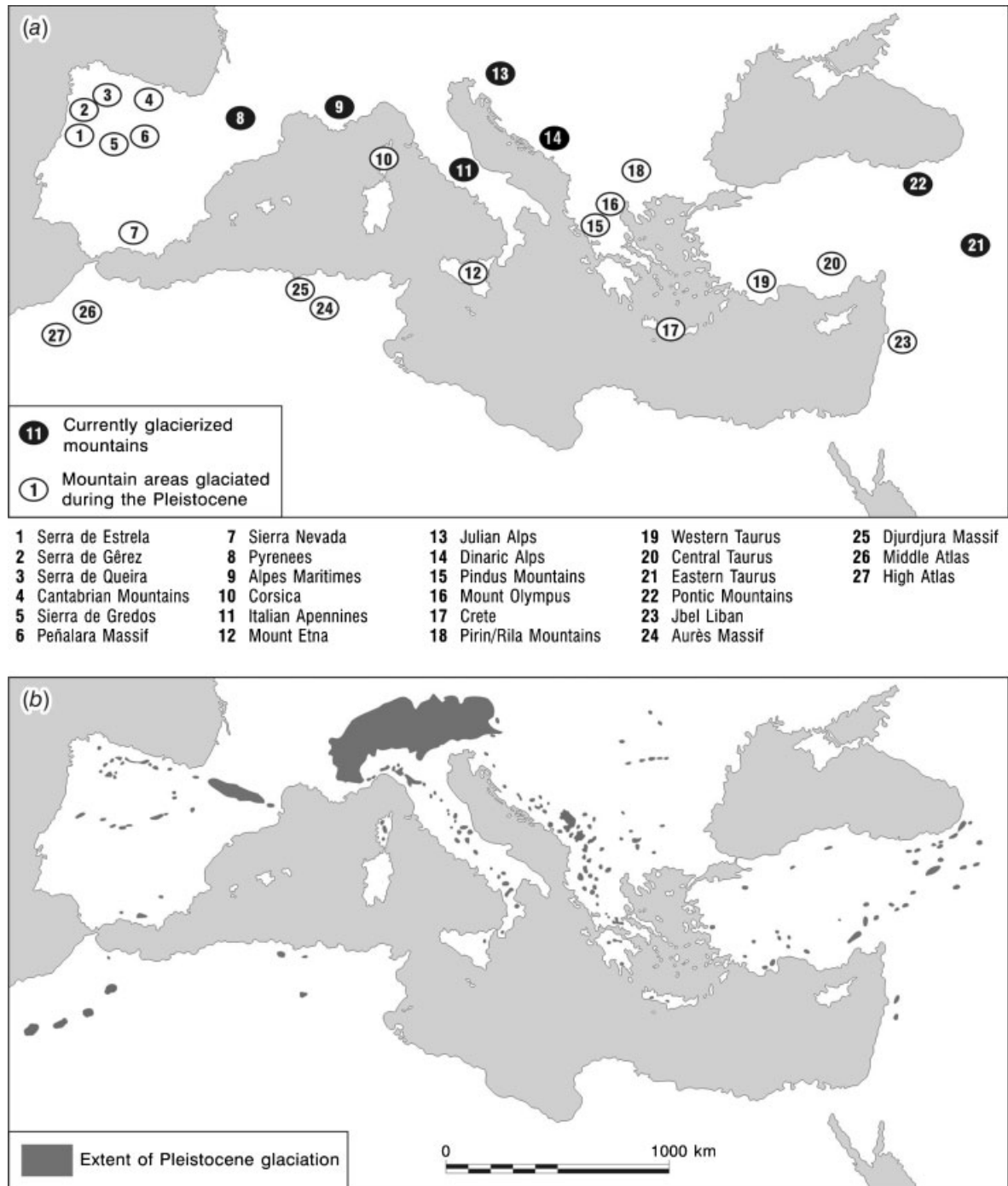
luminescence dates from glaciofluvial sediments of between  $16.6 \pm 2.5$  and  $10.6 \pm 1.6$  ka BP suggest glacial activity during the Lateglacial (Vieira *et al.*, 2001). These were the first radiometric ages to be published on the Estrela glaciations, although the precise timing of the last local glacial maximum in this region has not yet been established.

Further north in the Quiexa (Galicia, Spain) and Geres (Portugal) massifs (Fig. 1),  $^{21}\text{Ne}$  cosmogenic isotope analyses ( $n=5$ ) have been applied to date glacially polished bedrock surfaces and push-moraine boulders (Vidal-Romaní *et al.*, 1999; Fernadez Mosquera *et al.*, 2000). Three glacial phases have been identified. The oldest was dated to before ca.  $238 \pm 17$  ka, an intermediate phase to ca.  $131 \pm 17$  ka and the youngest to ca.  $15 \pm 7$  ka. The youngest age is supported by a radiocarbon date of  $13.4 \pm 0.4$   $^{14}\text{C}$  ka for the base of lacustrine sediments from a glacial lake in the same area (Vidal-Romaní and Santos, 1994). These later dates also provide support for the thermoluminescence ages of Vieira *et al.* (2001) from the Estrela massif, but none of the dates provide a clear picture of the timing of the last glacial maximum in this area.

### The Pyrenees

Several studies from lake and bog sequences within former glacier limits on both the northern and southern slope of the Pyrenees have produced radiocarbon ages suggesting maximum glacier advances that were asynchronous with the record of global ice volume – in several areas preceding the global LGM by tens of thousands of years (e.g. Mardones and Jalut, 1983; Andrieu *et al.*, 1988; Jalut *et al.*, 1988, 1992; Reille and Andrieu, 1995; García Ruiz *et al.*, 2003; González-Sampériz *et al.*, 2006). Some of the oldest radiocarbon ages were presented by Mardones and Jalut (1983) and Andrieu *et al.* (1988) from the Pau valley on the northern slope of the Pyrenees. Here a date of  $38.4$   $^{14}\text{C}$  ka BP was obtained near the base of a lacustrine sequence within piedmont moraines. Mardones and Jalut (1983) extrapolated this date to the base of the lacustrine sequence and calculated the onset of deposition at ca.  $45$   $^{14}\text{C}$  ka BP and suggested an age of between 70 and  $50$   $^{14}\text{C}$  ka BP for the piedmont moraines. The validity of an early last glacier maximum in the Pyrenees has been questioned by Turner and Hannon (1988, p. 56) who noted: 'Extraordinarily, Mardones and Jalut (1983) accept these as true dates of the deposits.' Nonetheless, similar findings have been reported elsewhere in the region, such as at the Llestui glacial lake in the Ribagorçana Valley in the south-central Pyrenees. Here, Vilaplana (1983) presented radiocarbon dates of between 34 and  $31.5$   $^{14}\text{C}$  ka BP. An early glacier maximum in the Pyrenees during the last cold stage was also proposed by Bordonnau (1992), who placed the maximum at ca.  $60$   $^{14}\text{C}$  ka BP and by Montserrat (1992), who placed the maximum between 50 and  $45$   $^{14}\text{C}$  ka BP. Turner and Hannon (1988, p. 57) suggested that the old  $^{14}\text{C}$  ages, first reported in Mardones and Jalut (1983), are likely to have been affected by hard-water error or possibly a mixture of reworked organic matter – a view reiterated by Pallàs *et al.* (2007).

Despite the issues of reliability that plague the early glacial geochronologies based on dates at the limit of the radiocarbon method, more recent studies do corroborate the idea of an early glacier maximum in the Pyrenees. For example, García-Ruiz *et al.* (2003) and González-Sampériz *et al.* (2006) presented radiocarbon dates from glacial lake sediments in the Upper Gállego Valley in the central Spanish Pyrenees. A date of  $28.3 \pm 0.37$   $^{14}\text{C}$  ka BP (ca. 32 977 cal. ka BP) derived from pollen concentrate from the base of lacustrine sediments resting

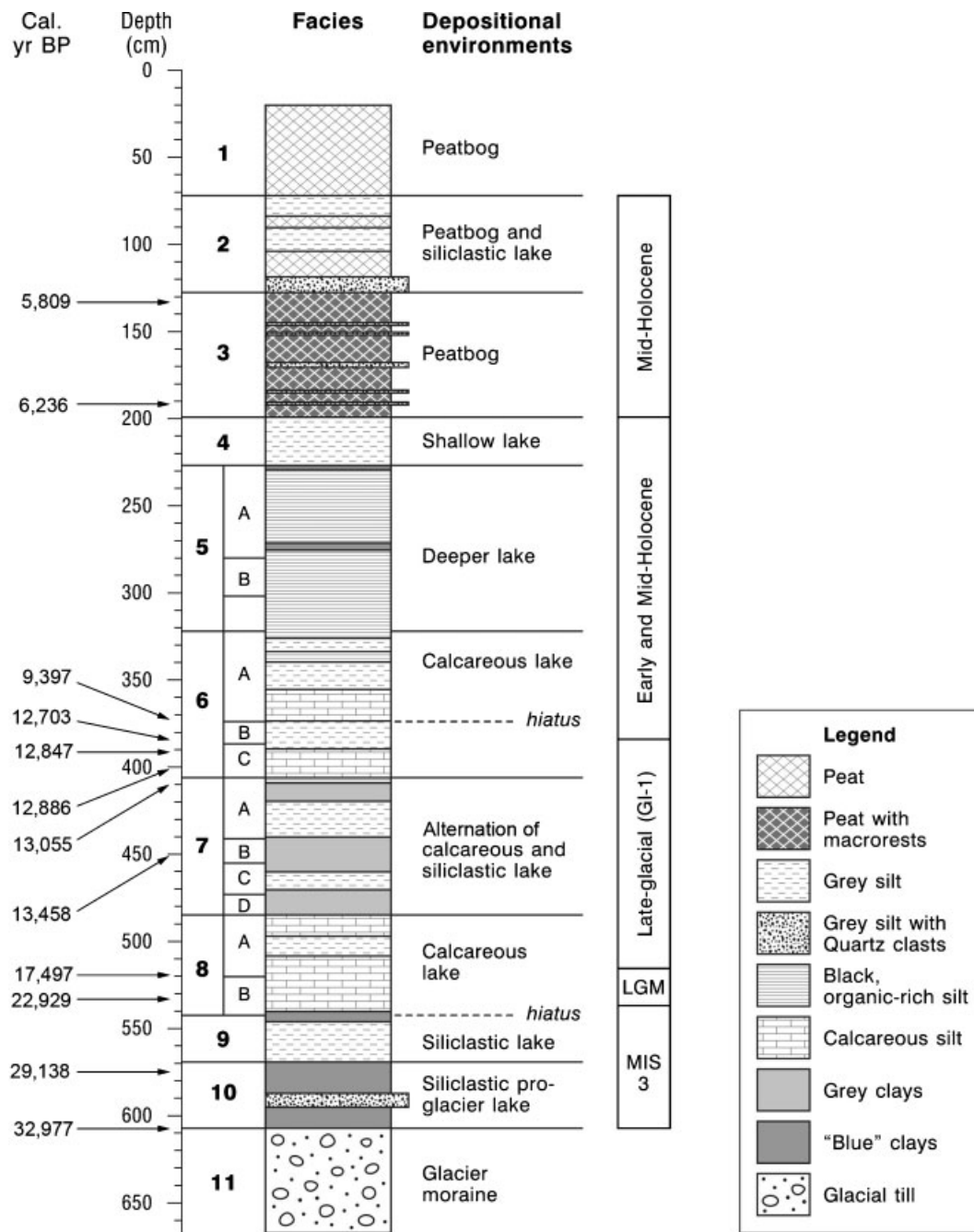


**Figure 1** (a) Mountains of the Mediterranean currently glacierised and glaciated during the Pleistocene. (b) Extent of Pleistocene glaciation in the Mediterranean (after Messerli, 1967, and Hughes *et al.*, 2006a). This map is schematic and, because of scale, does not intend to provide an accurate depiction of exact glacier sizes and locations

on moraine deposits at the El Portalet site (González-Sampérez *et al.*, 2006) suggests that the glacier maximum in this area during the last cold stage also pre-dates the LGM at  $18^{14}\text{C}$  ka BP (ca. 21 cal. ka BP) (Fig. 2). This is consistent with the findings elsewhere in the Pyrenees suggesting an early local last glacier maximum. A hiatus in the lacustrine sequence at  $19.25 \pm 0.12^{14}\text{C}$  ka BP is interpreted as an erosion surface caused by glacier readvance corresponding to the LGM. However, there is no direct evidence of glacier readvance at this time – other than the presence of a hiatus in the lacustrine sedimentary record represented by sharp changes in vegetation associations and very low sedimentation rates. All three features could have resulted from climatic deterioration in the absence of glacier advance, especially if conditions in the Mediterranean became

drier around the time of the global LGM (cf. Pons and Reille, 1988; Allen *et al.*, 1999; Fontugne *et al.*, 1999; Tzedakis, 1999).

Other geochronological data are available for the Pyrenees in the form of optically stimulated luminescence (OSL) ages. Sancho *et al.* (2002) interpreted OSL ages from till deposits in the Cinca Valley as indicating that the maximum extent of Late Pleistocene glaciers in this area was reached at ca.  $53.2 \pm 6.6$  ka (weighted average of two dates). This age is consistent with OSL ages of  $58.1 \pm 3.2$  ka (weighted average of six dates) obtained from sediments within a large terraced fluvial aggradation located downstream of the glacial deposits well above the active channel, which Sancho *et al.* (2002) interpreted as being related to former glacier outwash. Peña *et al.* (2004) also applied OSL to date glaciofluvial deposits in

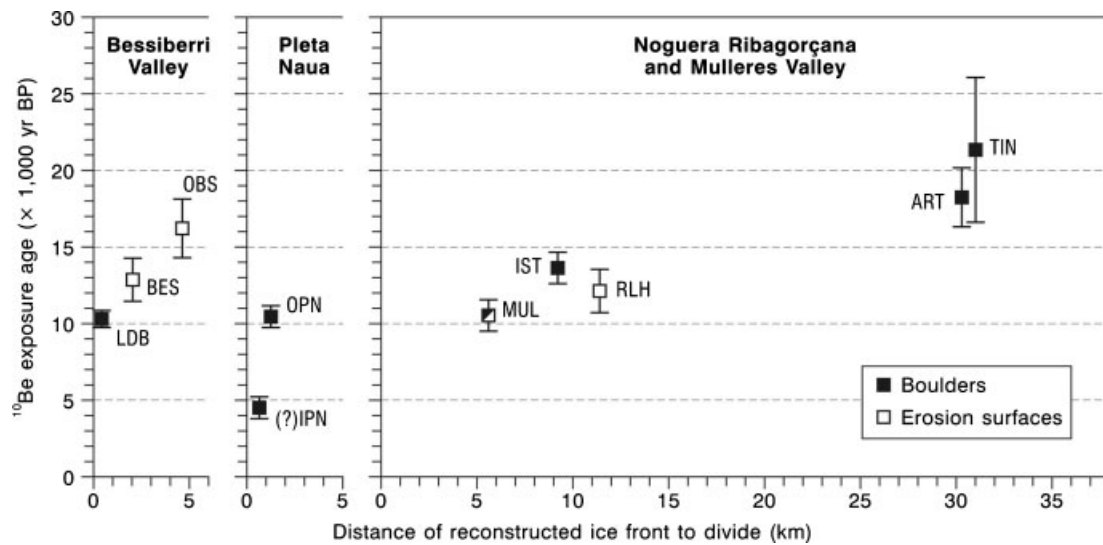


**Figure 2** Lithological description of the El Portalet sequence in the upper part of the Gallego valley in the central-western Spanish Pyrenees, showing radiocarbon ages down the core. The El Portalet peat bog is located within a small cirque and is enclosed by moraines (González-Sampérez *et al.*, 2006). The oldest radiocarbon dates provide minimum ages for the moraines. Redrawn with permission from Elsevier

the Gállego Valley to the west. They were able to differentiate between three phases of glacier advance using OSL, at ca. 155.8 ka (Sabiñánigo phase), 85 ka (Aurín phase) and 35.7 ka (Senegüe phase). The youngest phase of glaciation clearly pre-dates the global LGM by nearly 15 ka and provides some independent support for the radiocarbon-based dating frameworks from other glacial sequences in the Pyrenees.

Recent cosmogenic nuclide analyses appear to conflict with the dating frameworks that argue for an 'early' glacier maximum in the Pyrenees and suggest a local glacier maximum after 25 ka ago. Pallàs *et al.* (2007) presented 25  $^{10}\text{Be}$  exposure analyses for granodioritic glacial erosion surfaces and boulders in the Upper Noguera Ribagorçana Valley in the south-central Pyrenees (Fig. 3). On the lowermost glacial units, the oldest exposure age was  $21 \pm 4.4$  ka and was obtained from an erratic boulder. However, they also obtained a much younger

$^{10}\text{Be}$  exposure age of  $6.6 \pm 1.4$  ka on the same stratigraphical unit. Conversely, a  $^{10}\text{Be}$  exposure age of  $25.3 \pm 2.4$  ka has been obtained from some of the highest moraines (known as the 'Hospital moraines') in the Upper Noguera Ribagorçana Valley. Pallàs *et al.* (2007, p. 2954) argue that: 'Some  $^{10}\text{Be}$  dates are incoherent when compared with dates from the same moraine or dates from neighbouring sites. Such aberrant cases were avoided by withdrawing (1) one date (ART01) differing by more than two standard deviations with respect to the older dates from the same moraine, and (2) dates inconsistent with the geomorphologically based relative chronology. The minimum exposure age of each moraine was then deduced by calculating the error weighted mean of the remaining dates.' Despite these problems, which are common with cosmogenic exposure 'ages' and are discussed further below, the recent challenge to the idea of an early glacial maximum in the



**Figure 3** Time–distance diagram illustrating  $^{10}\text{Be}$  exposure ages against distance upvalley in the glaciated Noguera Ribagorçana and Mulleres valleys in the south-central Pyrenees (Pallàs *et al.*, 2007). The Bessiberri and Pleta Naua valleys are situated in the upper catchment of the Noguera Ribagorçana valley. The  $^{10}\text{Be}$  dates appear to suggest that the exposure ages of the lowest moraines straddle the global last glacial maximum (LGM) at ca. 21 ka (samples ART and TIN). Redrawn with permission from Elsevier

Pyrenees by Pallàs *et al.* (2007) is certainly intriguing and future progress may hinge on the parallel application of different dating techniques to test the various hypotheses.

### The Maritime Alps: France and Italy

The Maritime Alps of southern France and western Italy currently support 15 small glaciers (Federici and Pappalardo, 1995). These glaciers are the southernmost of the Alpine chain and some are situated less than 50 km from the Mediterranean coast (Fig. 1). During the last cold stage (Würmian Stage), the Maritime Alps were covered by ice that was contiguous with the main Alpine ice sheet to the north, extending over an area of ca. 126 000 km<sup>2</sup> (Ehlers, 1996). Lacustrine sediments at the glacial Lac Long Inférieur (2090 m a.s.l.) indicate that deglaciation had begun by  $14.19 \pm 0.13$   $^{14}\text{C}$  ka BP (Ponel *et al.*, 2001).

The lowest frontal and lateral moraines in the Gesso Valley have recently been dated using  $^{10}\text{Be}$  nuclide analysis (Granger *et al.*, 2006). Boulders sampled on two separate moraine crests gave mean  $^{10}\text{Be}$  cosmogenic ages of  $16.3 \pm 0.88$  and  $18.798 \pm 0.973$  ka. Granger *et al.* (2006) argued that these two moraines represent the inner and outer moraine crests of the same glacial event. The older maximum age of the Gesso glacier is broadly consistent with the Alps further north, where the northern lobe of the Rhône glacier reached its maximum extension between ca. 21 and 19.1 ka ago around the time of the global LGM (Ivy-Ochs *et al.*, 2004).

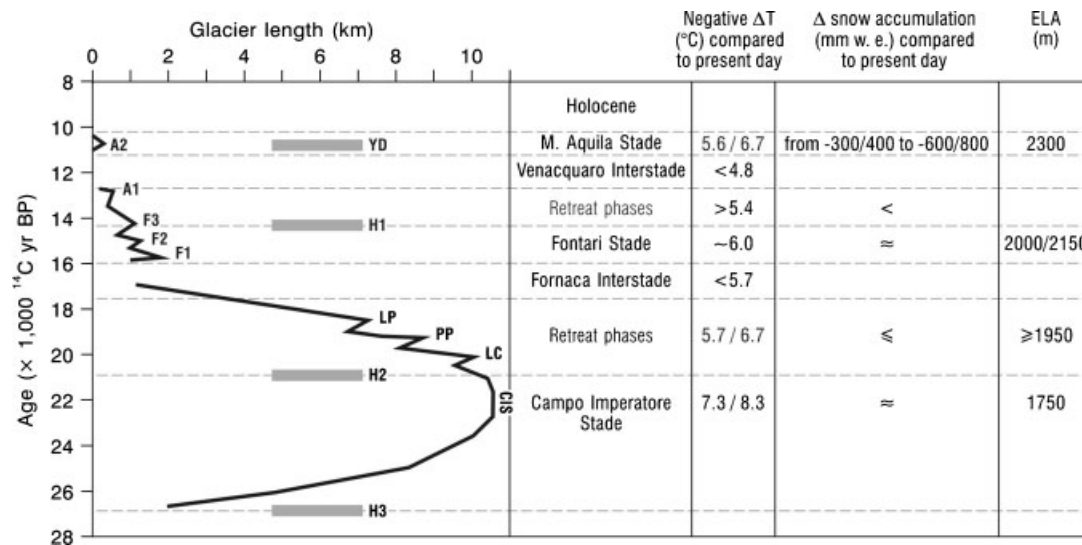
Later glacier advances at higher elevations in the Gesso valley have also now been dated using  $^{10}\text{Be}$  exposure age dating (Federici *et al.*, 2008). Four boulder samples from the Piano del Praiet frontal moraine gave a weighted mean age of  $11.34 \pm 0.37$  ka. Federici *et al.* (2008) suggest that the frontal moraine correlates with the Egesen stadial of the Alps (Younger Dryas) and they argue that this suggests a synchronicity of the Egesen deglaciation across the European Alps. Comparison with other areas of the European Alps suggests that the Maritime Alps experienced wet and cold climatic conditions during the Younger Dryas – in common with the Pindus Mountains of Greece further to the east (Hughes *et al.*, 2006c).

### The Italian Apennines

In the Gran Sasso massif of the Central Apennines (Fig. 1), Giraudi and Frezzotti (1997) mapped a series of moraines and rock glaciers and demonstrated that the maximum glacier extent occurred prior to  $22.68 \pm 0.63$   $^{14}\text{C}$  ka BP ( $27\,230 \pm 868$  cal. ka BP) in the Campo Imperatore valley (Fig. 4). This indicates that the valley glacier in this area reached its maximum prior to the global LGM. A series of recessional moraines and rock glaciers are thought to correspond to periods of glacier stabilisation or readvance between 20 and 10  $^{14}\text{C}$  ka BP, including during the Mount Aquila stadial, which is correlated with the Younger Dryas Chronozone (Fig. 4). Little geochronological evidence exists elsewhere in this region and many papers assume that moraine assemblages formed during the last cold stage (Würmian) (e.g. Boenzi and Palmentola, 1997).

### Montenegro

By Mediterranean standards, Montenegro was host to very large glaciers during the Pleistocene and included ice caps which submerged large areas of the central uplands (Liedtke, 1962). Extensive glaciers also developed on the coastal mountains, such as Orjen (1894 m a.s.l.) (Sawicki, 1911; Menkovic *et al.*, 2004). Recent U-series dates from secondary calcites within moraines from sites across Montenegro indicate that the largest glaciations occurred during the Middle Pleistocene cold stages (Hughes and Woodward, unpublished data). At the head of the Karlica valley in the Durmitor massif, there is a modern glacier with a suite of large frontal moraines dated using lichenometry to the late 19th and early 20th centuries (Hughes, 2007). Around 1 km down-valley of this small glacier, just above the Struga pass between the peaks of Međed (2287 m a.s.l.) and Savin kuk (2313 m a.s.l.), there are clear end moraines containing secondary calcites. These have recently been dated using U-series to  $10\,605 \pm 193$  ( $^{230}\text{Th}/^{232}\text{Th} = 99.3$ ) and  $9575 \pm 836$  ( $^{230}\text{Th}/^{232}\text{Th} = 49.9$ ) a (Fig. 5). These dates are significant because they show that Holocene glacier extent in



**Figure 4** Time–distance diagram illustrating glacial phases in the Campo Imperatore valley of the Gran Sasso massif, Italian Apennines (YD, Younger Dryas; H1, H2, H3, Heinrich events 1, 2, 3; F1, F2, F3, Fontari stadial advances; A1, A2, Aquila stadial advances; CIS, Campo Imperatore stadial) (Giraudi and Frezzotti, 1997). Redrawn with permission from Elsevier

this valley must have been restricted in size and situated close to the modern and 19th-century glacier limits. Furthermore, the U-series ages, which provide minimum ages for the moraines,

suggest that the last time a valley glacier extended as far as the Karlica Member moraines was during the Younger Dryas (12.9–11.5 cal. ka BP).



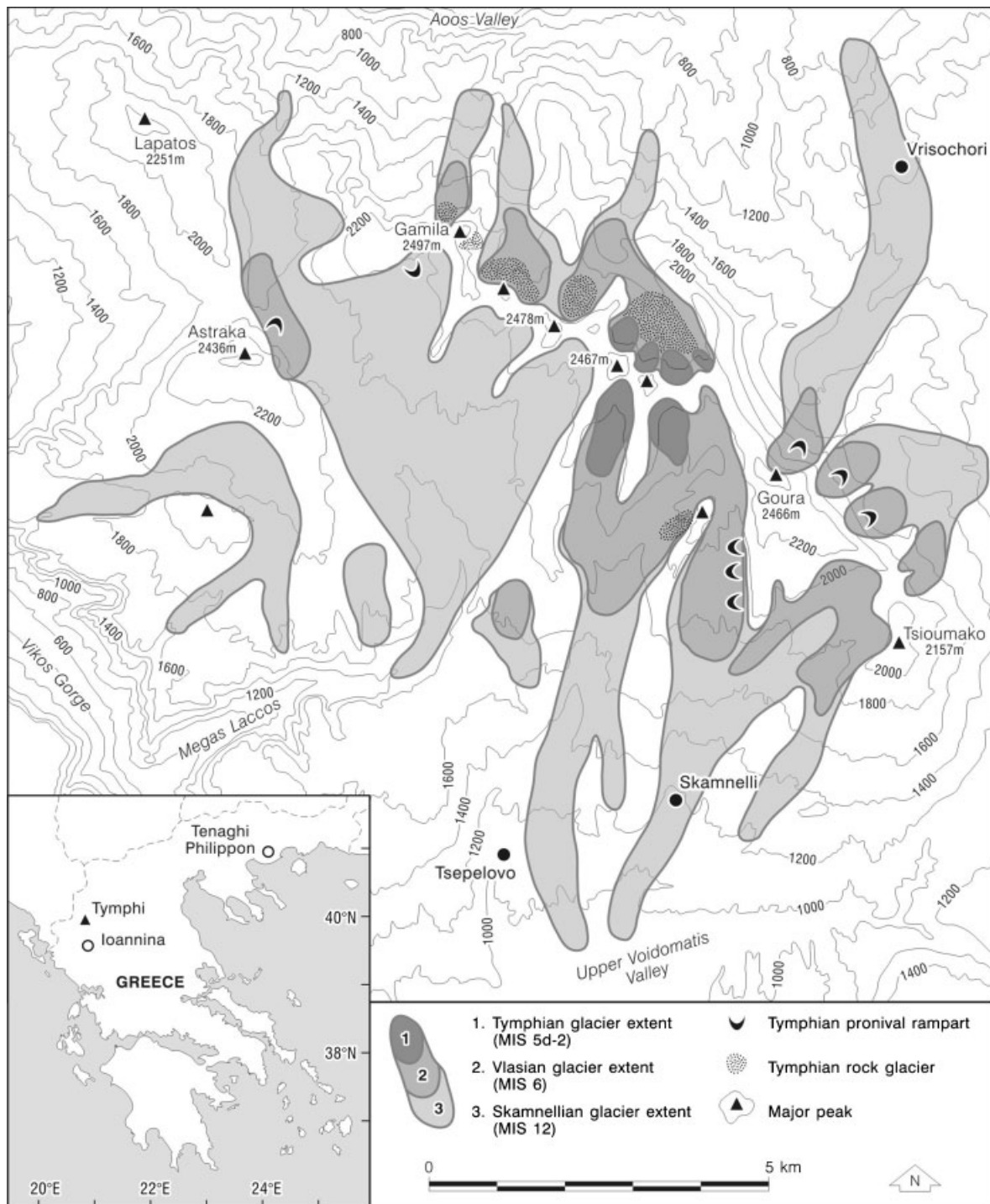
**Figure 5** Photograph showing moraines in the Karlica Valley in the Durmitor Massif, Montenegro. Secondary calcites within these moraines have been dated using U-series and provide a minimum age for the host moraines. A modern glacier – the Debeli Namet – is present at the head of the valley (Hughes, 2007). These U-series dates are important because they demonstrate that the valley moraines are likely to be Late Pleistocene in age – possibly correlating with the Younger Dryas. Moraines downvalley of these moraines have yielded progressively older U-series ages, with the lowest moraines in this area dating to the Middle Pleistocene

## Greece

Glacial deposits are widespread in the Pindus Mountains of Greece, from Taygetos (2404 m a.s.l.) in the south to Grammos (2520 m a.s.l.) in the north (Hagedorn, 1969; Mastronuzzi *et al.*, 1994; Woodward *et al.*, 2004) and Olympus in the east (Smith *et al.*, 1997). The Late Pleistocene (Pindus chronostratigraphy: Tymphan Stage) glaciers in the Pindus Mountains were much smaller than their Middle Pleistocene counterparts (Skamnellian and Vlasian Stages) (Fig. 6). The separation of Late and Middle Pleistocene glacial units has been achieved by detailed mapping and by applying U-series methods to date secondary calcite cements in glacial deposits on Mount Tymphi (Woodward *et al.*, 2004; Hughes *et al.*, 2006b). However,

radiometric ages have only been obtained from the Middle Pleistocene moraines because no secondary calcites were found in younger moraines. Nevertheless, some insights into the timing of Late Pleistocene glaciation can be inferred from radiometric dates obtained from fluvial sediments deposited by the Voidomatis River, which drains the southern slopes of Mount Tymphi.

A major alluvial unit with a glacially derived fine-grained matrix formed downstream of the largest Tymphan Stage glaciers on Mount Tymphi. This unit was dated to ca. 28.2–24.3 ka on the basis of a thermoluminescence date, three electron spin resonance dates and two U-series dates (Lewin *et al.*, 1991; Hamlin *et al.*, 2000; Woodward *et al.*, 2008). The sand and silt matrix of this unit is dominated by limestone-rich



**Figure 6** Pleistocene glacier extent on Mount Tymphi in the Pindus Mountains, northwest Greece (based on Hughes *et al.*, 2006b)

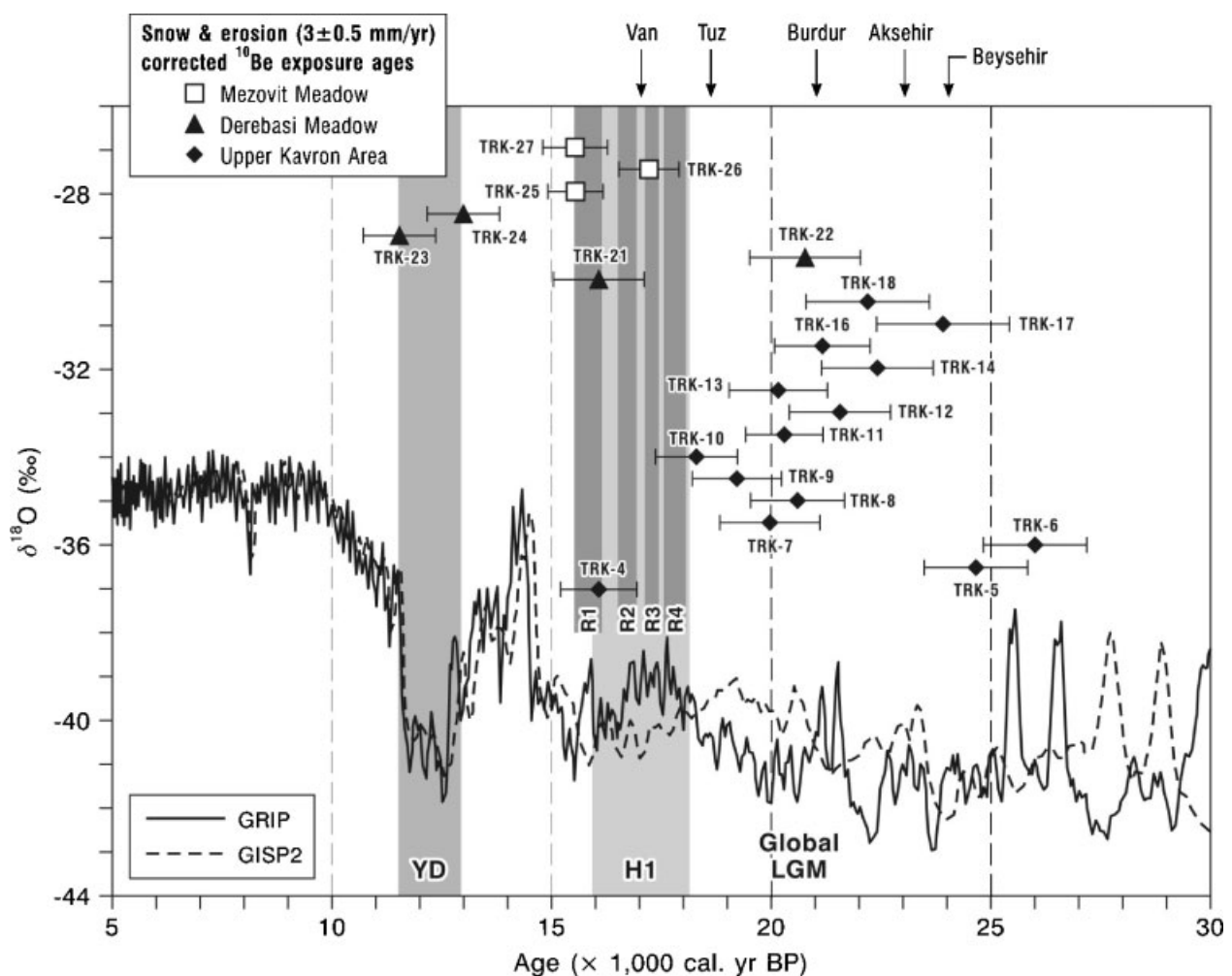
finer which are derived from glacial erosion in the catchment headwaters (Lewin *et al.*, 1991; Woodward *et al.*, 1992). The age of these fluvial sediments shows that this glacial activity occurred several thousand years prior to the global LGM. Meltwater erosion of older Middle Pleistocene glacial deposits may have also provided a significant contribution to the sediment load of the Late Pleistocene Voidomatis. In total, three alluvial units of Tymphan Stage age, with lithological characteristics that indicate aggradation in response to increased sediment supply from upper catchment glaciation, have been identified in the Voidomatis basin – at ca. 28.2–24.3 ka; 53 ± 4 ka; and 80 ± 7 ka (Lewin *et al.*, 1991; Hamlin *et al.*, 2000; Woodward *et al.*, 2008) (Fig. 8).

## Turkey

Until recently there were no dates for glacial deposits and landforms in Turkey (Çiner, 2004). However, recent projects have published cosmogenic nuclide results from several areas. In the Kaçkar Mountains bordering the Black Sea (Fig. 1), Akçar *et al.* (2007) have presented  $^{10}\text{Be}$  ages from granitic surfaces in the Kavron Valley on the southern slopes of the highest peak, Kaçkar Dağı (3932 m a.s.l.) (Fig. 7). The Kavron Valley glacier advance began at least 26 ± 1.2 ka ago and continued until

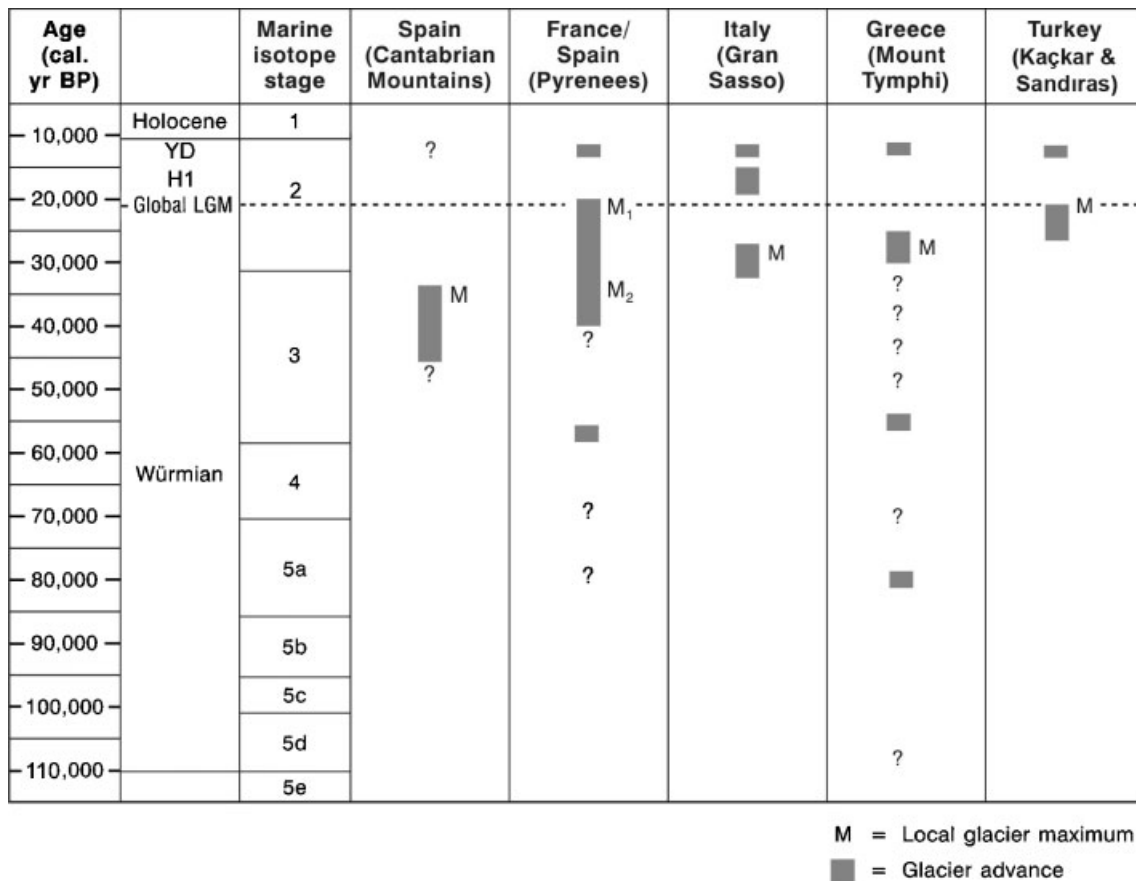
18.3 ± 0.9 ka ago. After this time the glacier retreated and by 15.5 ± 0.7 ka the main valley became ice-free with glaciers restricted to tributary cirques. A later glacier advance took place between 13 ± 0.8 and 11.5 ± 0.8 ka ago. A similar situation has been reported from a northward-draining valley of Mount Verçenik (3907 m a.s.l.), the second highest peak in the Kaçkar Mountains. Here, a valley glacier advanced before 26.1 ± 1.2 ka and continued to advance until 18.8 ± 1 ka ago. According to Akçar *et al.* (2008), the Verçenik glacier collapsed rapidly and after 17.7 ± 0.8 ka ago the main valley was ice-free with only five small glaciers in tributary valleys. Among these, the Hemşin glacier had completed its retreat by ca. 15.7 ± 0.8 ka ago. This was followed by a Lateglacial advance, identified on the basis of glacial erosion features (Akçar *et al.*, 2008).

In western Turkey, in the north-facing valleys of Mount Sandıras (2295 m a.s.l.), Late Pleistocene glaciers extended to ca. 1.5 km in length and terminated at an altitude of ca. 1900 m a.s.l. Sarıkaya *et al.* (2008) have utilised *in situ* cosmogenic  $^{36}\text{Cl}$  to ascertain the exposure age of boulders on moraine surfaces in these valleys and found that the last local glacier maximum occurred at approximately 20.4 ± 1.3 ka. In this valley, glacier retreat was interrupted by readvances at ca. 19 600 ± 1600 and 16.2 ± 0.5 ka. Glacier modelling suggest that temperatures during the last glacier maximum on Mount Sandıras were 8.5–11.5°C lower than modern values and that



**Figure 7** Erosion-corrected  $^{10}\text{Be}$  exposure ages from the Kavron Valley, in the Kaçkar Mountains, Turkey (Akçar *et al.*, 2007). The arrows at the top of the diagram illustrate the timing of major regression in closed lakes in Turkey. The labels R1 to R4 and associated grey shading indicate four major red layers deposited between 18 and 15.5 ka in the Black Sea. H1, Heinrich 1; YD, Younger Dryas; LGM, global Last Glacial Maximum. Redrawn and slightly modified with permission from Elsevier





**Figure 8** Timing of glacier advances and glacier maxima in the mountains of the Mediterranean. This diagram is based on fully published data from the Cantabrian Mountains (Jiménez-Sánchez and Fariás, 2002), the Pyrenees (e.g. García-Ruiz *et al.*, 2003; González-Sampériz *et al.*, 2006; Pallàs *et al.*, 2007), the Italian Apennines (Giraudi and Frezzotti, 1997), Greece (Hughes *et al.*, 2006d; Woodward *et al.*, 2008) and Turkey (Akçar *et al.*, 2007, 2008; Sarıkaya *et al.*, 2008) and excludes data presented only in published abstracts (e.g. Granger *et al.*, 2006; Palacios *et al.*, 2007). M<sub>1</sub>, based on <sup>10</sup>Be exposure dating (Pallàs *et al.*, 2007); M<sub>2</sub>, based on <sup>14</sup>C and OSL dating (García-Ruiz *et al.*, 2003; González-Sampériz *et al.*, 2006; Peña *et al.*, 2004). YD, Younger Dryas; H1, Heinrich 1. Question marks indicate tentative evidence for possible or potential glacier advances

precipitation was nearly double that of today (Sarıkaya *et al.*, 2008).

## Problems with the glacial geochronologies

A summary of the timing of glacial advances and maxima in different areas across the Mediterranean is provided in Fig. 8. Based on a range of geochronological data, there is evidence in the glacial records from the Pindus Mountains, the Italian Apennines and the Pyrenees for local glacial maxima preceding the LGM at ca. 18 <sup>14</sup>C ka BP/21 cal. ka BP by at least several thousand years. An early glacier maximum has also been reported from the Italian Alps. Recent radiocarbon dates from boreholes in the Tagliamento basin in the Italian Alps suggest a complex situation with an earlier glacier maximum between 26.5 and 23 cal. ka BP, which was followed by a later readvance between 24 and 21 cal. ka BP (Monegato *et al.*, 2007). However, all of the studies that have used *in situ* cosmogenic analyses to provide exposure ages for glacial landforms further to the south in the Mediterranean mountains (central Spain, Pyrenees, Maritime Alps, west and east Turkey) have yielded results showing a close correspondence between the local glacier maxima and the LGM. This body of new information is based on at least five separate studies. The results

of these Mediterranean studies are consistent with cosmogenic exposure ages from boulders on the northern European Alpine foreland where the northern lobe of the Rhône glacier reached a maximum between ca. 21 and 19.1 ka (e.g. Ivy-Ochs *et al.*, 2004).

A key problem for the development of robust dating frameworks for glacial sequences is the analysis and interpretation of the geochronological datasets. Many of the studies that employ cosmogenic nuclide analyses to derive exposure ages rely on statistical interpretation of the results. For example, in Pallàs *et al.* (2007), Akçar *et al.* (2008) and Sarıkaya *et al.* (2008), there are outlying ages pre-dating the LGM by several thousand years. Such outliers are to be expected with this approach and they are generally explained as the result of cosmogenic nuclide inheritance. A similar problem exists with young outliers, which may result from landform or boulder surfaces that have been exhumed or a where a boulder has toppled some time after deposition on a moraine surface.

Of course, other dating techniques have problems of interpretation too (Walker, 2005). Many of the radiocarbon dates used to support ideas of an early glacier maximum in the Pyrenees have been criticised by Pallàs *et al.* (2007). They cite problems such as hard water error in areas dominated by carbonate lithologies – which can produce ages which are much older than is really the case; the reworking or contamination of pollen concentrates used for some radiocarbon dates; and the uncertain stratigraphical context of some radiocarbon dates.

However, there is also the potential problem of 'old' OSL ages from till and glaciofluvial sediments in the Pyrenees (Sancho *et al.*, 2002; Peña *et al.*, 2004). Pallàs *et al.* (2007, p. 2959) have argued that: 'A simple way of reconciling the relatively young ages of the glacial features [based on  $^{10}\text{Be}$  analyses] with the older  $^{14}\text{C}$  data ( $\geq 30$  ka) and the recently published OSL ages (ca. 85–35 OSL ka from glacial and glaciofluvial sediments in the Cinca and Gallego valleys), if confirmed, would be to consider that pleniglacial conditions could have taken place during a longer period than generally assumed. Hence, the data available suggest a long Last Pleniglacial ( $>30$ – $20$  ka ago), which would include several glacier fluctuations recorded irregularly in different valleys, with a last major glacier readvance taking place around the LGM.' This explanation is certainly plausible and has been suggested elsewhere. For example, in the Pindus Mountains of Greece, Hughes *et al.* (2006d) suggested that at least 10 intervals were characterised by climatic conditions favourable for glacier formation during the last cold stage.

Ideally, multiple geochronological techniques should be applied whenever possible. This is especially the case for the Pyrenees, where  $^{10}\text{Be}$  exposure ages conflict with radiocarbon and OSL dates from the same area (Fig. 8). Resource constraints often hamper attempts to develop multiple geochronologies in glaciated areas, as does the availability of suitable samples.

## Mediterranean glacial environments during the last glacial cycle

The various glacial geochronologies from around the Mediterranean appear to produce two models of glaciation for the last cold stage: one where mountain glaciers reached their maximum extent before the global LGM and one where their maximum advance was broadly synchronous with the global LGM. It is instructive to view these findings within the wider palaeoclimatic context as each scenario has important implications for the transfer of precipitation-bearing depressions across the Mediterranean basin during the last cold stage.

It is clear that temperate tree populations were severely constricted across the Mediterranean region around the time of the global LGM because of cold and dry conditions (Pons and Reille, 1988; Allen *et al.*, 1999; Fontugne *et al.*, 1999; Tzedakis, 1999). In order for glaciers to advance at this time in the Mediterranean mountains, extremely large reductions in summer temperature compared with today would be needed to offset the reduced snow accumulation caused by the dry climate. This would have also been true during Heinrich events, which are also associated with cold and dry conditions, resulting in major reductions in tree populations in the Mediterranean (Tzedakis *et al.*, 2002).

Hughes *et al.* (2006d) suggested that palaeoglaciers in Greece are likely to have retreated during the extremes of both stadials (including Heinrich events) and interstadials and advanced during more *intermediate* phases of the last cold stage, when climate was sufficiently wet and cold for a positive glacier mass balance. Examples of intermediate phases of climate where these glacier–climate conditions may have occurred have been identified from the pollen record at Ioannina and are shown as Type B in Fig. 9. Glacier–climate reconstructions for the last local glacier maximum in northern Greece indicate that climate at the equilibrium line altitude (ELA) was characterised by annual precipitation of  $2300 \pm 300$  mm and mean summer temperatures of  $4.9^\circ\text{C}$  – a situation analogous with modern-day maritime Norwegian

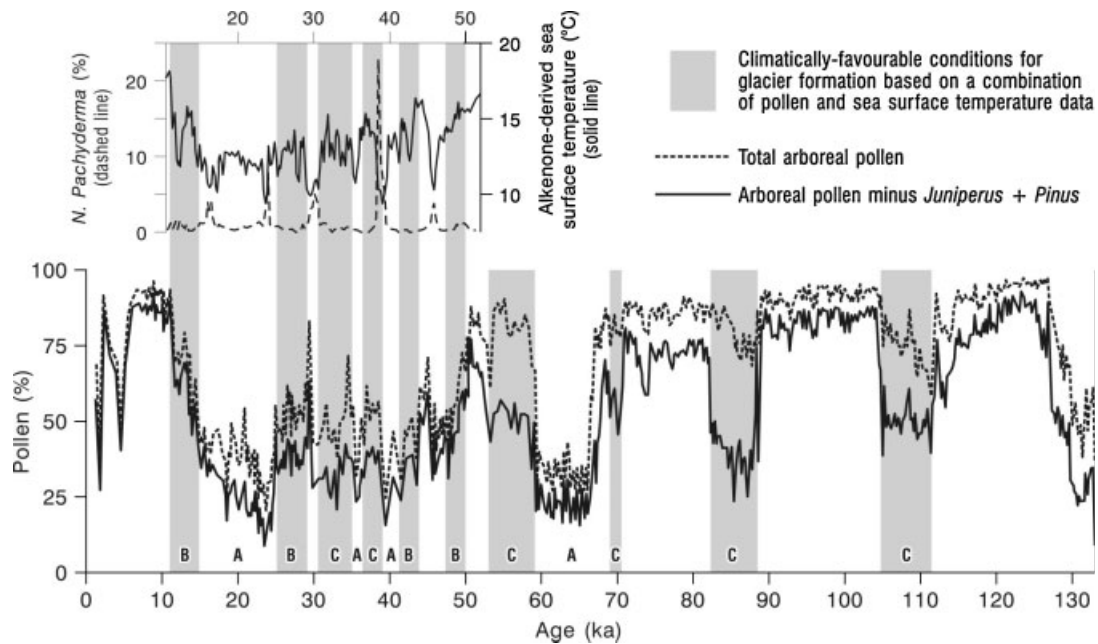
glaciers (Hughes *et al.*, 2006d). This climatic reconstruction for the last local glacial maximum in Greece is consistent with the glacial evidence in the Italian Apennines (Giraudi and Frezzotti, 1997) and western Turkey (Sarıkaya *et al.*, 2008) as shown below.

The last occurrence of potentially wet and cold conditions before the most severe and driest phase of the last cold stage was during the interval between ca. 30 and 25 ka ago (Fig. 9). However, theoretically favourable conditions for significant glacier formation can be recognised for at least nine other intervals within the last cold stage: the earliest being between ca. 111 000 and 105 000, corresponding to Stadial 1 in the Ioannina pollen record and MIS 5d (cf. Tzedakis *et al.*, 2002); and the last between ca. 15 and 10  $^{14}\text{C}$  ka BP, during the Lateglacial (cf. Lawson *et al.*, 2004). It is likely that Mediterranean glaciers waxed and waned throughout the last cold stage in response to climate change, but only the most extensive moraines have been preserved in many valleys. In fact, in some basins, the fluvial record downstream may provide a more detailed record of glacier activity for the last cold stage than the glacial geomorphological record itself (Hughes *et al.*, 2006d; Woodward *et al.*, 2008).

In the Italian Apennines, conditions were very cold and wet at the time of the local glacier maximum, with snowfall at the ELA similar to modern values (Giraudi and Frezzotti, 1997). As in Greece, the last local glacial maximum in the Italian Apennines appears to pre-date the most severe phase of climate represented in the pollen record at Monticchio, a long lacustrine sequence in southern Italy, when the lowest arboreal pollen abundances occurred between 25.9 and 14.3 cal. ka BP (22.35–12.5  $^{14}\text{C}$  ka BP) (Allen *et al.*, 1999, 2000).

In Turkey, two glacial records with similar geochronologies have yielded very different palaeoenvironmental interpretations. In the Kaçkar Mountains, at the easternmost fringe of Mediterranean climatic influence, Akçar *et al.* (2007, 2008) have argued that the advance of glaciers was paralleled by the almost complete absence of trees in central Anatolia during Pleniglacial to Lateglacial times (Fontugne *et al.*, 1999). However, this also coincided with a period of high lake levels in Turkey close to the global LGM (Kuzucuoğlu and Roberts, 1998). This apparent conflict has arisen elsewhere in Mediterranean lacustrine records (Prentice *et al.*, 1992; Tzedakis, 2007). In Turkey, the combination of cold steppe vegetation and high lake levels has been explained by reduced evaporation and evapotranspiration, enhanced by higher catchment runoff coefficients (Kuzucuoğlu and Roberts, 1998). Akçar *et al.* (2007, 2008) argue for glacier advance with arid conditions and very low temperatures at the last local glacier maximum in this region. However, in the mountains of western Turkey, Sarıkaya *et al.* (2008) used a glacier–climate model to argue that the local glacier maximum in this area, which was reached at around the same time as that in the Kaçkar Mountains, occurred under a wet and cold climate – with nearly double the precipitation of today. Further work is necessary to understand the relationship between glaciers and climate across Turkey and Akçar *et al.* (2007) themselves suggest that detailed mapping and regional reconstructions of former ice extent are needed to understand glacier–climate dynamics in these mountains. If the glacier–climate reconstructions of Sarıkaya *et al.* (2008) are correct, this has major implications for the interpretation of cold steppe vegetation assemblages in pollen record in lacustrine sequences across the Mediterranean.

Hughes *et al.* (2006a) argued that the small glaciers of the Mediterranean mountains would have responded rapidly to millennial-scale climate change, in contrast to the extensive ice sheets that covered the Alps and northern Europe.



**Figure 9** Summary pollen percentage curves from the Ioannina 1284 sequence in northwestern Greece, spanning the last glacial cycle. Potential intervals suitable for glacier formation are indicated by letters A: major stadials characterised by low arboreal pollen, both including and excluding *Pinus* and *Juniperus*; B: intermediate phases between the apices of major stadials and interstadials; C: intervals characterised by large differences between total arboreal pollen frequencies and arboreal pollen frequencies, excluding *Pinus* and *Juniperus*. All other intervals represent major interstadials or interglacials. Both B and C types – the more favourable conditions for glaciation – are highlighted by shading. The upper graph depicts variations in the percentage of *Neogloboquadrina pachyderma* (sinistral) and alkenone-derived sea-surface temperatures in marine core MD95-2043 from the Alboran Sea, in the western Mediterranean (adapted from data in Cacho *et al.*, 1999, and Tzedakis *et al.*, 2002). Redrawn from an original figure in Hughes *et al.* (2006d) with permission from Elsevier

Consequently, the Mediterranean glaciers are likely to have advanced and retreated much more quickly and reached their maximum extent in the last cold stage before the large ice sheets. The potentially rapid response of mountain glaciers to the increased aridity in southern Europe around the time of the global LGM may explain the evidence for an early glacial maximum in the mountains of this area. This situation applied not only in the Mediterranean mountains but also in the locally glaciated mountain areas of Europe such as the Vosges (Seret *et al.*, 1990) and the Massif Central (Etlicher and De Goer de Hervé, 1988), where glacial geochronologies based on radiocarbon dating indicate local glacier maxima prior to 30  $^{14}\text{C}$  ka BP.

A growing number of studies using cosmogenic nuclide analyses point to local glacier maxima in the Mediterranean mountains close to the global LGM at ca. 21 ka ago. These include cosmogenic exposure geochronologies for glacial sequences in the Sierra de Gredos of Spain, the Pyrenees, the Maritime Alps and both the western and eastern mountains of Turkey. It is possible that moisture availability to nourish glacier development could have been facilitated by a southerly track of Atlantic depressions through the Mediterranean basin during MIS 2 (Florineth and Schlüchter, 2000). This is plausible but would appear to conflict with the palaeoecological data from long lacustrine records and the established view of a cold and dry Mediterranean climate around the time of the LGM (Tzedakis, 2007). Reduced precipitation during Heinrich events is also likely to have restricted glacier growth. As noted earlier, the palaeoglacier record in western Turkey appears to show evidence of cold and wet conditions at the LGM (Sarikaya *et al.*, 2008).

Given the context of high-amplitude millennial-scale climate change known to have occurred in the Mediterranean region during the last cold stage, it is likely that Mediterranean

mountain glaciers oscillated in response to these climate signals, as noted earlier. Dynamic modelling of glacier–climate response over the last cold stage may help provide some insight into the oscillations of the Mediterranean glaciers to millennial-scale climate change – especially with respect to major collapses in precipitation that are thought to have occurred during intervals coinciding with Heinrich events in the North Atlantic (Allen *et al.*, 1999; Tzedakis *et al.*, 2002). Glacial landforms such as moraines reflect ‘events’ in the stratigraphical record and it is possible that local and regional climatic variations resulted in variability in the timings of local glacier maxima in the mountains. It is therefore not surprising, perhaps, that there appear to be conflicts between different records of environmental change. Tzedakis (2007) argued that higher-resolution analyses and improved chronologies have led to a revised framework of geographically coherent environmental changes in the Mediterranean region during the last cold stage. Of course, glacial sedimentary records cannot rival the lacustrine or speleothem records in terms of temporal resolution. Nevertheless, it can be argued that glacial ‘events’ such as local glacier maxima can provide some of the most reliable palaeoclimate reconstructions in the Mediterranean region.

## Conclusions

Recent work using a range of geochronological techniques has produced contrasting results for the timing of the glacier maxima across the Mediterranean mountains. Two scenarios have emerged. These suggest:

1. Early local glacier maxima several thousand to tens of thousands of years earlier than the global LGM (ca. 18 <sup>14</sup>C ka BP/ 21 cal. ka BP) of MIS 2. This is based on radiocarbon, U-series and OSL dating in the Cantabrian Mountains, Pyrenees, Italian Apennines and Pindus Mountains.
2. Local glacier maxima correlating closely with the global LGM. This is based on <sup>10</sup>Be and <sup>36</sup>Cl cosmogenic isotope analyses from the mountains of central Spain, the Pyrenees, the Maritime Alps and the mountains of western and eastern Turkey.

The first scenario is consistent with biological records from long lacustrine sequences which indicate severe aridity around the time of the global LGM that would have hindered glacier development in the Mediterranean mountains. It is also consistent with the observations of Gillespie and Molnar (1995), who noted the asynchronicity of glacier maxima between continental and mountain glaciers around the world as a result of the particular sensitivity of mountain glaciers to regional climate as well as global conditions. Since Mediterranean glaciers were relatively small in size they would have reached their maximum extent before the much larger ice sheets of the Alps and northern Europe. Moreover, it is likely that increasing ice cover over the Alps and northern Europe, and the southward migration of dominant polar–continental anticyclonic conditions, would have pushed cyclones to the southern edge of the Mediterranean basin and along the North African coast. Mediterranean mountain glaciers in southern Europe are likely to have been starved of moisture at this time and undergone retreat.

The second scenario runs counter to the climatic scenario outlined above. In this situation, the maximum extent of some Mediterranean mountain glaciers appears to have coincided with the peak in global ice volume indicated in the marine isotope record. Glacier maxima at this time in the Mediterranean mountains would have coincided with the driest conditions of the last cold stage. A lack of moisture would have required exceptionally low summer temperatures to sustain these glaciers. This is counter to glacier–climate simulations for local glacier maxima in areas such as Greece (Hughes *et al.*, 2006d). However, in western Turkey, a cold and wet climate has been inferred from local mountain glaciers coinciding with the LGM (Sarikaya *et al.*, 2008).

Of course, it is possible that regional mass balances and glacier dynamics could have varied across the different parts of the Mediterranean and that the two scenarios outlined above could coexist side by side. This is certainly plausible when comparing areas separated by great distance such as the easternmost dated sequences in Turkey (Akçar *et al.*, 2007, 2008) with those in the western Mediterranean. However, where different geochronologies from the same region are in conflict, then there is an obvious problem of choosing which geochronology is correct – such as in the Pyrenees (Pállas *et al.*, 2007). The same is true of conflicting palaeoclimatic interpretations of glacial records with similar geochronologies (e.g. Akçar *et al.*, 2007, 2008; Sarikaya *et al.*, 2008).

In addition to the issues relating to the maximum extent of glaciers during the last cold stage, important new evidence is becoming available for glaciation during the Younger Dryas in the Mediterranean. This includes geochronological data from glacial landforms in the Maritime Alps (Federici *et al.*, 2008) the Italian Apennines (Giraudi and Frezzotti, 1997), Montenegro (Hughes and Woodward, this paper) and northeastern Turkey (Akçar *et al.*, 2007). Future progress in understanding the glacial history of the Mediterranean mountains during the last cold stage will require multiple dating techniques to be applied in

order to rigorously test the glacial geochronologies. The wider application of different geochronological techniques to other areas of the Mediterranean will no doubt generate new research questions and challenge current views on the timing and palaeoclimatic significance of glaciation in the Mediterranean mountains.

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