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Quaternary glacial history of the Mediterranean mountains

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Abstract: Glacial and periglacial landforms are widespread in the mountains of the Mediterranean region. The evidence for glacial and periglacial activity has been studied for over 120 years and it is possible to identify three phases of development in this area of research. First, a pioneer phase characterized by initial descriptive observations of glacial landforms; second, a mapping phase whereby the detailed distribution of glacial landforms and sediments have been depicted on geomorphological maps; and, third, an advanced phase characterized by detailed understanding of the geochronology of glacial sequences using radiometric dating alongside detailed sedimentological and stratigraphical analyses. It is only relatively recently that studies of glaciated mountain terrains in the Mediterranean region have reached an advanced phase and it is now clear from radiometric dating programmes that the Mediterranean mountains have been glaciated during multiple glacial cycles. The most extensive phases of glaciation appear to have occurred during the Middle Pleistocene. This represents a major shift from earlier work whereby many glacial sequences were assumed to have formed during the last cold stage. Glacial and periglacial deposits from multiple Quaternary cold stages constitute a valuable palaeoclimatic record. This is especially so in the Mediterranean mountains, since mountain glaciers in this latitudinal zone would have been particularly sensitive to changes in the global climate system.

Key words: glacial geomorphology, glaciation, Mediterranean, palaeoclimate, periglacial geomorphology, Quaternary.

I Introduction

The mountains of the Mediterranean basin have been subjected to repeated phases of glacial and periglacial activity during the Quaternary and the geomorphological legacy of these processes is frequently well preserved. The style of glaciation in the Mediterranean mountains involved localized cirque and valley glaciation, although in some places glaciers covered more extensive upland areas as ice fields or ice caps. In addition, evidence of former periglacial activity is widespread in many upland areas. Today, few glaciers exist in the region, although there are notable examples above 2500 m in the Pyrenees, the Alpes Maritimes, the Italian

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Apennines and the mountains of Slovenia and Turkey.

The presence of Pleistocene glacial features in the Mediterranean mountains has been known for over 120 years. The classic review by Bruno Messerli (1967), 'Die eiszeitliche und die gegenwärtige Vergletscherung im Mittelmeerraum' published in *Geographica Helvetica*, probably represents the most comprehensive synthesis of Mediterranean Quaternary glaciation to date. However, it is only in the last decade or so that researchers have begun to develop robust geochronological frameworks for the glacial record. Three phases in the development of our understanding of glaciation in the Mediterranean mountains can be recognized. These phases are broadly defined (and may have overlapping boundaries) and are described below under the titles of pioneer, mapping and advanced phases.

1 Pioneer phase

This phase is characterized by initial observations of glacial features in the upland landscape and largely involves descriptive accounts of features such as cirques, U-shaped valleys, moraines and erratics. In the Alps and northern Europe, many pioneer studies were published in the late nineteenth century following the establishment of glacial theory, most influentially by Agassiz (1840). Most of the pioneer work on Mediterranean mountain glaciation took place later than in the Alps and northern Europe. Notable exceptions include work by pioneers such Albrecht Penck (1885) in the Pyrenees and Jovan Cvijić (1898) in the Balkans who were at the forefront of early glacial research. They were later followed by a variety of authors who reported on glacial geomorphological features throughout the Mediterranean mountains (Messerli, 1967). Most of this early literature represents reconnaissance studies upon which much of the later work has been based. However, in several areas, such as the Atlas Mountains of North Africa, it can be argued that our knowledge of glaciation remains in this pioneer phase (Hughes *et al.*, 2004).

2 Mapping phase

This phase is characterized by a move towards more detailed geomorphological mapping and an appreciation of glacial stratigraphy. Such studies usually followed pioneer studies described above and were largely published in the second half of the twentieth century. For example, detailed geomorphological studies such as that of Daveau (1971), in Portugal, built on existing pioneer studies by Lautensach (1929; 1932). In some areas, this phase came much later. For example, geomorphological maps were produced for the mountains of northern Greece by Boenzi *et al.* (1992) and Palmentola *et al.* (1990) following pioneer studies of Sestini (1933) and Niculescu (1915). However, these studies did not provide evidence for the chronology of glaciation and most considered the glacial sequence to have formed during advance and retreat phases of the last cold (Würmian) stage. In fact, few of the studies reviewed by Messerli (1967) presented detailed geomorphological maps and Messerli's paper could be regarded as the watershed in pioneer phase research. Some more recent studies present comprehensive geomorphological and stratigraphical assessments of the glacial record and have postulated the idea of multiple glaciations in the Mediterranean. However, the development of a geochronology has been hampered by the absence of suitable samples for radiometric dating. The work of Smith *et al.* (1997) on Mount Olympus in northeast Greece is a good example.

3 Advanced phase

Research has advanced beyond the mapping phase in only a few glaciated areas of the Mediterranean mountains. This phase is characterized by the application of radiometric dating, and the development of detailed geochronologies combined with modern sedimentological and stratigraphical analyses. In recent years, the geochronology of several glacial sequences has been established using radiometric dating and this has provided valuable new insights into the glacial record. For example, Uranium-series dating of cemented glacial deposits in limestone areas of Italy and Greece has shown that some of the more extensive glacial deposits date from the Middle Pleistocene (Kotarba *et al.*, 2001; Woodward *et al.*, 2004). Similar findings have emerged in northwest Iberia based on cosmogenic dating of glacial boulders and glaciated surfaces in granite terrains (Fernandez Mosquera *et al.*, 2000). Also, in the Pyrenees and Spain, radiocarbon dating of lacustrine sequences inside glacial limits has shown that the last glacier maxima predate the global Last Glacial Maximum (Jiménez-Sanchez and Farias, 2002; García-Ruiz *et al.*, 2003). It is now becoming clear, therefore, that the glacial and periglacial record of the region is much more complex, both spatially and temporally, than previously thought. The development of robust age frameworks has also allowed correlation with other proxy climate records in the region and beyond. However, while radiometric dating has been applied to several sequences, detailed sedimentological and stratigraphical analyses are still lacking in many cases.

These recent developments in our understanding of Mediterranean glacial sequences, especially from a geochronological perspective, warrant a fresh review of the glacial and periglacial record in the region. All those studies that may be considered to be in the mapping or pioneer phase provide valuable platforms from which progress can be made to understand the detailed stratigraphical and geochronological relationships between different areas. It is only in this advanced phase that palaeoclimatic reconstructions, based on the geomorphological record, can be compared with other Quaternary records.

The evidence for current and past glacial and periglacial activity in the mountains of the Mediterranean is reviewed here for particular mountain groups or physically distinct regions. In this review, the mountains of the

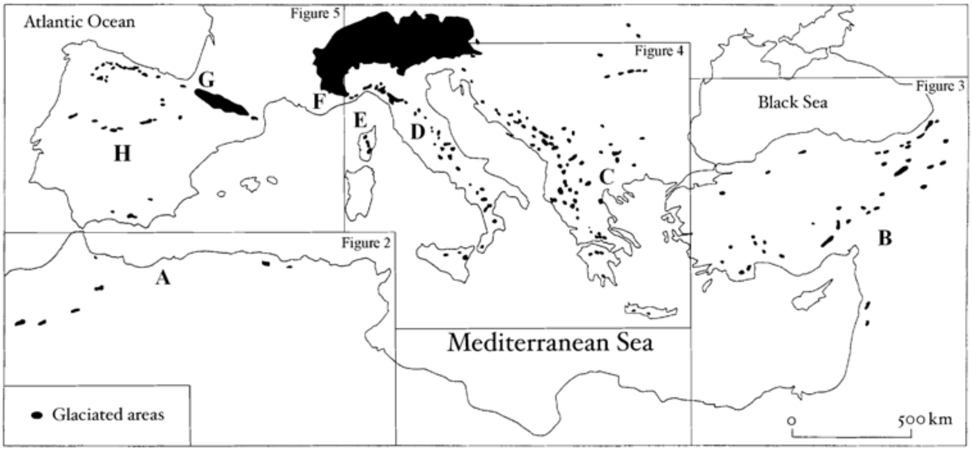

Figure 1 Distribution of Quaternary glacial features in the Mediterranean region recognized in this paper based on a similar map produced by Messerli (1967). The areas discussed here are: (A) the Atlas Mountains; (B) the eastern Mediterranean (Lebanon and Turkey); (C) Greece and the Balkans; (D) the Italian Apennines; (E) Corsica; (F) the Alpes Maritimes; (G) the Pyrenees; and (H) the Iberian peninsula

Table 1 Relationship between Alpine, northern European and marine isotope chronostratigraphical stages. The upper boundary of the last cold stage is taken as 11,500 cal. years BP, equivalent to *c.* 10,000 ^{14}C years. All other stage boundary ages are based on the orbitally tuned marine isotope record documented in Imbrie *et al.* (1984) and Martinson *et al.* (1987)

Geochronology (calendar years BP)	Marine isotope stage/substage	Alpine stage	Northern Europe stage
c. 11,500–110,790	5d–2	Würmian	Weichselian
c. 110,790–129,840	5e		Eemian
c. 129,840–362,000	6–10	Rissian	Saalian
c. 362,000–423,000	11		Holstenian
c. 423,000–478,000	12	Mindelian	Elsterian

Mediterranean include all those that border the Mediterranean Sea. This includes some mountain ranges, such as in Iberia and eastern Turkey, for example, which do not drain into the Mediterranean Sea or do not display all the characteristics of the classic Mediterranean climate (Figure 1).

It is important to point out that most workers in the Mediterranean region apply the classic Alpine morphostratigraphical terms of Günz, Mindel, Riss and Würm as first proposed by Penck and Brückner (1909). Although this scheme has little formal chronostratigraphical basis (Bowen, 1978), except for the Würm(ian) Stage, which was formally defined by Chaline and Jerz (1983; 1984), it is still widely used today. A summary of terms and their chronostratigraphical relationships for the timespan discussed in this review is shown in Table 1. All elevations are given in metres above sea level.

II The Atlas Mountains

Quaternary glacial and periglacial features are present throughout the Atlas Mountains of northwest Africa. However, little is known of the timing and extent of glaciation and most published studies constitute reconnaissance work (cf. Hughes *et al.*, 2004).

The highest peaks occur in the High Atlas, which includes Jbel Toubkal (4165 m), Irhil M'Goun (4071 m) and Jbel Ayachi (3751 m) (Figure 2). Glacial features such as cirques, troughs, roche moutonées, riegels and moraines have been reported from all of these massifs (Dresch, 1941; 1949; Heybrock, 1953; Mensching, 1953; Wiche, 1953; Awad, 1963; Beaudet, 1971). For example, in the Toubkal area, glacial erosion has resulted in a web of arêtes around the highest peaks, as well as deep troughs. To the northeast, in the Irhil M'Goun area (Figure 2), cirques and associated moraines were reported on the northern slopes by Wiche (1953).

Periglacial features are also widespread in the High Atlas and solifluction lobes, thufurs (mounds formed by heaving of the ground surface), polygons, stone stripes and felsenmeer (German: *sea of rock*; a mantle of angular shattered boulders) are active today above *c.* 2000 m (Couvreur, 1966). Rock glaciers, almost certainly relict since they form in areas of discontinuous permafrost, have been recorded on Irhil M'Goun and on nearby Jbel Ouaougoulzat (Wiche, 1953). On the latter mountain, these features form below cirque moraines and it is likely that they represent debris rock glaciers, as defined by Barsch (1996), whereby they are supplied with debris from the cirque glacier moraines above. Frosts are frequent as winter minimum temperatures at 2000 m are often in the range 0 to –10°C and can fall to –20°C (Robinson and Williams, 1992). Blockfields are widespread on Jbel Toubkal and extensive talus slopes supply the lower valleys with huge amounts

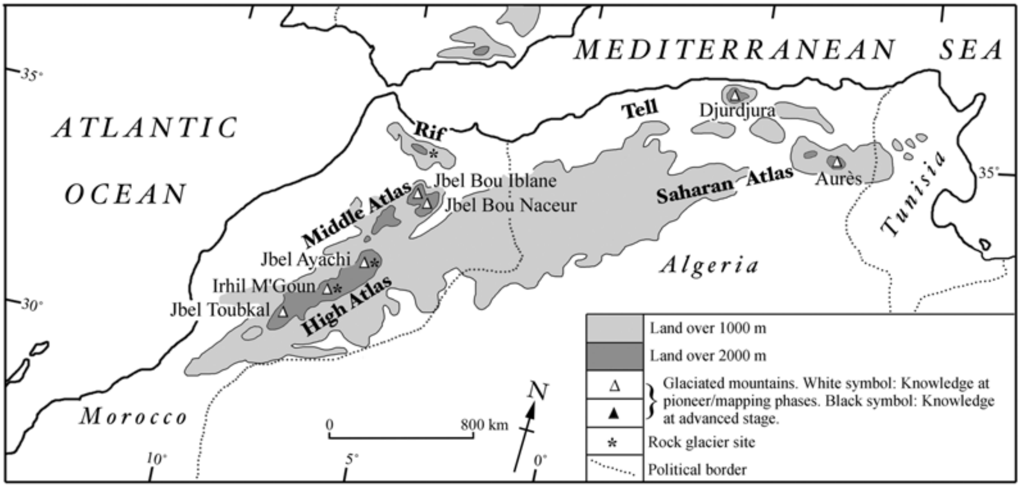

Figure 2 Location map of the North African Atlas Mountains, showing the location of formerly glaciated areas mentioned in the text

of frost-shattered debris. The valley containing Lac D'Infi (2312 m), to the east of Toubkal, for example, is choked with coarse angular debris derived from periglacial weathering in the surrounding catchment.

Even today, in some sheltered cirques on Toubkal, snow fields may persist throughout the year, although the true snowline lies slightly above the highest peaks, probably at *c.* 4200 m (Messerli, 1967). During the Pleistocene cold stages, however, snowlines descended to much lower altitudes and glaciers formed in many locations. Dresch (1941) reconstructed Pleistocene cold stage snowlines for the High Atlas at 3600–3700 m while later workers have derived slightly lower estimates at 3400–3500 m (Mensching, 1953) and at 3300–3400 m (Awad, 1963).

The Middle Atlas lie to the northeast of the High Atlas (Figure 2) and the highest peaks of Jbel Bou Iblane (3340 m) and Jbel Naceur (3310 m) display evidence of former glaciation (Dresch and Raynal, 1953; Raynal *et al.*, 1956; Awad, 1963; Beaudet, 1971). According to Awad (1963), the most remarkable collection of glacial troughs in the Atlas Mountains is found on the southern and eastern slopes of Jbel Bou Iblane. Terminal and lateral moraines are also well developed and extend down to *c.* 2400–2500 m (Raynal *et al.*, 1956). Here in the Middle Atlas, the former regional snowline is estimated at *c.* 2800 m during the most extensive glacial phase (Awad, 1963). Further north, the Rif Mountains are thought to have been beneath the regional snowline although, according to Mensching (1960), there is evidence for former perennial snow patches and rock glaciers on the highest mountain Tidirhin-Kette (2456 m).

Periglacial features are also present in the Middle Atlas. Stone polygons, solifluction features and rock glaciers have been described on Bou Iblane and Jbel Bou-Naceur by numerous workers (Raynal, 1952; Dresch and Raynal, 1953; Awad, 1963). Relict rock glaciers are especially abundant between 2100 and 2500 m in the eastern valleys of the Bou-Naceur massif (Awad 1963) (Figure 2).

Glacial and periglacial features have also been noted in the Djurdjura massif of the Algerian Tell (Barbier and Cailleux, 1950; Büdel, 1952; Tihay, 1972; 1973) and in the Aurès massif of the Saharan Atlas (Ballais,

1983) (Figure 2). In the Djurdjura massif (2308 m), cirques, U-shaped valleys and terminal moraines are all in evidence according to Barbier and Cailleux (1950). They note the transition from glacially smoothed limestone pavements on the upper slopes to subaerially eroded karstic forms on the lower slopes. Glacial deposits extend to exceptionally low altitudes for this latitude (*c.* 36°N), reaching as low as 750 m on the northern slopes, and 1270 m on the west. The formation of glaciers was probably aided by snow accumulation in dolines and even today snow lies in dolines throughout the summer above 2000 m. This probably arises from the high precipitation of this area, which exceeds 2000 mm, and largely falls during the winter months (Vita-Finzi, 1969). During the most extensive glacial phase, the snowline in the Djurdjura massif was as low as 1900 m, although Büdel (cited in Messerli, 1967) puts the snowline slightly higher at 2100 m. This probably reflects the influence of maritime air masses from the nearby western Mediterranean, as is the case today (Griffiths, 1972).

Southeast of the Djurdjura massif, in the Aurès massif of the Saharan Atlas, Ballais (1983) noted the presence of glacial moraines above 1600 m on Jbel Ahmar Khaddou (2017 m) and Jbel Mahmel (2321 m). In the latter area, two phases of glaciation are evident. However, no glacial deposits were noted on the highest peak, Jbel Chélia (2326 m). It is likely that lower precipitation in this region resulted in conditions that were marginal for glaciation with glaciers only forming in favourable topographical localities. Unfortunately, the chronology of glaciation here and elsewhere in the Atlas Mountains has not been established and remains the biggest obstacle to understanding the glacial sequence in this area.

III The eastern Mediterranean (Lebanon and Turkey)

Evidence of former glaciation in the mountains of Lebanon was first noted by Diener (1886) on the mountains of the Jbel Liban, particularly on the highest peak Qornetes Saouda (3088 m) and on Mount Hermon (2814 m) in the southern Anti-Lebanon (Figure 3). The lowest moraines are preserved at *c.* 2500 m. On Mount Hermon, two moraine systems are preserved and on the southern slopes a terminal moraine at *c.* 2500 m was considered by Messerli (1967) to be the 'best' glacial feature in the whole Lebanese mountain area. Today, perennial snow patches are present, but they are probably a function of karstic topography and local climate since the modern snowline is estimated to be at *c.* 3700 m, well above the highest summits (Messerli, 1967; 1980). It is important to appreciate, however, that other than general morphological observations, little detailed work on glaciation has been published for this area and it can be considered to be in the pioneer phase as described earlier.

Further north, in Turkey, most glacial observations are also at the pioneer phase. However, recent work by Çiner *et al.* (1999) presents a detailed assessment of the sedimentological and geomorphological relationships in the Namaras and Susam valleys of southwest Turkey. In addition, a programme of cosmogenic dating of former glacier forelands is in progress and thus offers the potential for the development of an advanced geochronology for the region (cf. Çiner, 2004).

Evidence of Quaternary glaciation in Turkey can be found in the Taurus and Pontic Mountains. The Taurus Mountains are in southern Turkey and extend from Beydağlari (3086 m) in southwest Turkey to Cilo Dağ (4135 m) in Kurdistan (Figure 3). The Taurus Mountains include some of the highest peaks in Turkey and two-thirds of the modern glaciers are found here (Çiner, 2004). The presence of glaciers in the Taurus Mountains was noted in the nineteenth century by Ainsworth (1842) and Palgrave (1872). More recently, the extent of modern glaciation in Turkey was reviewed by Kurter and Sungur (1980) and Kurter (1991).

Most modern glaciers occur in the eastern part of the Taurus Mountains in the Kurdistan

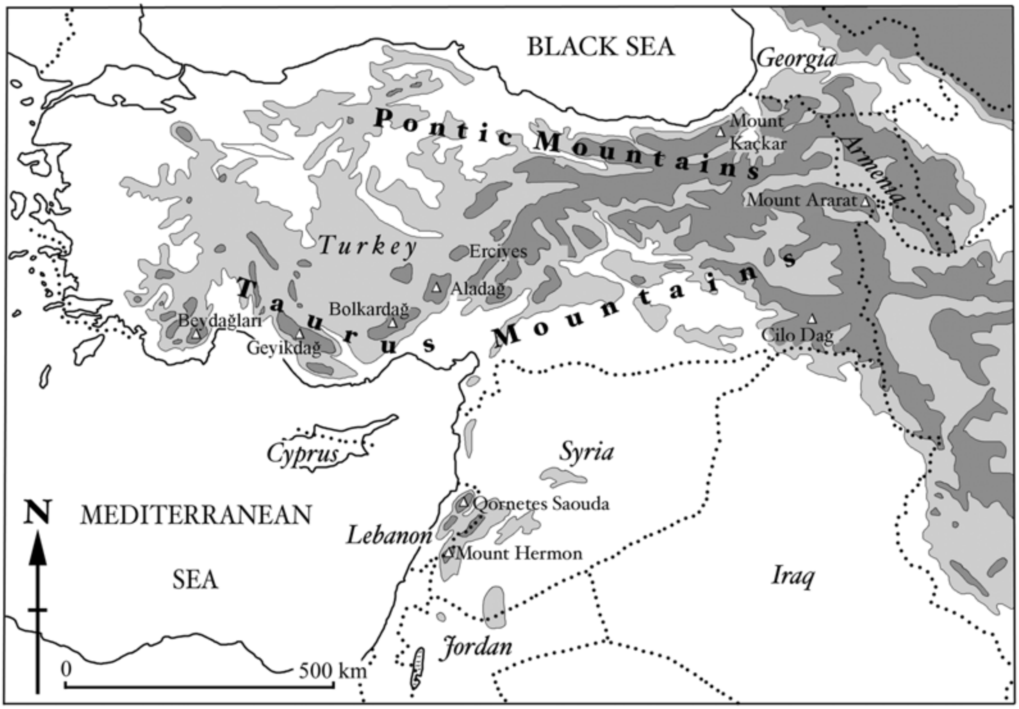

Figure 3 The eastern Mediterranean mountains, including glaciated areas of Turkey and Lebanon, showing the location of formerly glaciated areas mentioned in the text. A key is provided in Figure 2

region of southeastern Turkey (Figure 3). Here, at least 20 modern glaciers exist, and the Reçko valley glacier on Mount Cilo is 4 km long and covers an area of *c.* 8 km^2 (Çiner, 2004). Further north, on Mount Ararat (5165 m) near the border with Armenia, a modern ice cap exists covering *c.* 10 km^2 with a snowline at *c.* 4300 m. During the Pleistocene, the snowline on Mount Ararat was depressed to *c.* 3000 m and the volcanic cone was covered by an ice cap of *c.* 100 km^2 (Blumenthal, 1958). However, moraines are not well preserved in this area and Blumenthal (1958) suggests that this is because of a lack of confining ridges to support valley glaciers, insufficient debris load to form moraines and volcanic eruptions that later covered the pre-existing moraines with lava and ash. Wright (1962) estimated that Pleistocene snowlines across Kurdistan were depressed by 1200–1800 m and that much of this depression can be attributed to increased snowfall and moderately lower temperatures compared with today.

In the central Taurus, modern glaciers are smaller and less extensive than in the east, although a 1 km long glacier, the Lolut glacier, exists on Aladağ (3756 m) in addition to smaller cirque glaciers on Bolkardağ (3524 m) (Figure 3). In the latter area, Pleistocene glaciers appear to have extended down to *c.* 1700 m in the Maden valley of Medetsiz peak, and very distinct moraines clearly delimit the extent of these former glaciers (Blumenthal, 1956; Messerli, 1967; Birman, 1968). In the Namars and Susam valleys, on Geyikdağ (2850 m), chaotic knob-and-kettle topography is interpreted as glacially deposited hummocky moraines by Çiner *et al.* (1999). U-shaped valleys and cirques, as well as the widespread distribution of diamicts containing striated and bullet-shaped clasts, support the interpretation that this area was glaciated during the Pleistocene. Glacial deposits are also preserved on the Erciyes volcano (3916 m) and a 700 m long modern glacier was reported by Penther (1905). However, a more recent survey by Güner and Emre (1983) showed that the glacier had retreated to a length of only 380 m, a situation mirrored by many other glaciers in the Turkish mountains through the twentieth century (Çiner, 2004). Moraines in the lower parts of the mountain indicate that glaciers once reached lengths of 5 km and were assumed by Messerli (1967) to have formed during the Würmian Stage. In addition, erratics have been found 2 km beyond these glacial limits and Messerli (1967) suggested that these erratics may have been deposited during the Rissian Stage, although no dates exist to support this theory.

The western Taurus Mountains do not support any modern glaciers, although glacial landforms are well preserved. Cirque moraines are evident on Beydağlari (3086 m) and Akdağ (3016 m) (Figure 3) and may represent former Holocene glaciers since, in many areas of Turkey, glaciers retreated through the last century (Çiner, 2004). Moraines are also evident in the lower valleys down to 2000 m, indicating the former presence of valley glaciers in this area. Messerli (1967) estimates former Pleistocene snowlines at around 2500 m on Akdağ. On Mount Sandıras (2294 m), near Denizli, however, snowlines appear to have been 200–300 m lower (Messerli, 1967). This may reflect the western position of this mountain and higher orographic precipitation from air masses coming off the Aegean Sea.

The Pontic Mountains border the Black Sea in northern Turkey (Figure 3). On Mount Kaçkar (3932 m), the highest peak, five glaciers exist and the longest reaches 1.5 km in length (Kurter, 1991). The modern snowline in these mountains is above 3000 m, and glaciers extend down to elevations as low as *c.* 2850 m (Erinç, 1952). U-shaped valleys, moraines, roches moutonnées and glacial lakes are preserved in many areas of the Pontic Mountains, indicating formerly extensive glaciation during the Pleistocene. However, in common with elsewhere in Turkey, most of the landforms have not been studied in detail and the sequence and age of the glacial record has not been established (Çiner, 2004).

IV The Balkan peninsula

The Balkan peninsula is particularly mountainous, containing major mountain ranges with peaks over 2000 m in Greece, Albania, Bulgaria and the Former Yugoslavian republics. Glaciers formed in the mountains of all of these areas during the Pleistocene (Messerli, 1967) (Figure 1).

Greece is dominated by the Pindus chain which occupies most of the mainland running from the Albanian border in the north to the Gulf of Corinth in the south (Figure 4). This range and adjacent massifs in eastern Greece, the Peloponnese and Crete display evidence of former glaciation and intense periglacial activity. However, no glaciers exist today, although periglacial processes represent an important geomorphological agent on the highest peaks. Greece represents one of the few areas in the Mediterranean where the full progression from pioneer to advanced research phases has taken place and the glacial sequence in northwest Greece is currently the best dated of all Mediterranean mountains.

Evidence of glaciation in the mountains of Greece was first reported by Niculescu (1915) who noted the moraines on Mount Smolikas (2637 m), the highest peak of the Pindus chain (Figure 4). Other pioneering studies reporting glacial and periglacial features included those of Sestini (1933) and Mercer (1963) in the mountains of Epirus. Further south, in the region of Sterea Ellas, Mistardis (1952) mapped glacial features on Mounts Oeta and Oxia, Hunt and Sugden (1964) noted corries-like forms on peaks above

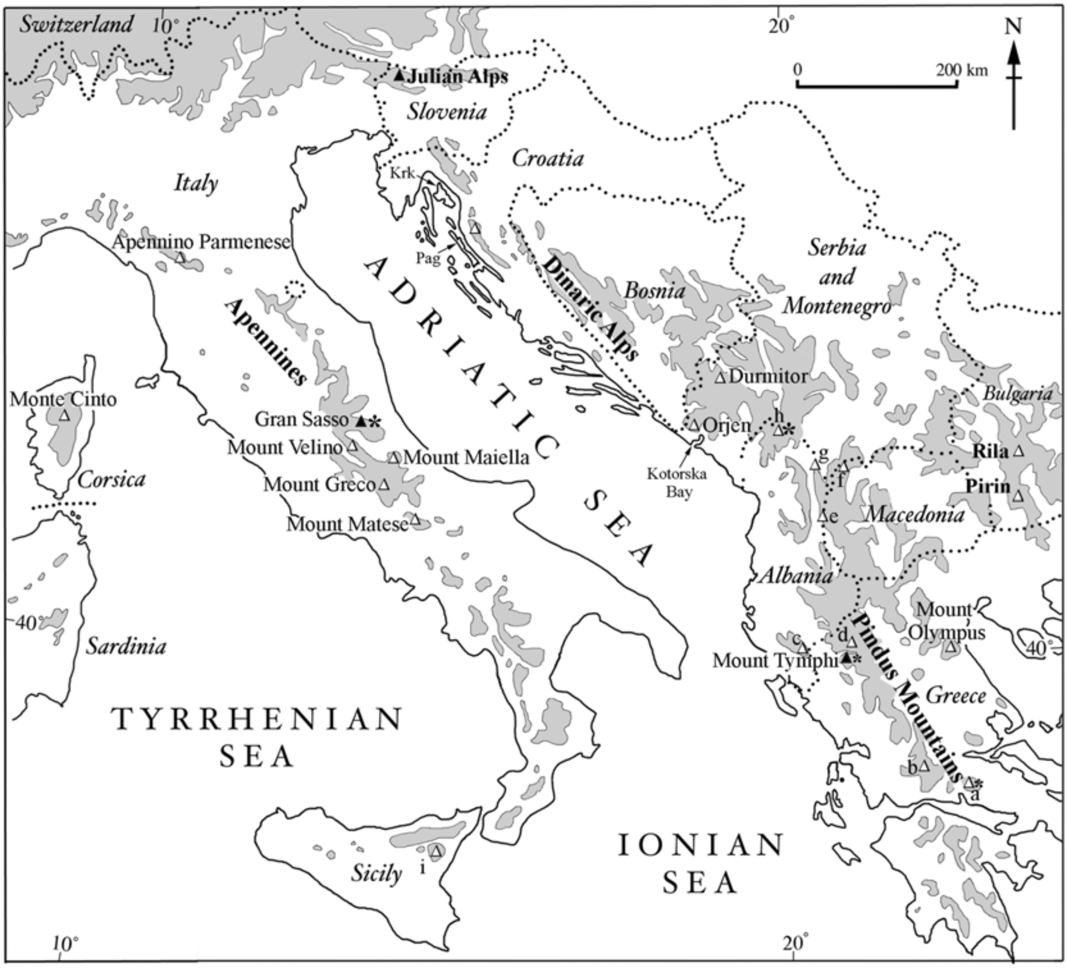

Figure 4 Location map showing some of the glaciated mountains of Greece, the Balkans, Italy and Corsica, showing the location of formerly glaciated areas mentioned in the text. Areas depicted by letters are: (a) Mount Parnassus; (b) Mounts Oxia and Oeta; (c) Mount Nëmerçka and Mali i Lunxheriës; (d) Mount Smolikas; (e) Korab Mountains; (f) Sara Mountain; (g) Koritnik Mountains; (h) Prokletije Mountains; (i) Mount Etna. A key is provided in Figure 2. Areas over 2000 m are not depicted due to scale

2000 m in the Agrafa area, and Pechoux (1970) documented moraines and relict rock glaciers on Mount Parnassus (2457 m).

More recently, on Mounts Tymphi and Smolikas (Figure 4), Palmentola *et al*. (1990) and Boenzi *et al*. (1992) identified and mapped major moraine systems and assumed that all of the moraines were formed during the Late Würmian. However, this was not supported by any geochronological data and this work represents a good example of mapping phase research as defined earlier. Other mapping surveys were developed using remote sensing techniques by Smith *et al*. (2000) who showed that it was possible to clearly delineate the boundaries of glacial landforms using TM and SPOT imagery. Progress towards a chronology for the glacial sediments on Mount Tymphi was first made indirectly by Bailey *et al.* (1990) and Lewin *et al.* (1991) who worked on the fluvial sequence in the Voidomatis River valley downstream of the glaciated headwaters. These authors linked the Late Pleistocene fluvial sequence to glacial deposits upstream on the basis of clast lithology and geomorphological relationships. More recent U-series dates from cemented tills have shown that the most extensive glacial deposits formed before 350,000 cal. years BP (Woodward *et al.*, 2004). Detailed geomorphological and sedimentological study by Hughes (2004) identified evidence for three glacial phases on Mount Tymphi and extended the geochronology further using U-series dating coupled with a relative-age pedostratigraphy. This work on Mount Tymphi has taken our understanding of the glacial sequence in the Pindus Mountains into an advanced phase and it now constitutes the best-dated glacial record in the Mediterranean (Woodward *et al.*, 2004; Hughes *et al.*, 2006).

The most extensive recorded glaciation on Mount Tymphi (>350,000 cal. years BP) was characterized by extensive valley glaciers and ice fields. Ice covered an area of *c.* 60 km^2 and extended down to altitudes as low as 850 m. The mean equilibrium line altitude (ELA – synonymous with the term 'snowline' used elsewhere in this paper) was *c.* 1741 m. Sediments and landforms also record a second glaciation prior to the last interglacial, before *c.* 127,000 cal. years BP. This was characterized by glaciers that reached mid-valley positions and covered *c.* 21 km^2 with a mean ELA of *c.* 1862 m. Interestingly, during the last cold stage, only small cirque and valley glaciers formed and covered a total area of *c.* 4 km^2 with an ELA of *c.* 2174 m. Periglacial rock glaciers also formed above altitudes of *c.* 1800 m during the last cold stage and show that temperatures at the time of formation would have been *c.* 8–9°C lower than today (Hughes *et al.*, 2003).

Hughes *et al.* (2006) correlated the various glacial and periglacial units recorded on Mount Tymphi with cold stage intervals recorded in the pollen stratigraphy at nearby Lake Pamvotis, Ioannina (Tzedakis, 1994; Tzedakis, *et al.* 2002). The Ioannina sequence was then used as a parastratotype to define a glacial chronostratigraphy for the Pindus Mountains and to allow correlation with the marine isotope record. The oldest and most extensive glacial unit and was correlated with the oldest cold stage recorded in the Ioannina sequence and correlated with MIS 12. This interval was termed the Skamnellian Stage in the Pindus chronostratigraphy. The next glacial unit, corresponding with glaciers that reached mid-valley positions, has been correlated with MIS 6. This interval was termed the Vlasian Stage in the Pindus chronostratigraphy. The youngest glacial unit on Mount Tymphi was correlated with the last cold stage at Ioannina and MIS 5d-2 and, in the Pindus chronostratigraphical scheme, was termed the Tymphian Stage (Hughes *et al.*, 2006).

Glacial and periglacial processes on Mount Tymphi have exerted an important influence on the long-term behaviour of the Voidomatis River, which drains the mountain's southern and western slopes. The terraced alluvial sediments of the middle and lower reaches of the Voidomatis River record major phases of major aggradation during the Late Pleistocene and possibly earlier glacial stages. Enhanced sediment supply from the glaciated uplands was an important control on fluvial aggradation, since the Pleistocene river sediments are dominated by clasts and fine sediment from glaciated limestone areas in the headwaters (cf. Bailey *et al.*, 1990; Lewin *et al.*, 1991; Woodward *et al.*, 1995; 1995; Hamlin *et al.*, 2000).

Hughes (2004) found evidence of a similar glacial sequence to Mount Tymphi on neighbouring Mount Smolikas (2637 m). However, here there is evidence for a fourth, later, glacial phase in the highest cirques where small cirque glaciers developed with an ELA of *c.* 2420 m and total area of <0.5 km^2. This phase of glaciation is likely to have taken place after the glacial maximum of the Tymphian Stage. It is probable that these glaciers formed during an interval equivalent to the Lateglacial Substage of northwest Europe, although in the absence an independent geochronology for these deposits, the exact timing of this phase can only be confirmed by future work.

The glacial history of Mount Olympus (2917 m), the highest mountain in Greece (Figure 4), has most recently been investigated by Smith *et al.* (1997). Olympus is usually regarded as separate from the Pindus chain and lies to the east, close to the coast of the Aegean Sea (Figure 4). Smith *et al.* (1997) argued that the Mount Olympus glaciers extended down to 100 m in the form of piedmont lobes. This represents a radical revision of the earlier work of Faugères (1969) and Messerli (1967), who both concluded that the Pleistocene glaciers on Mount Olympus did not descend to altitudes below 1600 m. In fact, Faugères (1969) interpreted many of the lowest piedmont deposits not as glacial deposits, but as fluvial deposits and alluvial fans. Moreover, Messerli (1967) and Faugères (1969) attributed all of the glacial deposits to the last glacial stage (Würmian Stage) unlike Smith *et al.* (1997) who recognized three main phases of glaciation during three separate glacial stages.

A provisional chronology for glaciation on Mount Olympus was proposed by Smith *et al.* (1997). This was based on correlating soils on glacial deposits with dated soils in the river deposits of the Larissa basin (Demitrack, 1986; van Andel *et al.*, 1990). Smith *et al.* (1997) tentatively placed the oldest and most extensive glaciation, where glaciers extended as low as 100 m over the eastern piedmont, before 200,000 cal. years BP, and suggested that this glaciation may have occurred during Marine Isotope Stage (MIS) 8. A second glaciation involved the production of upland ice and valley glaciers which did not reach the piedmont, and Smith *et al.* (1997) correlated this phase with MIS 6. The ELA of glaciers during this phase is estimated at 1000–1030 m. A third phase of glaciation was restricted to valley heads, and glaciers extended to only mid-valley positions where ELAs were *c.* 2200 m (1300 m snowline depression subtracted from modern estimate of 3500 m; Smith *et al.*, 1997). The latter phase is correlated with part of the Würmian Stage (MIS 4 to 2). A further set of moraines are found in the high cirque of Megali Kazania and Smith *et al.* (1997) have suggested that they may be Holocene Neoglacial features.

More recently, Manz (1998) attempted to improve the geochronology of the Olympus glacial sequence by applying cosmogenic dating to recessional moraine complexes on the eastern piedmont. Chlorine-36 ages were obtained from two sites, on boulders that formed part of the lowest stratigraphical glacial unit. Exposure ages in the range 49,000–32,000 cal. years BP were obtained from limestone boulders at one site and 56,000–43,000 cal. years BP from igneous, metamorphic and carbonate lithologies at another. At the latter site, one boulder gave an age of 146,000 cal. years BP, although this outlier has been attributed to either previous exposure or evidence of an earlier glacial phase. Manz (1998) suggested that the cosmogenic dates from the site containing igneous and metamorphic rocks provide the more reliable exposure ages. However, these ages are far younger than the model proposed by Smith *et al.* (1997) and differ considerably from the age of the oldest glacial sediments on Mount Tymphi. Also, it is difficult to reconcile the relatively young exposure ages of Manz (1998) with the substantial pedogenesis that has occurred on the lower Mount Olympus glacial deposits (Woodward *et al.*, 2004). It is possible that the exposure-dated boulders by Manz (1998) have been exhumed following deposition due to erosion processes and further dating is needed from Mount Olympus to clarify the issue. In view of the similar morphostratigraphical sequence of four glacial units on Olympus as in the Pindus Mountains, less than 120 km to the west at the same latitude, it would be expected that these sequences correlate.

The southernmost glacial and periglacial landforms in Europe have been identified in the mountains of the Peloponnese (Mastronuzzi *et al.*, 1994) and Crete (Poser, 1957; Bonnefont, 1972; Boenzi *et al.*, 1982; Fabre and Maire, 1983). In Crete, a periglacial zone, including features such as boulder pavements extending down to an altitude of 800 m, is considered to represent the range of Pleistocene periglacial action in this area (Poser, 1957). In the White Mountains, the highest in Crete, Poser (1957), Bonnefont (1972) and Boenzi and Palmentola *et al.* (1982) did not find evidence of glaciation. However, Nemec and Postma (1993) have 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 and Postma, 1993: 237–38). They studied a series of alluvial fans and have argued that they were formed by large water discharges associated with ice-cap melting in the White Mountains. Alternating periods of fan growth and fan abandonment were considered to be related to periods of deglaciation and renewed glaciation and as many as five consecutive periods of high water runoff have been recognized. Thus, it is possible five phases of deglaciation are recorded in the alluvial fan record in Crete. However, Nemec and Postma (1993) did not present detailed evidence for glaciation in the mountains, or its timing, and their model of glacier-alluvial fan interaction is yet to be substantiated and was questioned by Blair and McPherson (1995). However, further east on Mount Idi, Fabre and Maire (1983) recognized a cirque and associated moraines, the latter at an altitude of *c.* 1945 m. Even so, the issue of glaciation on Crete, especially spatial and temporal patterns, remains unclear and requires further investigation.

Mountainous terrain continues northwards from Greece into Albania and the former Yugoslavia, as well as into Bulgaria where the highest Balkan peaks can be found (Figure 4). All of these mountain regions drain into the Mediterranean Sea and are included in this review. Evidence of glaciation has been reported throughout these mountains, although most studies are based only on the observation of morphological features (see below). Only one site from the whole of this area has some geochronological control, and even here it is paraglacial and not glacial sediments which are dated, and few detailed geomorphological maps have been published. Therefore, current knowledge remains largely in the pioneer and mapping phases as defined earlier.

Early reports of relict glacial features in the Bulgarian mountains include those of Cvijić (1898; 1900) and later studies by Louis (1930) in which glacial deposits were noted on all of the high mountains of the Pirin (2925 m) and Rila (2920 m) ranges (Figure 4). In fact, Bozilova and Tonkov (2000) claim that there is abundant evidence for glacial activity for at least the last two cold stages of the Pleistocene. The snowline during the last glaciation is estimated at *c.* 2200–2300 m, 800–900 m lower than present, with glaciers extending down to *c.* 1300 m (Glovnja, 1963). However, few radiometric age determinations exist, apart from a few radiocarbon dates from lake sediment cores indicating the onset of organic sedimentation during the Lateglacial Substage (Bozilova and Tonkov, 2000; Stefanova and Ammann, 2003). These cores bottomed in sands and gravels and, unfortunately, only provide minimum ages for deglaciation. Interestingly, at Lake Dalgoto (2312 m), a glacial lake in the northern Pirin Mountains, there is no evidence of a marked climatic oscillation during the Lateglacial Substage (14–10,000 ^{14}C years BP) with pollen assemblages suggesting that open xerophytic herb vegetation existed throughout the Lateglacial Substage (Stefanova and Ammann, 2003). More significantly, it also implies that this cirque was ice-free at the altitude of Lake Dalgoto (2312 m) during the Younger Dryas Chronozone (*c.* 11–10,000 ^{14}C years BP).

In Albania, some of the earliest reports describing evidence for glaciation include those by the Italian geographer Roberto Almagià (1918) and the Polish geologist Ernest Nowack (1921), who was employed by the Austro-Hungarian Army to survey the mineral resources of Albania during the first world war. In slightly later work, Louis (1926) documented detailed evidence for glaciation on the mountains of Nëmerçka (2495 m), on the Epirus (Greece) border, and Mali i Lunxheriës (2200 m), southwest of Gjirokastër (Figure 4). More recently, Menkovic *et al.* (2004) used satellite images and small-scale topographical and geological maps, supplemented by field observations, to compile evidence of glaciation in the Korab Mountains (2753 m), the Koritnik Mountains (2394 m) and the Prokletije Mountains (2692 m) on the Serbia–Albania border (Figure 4). In the Prokletije Mountains, Palmentola *et al.* (1995) also noted the presence of relict rock glaciers above 1700 m, set within more extensive glacial features. They suggested that these rock glaciers may be of Lateglacial age because they believed the more extensive glacial features formed during the global LGM of the Late Würmian. However, there are no radiometric dates to support such an assumption in this area, and the chronology of glaciation in this area has not been established.

In the former republics of Yugoslavia, Jovan Cvijić was the pioneer of glacial research (Cvijić, 1900; 1917) and he represents one of the most significant glacial researchers in the Mediterranean region at this time. In many areas, glacio-karst landscapes dominate the highest uplands and on Mount Durmitor (2530 m), in Montenegro (Figure 4), Alpine-type valley glaciers descended from the highest peaks into a large plateau ice field above canyons incised by the Piva and Tara rivers. Additional glaciers descended from this ice field forming the major U-shaped troughs of the Komarnica, Pirni Do and Sušica valleys. In addition, numerous glacial lakes occur all over the Durmitor massif with some dammed by moraines such as the Crno Jerzero lake near the town of Zabljak (Nicod, 1968; Menkovic *et al.*, 2004). The snowline in the Durmitor region during the most extensive glaciation is estimated at *c.* 1600 m a.s.l. (Nicod, 1968). Further west, near the Adriatic coast on Mount Orjen (1895 m), glacial cirques and valleys exploited older karstic forms such as sink holes (dolines) and uvalas (larger closed depressions commonly formed by coalescence of several dolines) to form extensive glaciers. The evidence for glaciation on Mount Orjen was first noted by Penck (1900) and Sawicki (1911) and most recently by Menkovic *et al.* (2004). According to Menkovic *et al.* (2004), the most extensive glacier in the area was *c.* 2 km wide, 3 km long and 300 m thick with a snowline of *c.* 1300 m. Sawicki (1911) estimated that the glaciers on Mount Orjen covered an area of *c.* 39 square miles (*c.* 63 km^2). The extensive glaciation on lowly Mount Orjen (1895 m) was probably a function of very high precipitation and today precipitation in this area exceeds 5000 mm (Furlan, 1977). Glacial landforms are also evident on Sara Mountain (2747 m), on the border of Serbia and Macedonia. Here, a plateau-type ice cap covered an area of 30–35 km^2. On the mountain's northwestern slopes around 30 cirques are present and moraines are preserved in the upper courses of the Lepenec and Prizrenska Bistrica rivers down to elevations of 1250–1300 m (Menkovic *et al.*, 2004). In fact, many of the mountains of the former Yugoslavia were extensively glaciated during the Pleistocene and research is under way to further understand the glacial history of this region.

In Croatia, Marjanac and Marjanac (2004) reviewed the evidence for glaciation in the coastal Dinaric Alps (Figure 4). Significantly, they document glacial deposits on very low-altitude mountains in comparison with the rest of the Mediterranean. For example, they present evidence for moraines at an altitude of only 270 m at Velika Paklenica canyon. However, even more interesting are Marjanac and Marjanac's (2004) descriptions of features, which they argue are glacial in origin, on some of the Croatian coast and islands in the Adriatic. These include kame-terraces on the Krk and Pag islands (Figure 4) as well as glacial and periglacial deposits on the mainland coast nearby at Novigradsko More and Karinsko More. Marjanac and Marjanac (2004) They attribute the coastal glacial deposits to a glaciation during the Early or Middle Pleistocene but acknowledge that more work is needed to clarify the chronology of the Croatian glacial sequence. Gregory (1915) also noted features in Dalmatia resembling those characteristic of glacial erosion, such as subdued relief and rounded rocks, bare rock surfaces, spburless valley sides, trough valleys and hanging valleys. In fact, Gregory (1915) stated that 'the resemblance of so many of the topographic features of Dalmatia to glacial forms is so striking that it is difficult when visting the country to resist the conviction that it has been glaciated'. However, Gregory (1915) found no evidence of moraines or glacial deposits, except in the mountains, and concluded that the landscape of lowland Dalmatia was characterized by *pseudo-glacial* features, which formed as result of fluvial and karstic processes in combination with structural geological controls. Thus, the evidence of lowland glaciation along the Adriatic coast is ambiguous. If glaciers did extend down to the eastern Adriatic coast, then these glaciers would represent some of the lowest in the Mediterranean and these features would assume major palaeoclimatic significance. Such a scenario is perhaps plausible given the fact that today the area is characterized by some of the highest precipitation in Europe (Furlan, 1977), but further work is needed in the area to confirm the extent of glacial activity.

Unfortunately, as with elsewhere in the Balkans outside of Greece, the timing of glaciation in the former Yugoslavian republics is largely unknown. However, in the upper Soca̦ river region of the southern Julian Alps (Figure 4), Bavec *et al.* (2004) analysed paraglacial mass-flow, fluvial and lacustrine deposits. These deposits were dated using radiocarbon, Uranium-series and Infrared Stimulated Luminescence methods. The results suggest two phases of paraglacial sedimentation with glaciers present in the uplands: during the penultimate glacial stage (MIS 6) between 154,740 ± 22,880 and 129,930 ± 7,990 cal. years BP and during the last glacial stage (MIS 2) through to the Early Holocene. However, Bavec *et al.* (2004) only dated the paraglacial sediments and did not directly date the glacial deposits higher up-valley. Most glaciers in this area have long since disappeared, although a small glacier exists today on Triglav (2863 m), the highest mountain of the Julian Alps in Slovenia (Figure 4). This glacier has retreated rapidly during the twentieth century (Gams, 1994) and in 1998 covered an area of less than 3 hectares (Gabrovec, 1998).

V The Italian Apennines

The Apennines rise to 2912 m in the Gran Sasso at Corno Grande (Figure 4). The Calderone glacier is situated on this mountain and is Europe's southernmost glacier (*c.* 42° 30′ N). Today it covers only a few hectares and lies well below the regional snowline with its snout at *c.* 2700 m. The glacier survives as a result of the very steep cirque walls and a northeastern aspect. A glacier is thought to have persisted in this cirque throughout the Early Holocene, although the cirque was ice-free between *c.* 4300 and 3890 ± ^{14}C years BP. Several phases of Late Holocene Neoglacial expansion have been recognised, after 3890 ± 60, 2650 ± 60, 1450 ± 40 and 670 ± 40 ^{14}C years BP (Giraudi, 2003; 2004). The last major readvance occurred during the Little Ice Age, between AD 1550 and 1850, when it is thought that the Calderone glacier extended down to 2500 m (Gellatly *et al.*, 1994). The most widespread and best preserved relict glacial features in the Apennines are usually attributed to the Late Würmian Substage of the Late Pleistocene, although older, more extensive, glacial deposits are thought to be of Middle Pleistocene age.

The Gran Sasso massif of the Central Apennines has the best glacial geochronological sequence presently available in the Apennines. Giraudi and Frezzotti (1997) mapped a series of moraines and rock glaciers and demonstrated that the maximum glacier extent occurred just prior to 22,680 ± 630 ^{14}C years BP in the Campo Imperatore area. This indicates that the valley glacier in this area reached its maximum prior to the global LGM which occurred at *c.* 18,000 ± 1000 ^{14}C years BP based on the orbitally tuned marine oxygen isotope chronostratigraphy of Martinson *et al.* (1987). Ice in the Campo Imperatore area of the Gran Sasso covered an area of 19 km^2 with an ELA of *c.* 1750 m during the glacier maximum of the last cold (Würmian) stage. This compares with cirque glaciers totalling only *c.* 4 km^2 and with a mean ELA of 2174 m on Mount Tymphi the Pindus Mountains of Greece during the Würmian Stage (Hughes, 2004). The smaller glaciers in Greece may reflect latitudinal controls on solar radiation and temperature. The latter is supported by the fact that rock glaciers fronts and associated lower limits of permafrost in the Pindus Mountains were at least 140 m higher than in the Gran Sasso (Hughes *et al.*, 2003).

Using the lower altitude of rock glaciers at 1660 m as indicators of the limit of discontinuous permafrost, Giraudi and Frezzotti (1997) concluded that mean annual temperatures during the last glacial stage were 7.3–8.3°C lower than present-day values. They extrapolated this temperature reduction to the ELA of the contemporaneous valley glacier in the Campo Imperatore area and, based on the well-established relationship between accumulation and precipitation at the ELA of modern glaciers (cf. Ohmura *et al.*, 1992), concluded that snowfall was the same as today. This is an interesting finding since it conflicts with evidence from the pollen record at long lacustrine sequences in Italy such as at Lago Grande di Monticchio, where the evidence suggests a very arid LGM (Allen *et al.*, 2000). However, Giraudi and Frezzotti (1997) do stress that similar snowfall to today may not imply similar rainfall during the summer season. Even so, it is likely that the glacier maximum in the Gran Sasso and the most severe arid phase of climate indicated in the pollen record at Monticchio were not synchronous. In fact, for the interval 21,000–18,000 ^{14}C years BP corresponding to the global LGM, Giraudi and Frezzotti (1997) suggest that climate was very cold and dry compared with very cold and wet during the earlier *local* glacier maximum.

A series of recessional moraines and rock glaciers in the Gran Sasso are thought to correspond to periods of glacier stabilization or readvance between 20,000 and 10,000 ^{14}C years BP. They have been named the Fontari Stadial, which started after 17,840 ± 200 ^{14}C years BP and ended at *c.* 16,000 ^{14}C years BP and the Mount Aquila Stadial, corresponding with the Younger Dryas Chronozone between 11,000 and 10,000 ^{14}C years BP. During the Mount Aquila Stadial, glacier reconstructions place the ELA in this area at *c.* 2300 m. Rock glaciers in this massif, with fronts between 1850 and 1950 m, have also been correlated with the glacier readvance of the Mount Aquila Stadial. Rock glaciers, ascribed to the Mount Aquila Stadial and the Younger Dryas Chronozone, have been described elsewhere in the Italian Apennines, such as on Mount Velino and Mount Maiella (Figure 4) where relict forms occur down to 1910 m (Dramis and Kotarba, 1994). In the latter area, some high rock glaciers, with fronts above 2600 m, contain ice and may be active today. This would imply that the modern limit of discontinuous permafrost occurs at around 2600 m in central Italy (Dramis and Kotarba, 1994).

The occurrence of a climatic deterioration during the Younger Dryas has also been demonstrated in lacustrine sediments by Lowe (1992) in the Apennino Parmenese (2165 m) (Figure 4). Both the lithostratigraphy and pollen stratigraphy provide evidence for a climatic oscillation in lake sediments inside extensive valley glacier moraines but outside cirque moraines. Inside the cirque moraines, no climatic oscillation comparable to the Younger Dryas is recorded in the pollen and lithostratigraphy. This led Lowe (1992) to suggest that the cirque moraines formed during the Younger Dryas and that the more extensive valley glacier moraines formed during the LGM of the Late Würmian. However, the snowline altitude of the supposed Younger Dryas glacier is estimated at *c.* 1650 m. This is far lower than in the Gran Sasso, further south, where snowlines were placed at *c.* 2300 m and where rock glaciers occurred no lower than 1850 m. It is also considerably lower than in the Italian Alps further north where the Younger Dryas snowline is estimated at *c.* 2450 m (Porter and Orombelli, 1982). This is acknowledged by Lowe (1992) who left open the possibility that these cirque moraines may in fact be older, which would seem highly probable given the snowline reconstructions elsewhere in Italy.

The presence of glacial deposits older than the Würmian Stage in the Italian Apennines was highlighted over 25 years ago by Federici (1980), who documented evidence dispelling the myth of a single Apennine glaciation. There is evidence for more than one Pleistocene glaciation in the Gran Sasso area. Here, glacial deposits exist outside the Würmian Stage Campo Imperatore moraines dated by Giraudi and Frezzotti (1997), although they are less well preserved and are strongly eroded, smoothed and reduced in size (Kotarba *et al.*, 2001). Calcite cements within these moraines have been dated, using Uranium-series, to at least 135,000 ± 10,000 cal. years BP and probably formed during the last interglacial (Eemian Stage). These moraines are believed to have formed during the preceding glacial, equivalent to the Rissian Stage in the Alps (Kotarba *et al.* 2001) and may be correlated with similarly dated glacial deposits in Greece (cf. Woodward *et al.*, 2004; Hughes, 2004). It is therefore clear that at least two major glacial advances are recorded in the Gran Sasso area, with readvances also recorded during the Lateglacial. However, it is quite possible that the outermost glacial deposits dated by Kotarba *et al.*, (2001) predate the Rissian Stage since the Uranium-series age represents a minimum age. In addition, it would be helpful to have Uranium-series ages from calcite cements in the higher Campo Imperatore moraines to confirm the Late Würmian age suggested by the radiocarbon dates obtained by Giraudi and Frezzotti (1997).

Glacial deposits that extend lower than moraines assigned to the Würmian have been noted in many other areas of the Italian Apennines. As in the Gran Sasso, they are often partially cemented and show a strong pink alteration colour indicative of prolonged weathering. However, they are often fragmentary and, unlike in the Gran Sasso, their age has not been established. Glacial deposits of this type can be found in the northern Apennines on Mount Navert (Federici, 1977; 1980) and in the central Apennines in several localities on Mount Velino (2487 m) (Federici, 1980; Cassoli *et al.*, 1986; Giraudi, 1998) and Mount Greco (2283 m) in Abruzzo (Cinque *et al.*, 1990) (Figure 4). In addition, in the southern Apennines, erosional evidence suggests extensive glaciation before the most recent Würmian glaciers. For example, on Mount Matese (2050 m), some cirques are located at altitudes lower than the snowline associated with the accepted Late Würmian glacial deposits (Palmentola and Acquafredda, 1983). Also in the southern Apennines, on Monte Cozzo del Pellegrino, moraines have been ascribed as pre-Würmian, although only on the basis of morphostratigraphy (Boenzi and Palmentola, 1975; Federici, 1980).

In addition to the dated moraines in the Gran Sasso, the age of the pre-Würmian glacial deposits has been established further to the south in the Campo Velice in the Velino massif (Giraudi, 1998). Here, moraines are overlain by aeolian deposits containing a Mousterian chert artifact. In central Italy, humans of the Mousterian culture were present from at least the last interglacial (*c.* 130–115,000 cal. years BP) until *c.* 58,000 years cal. years BP (equivalent to MIS 5e to the end of MIS 4), implying that the underlying till must have formed prior to this. Giraudi (1998; 2003; 2004) suggests that the till was deposited during one of the cold stages preceding the last interglacial. Given the fairly good preservation of these moraines, he suggested that they may have formed during an interval equivalent to the Rissian Stage of the Alps. This is corroborated by the Uranium-series dates obtained from similar deposits in the Gran Sasso massif (Kotarba *et al.*, 2001). However, whether they relate to the glaciation immediately preceding the last interglacial or earlier is unknown since these are minimum age estimates. Jaurand (1994; 1998) has suggested that a moraine on Mount Navert in the northern Apennines could be even older and may have formed before the late Middle Pleistocene, although no dating evidence is presented. This is important and requires further work as it could imply that three glacial stages are recorded in the Italian Apennines, in common with the record in Greece to the east.

Outside of the Italian Apennines, apart from the Alps, Mount Etna (3323 m) is likely to have been glaciated during the Pleistocene. However, there is little documented evidence for this. Glacial deposits may well be preserved and it is possible that these are covered or intercalated with lavas and ashes of the Quaternary volcanic record. If this is the case, then the volcanic horizons could potentially provide a way of dating glacial units using techniques such as Potassium-Argon dating (cf. Dalrymple and Lanphere, 1969).

VI Corsica

The mountains on the island of Corsica rise to 2710 m at Monte Cinto (Figure 4). Glacial deposits were first reported by Pumpelly (1859) and the most recent published studies are those of Heybrock (1954), Letsch (1956) and Conchon (1978; 1986). Conchon (1986) recognized four suites of glacial deposits and concluded that glaciers had existed at least four times during the Quaternary. The oldest deposits were believed to be of pre-Würmian Stage age, two valley glacier phases were presumed to belong to the Würmian Stage and small cirque glaciers to the Lateglacial Substage. Evidence from cores inside the most recent moraines has shown that the highest cirques contained small glaciers between 15 and 14,000 ^{14}C years BP, but have been free of ice since the Allerød Interstadial at *c.* 12,500 ^{14}C years BP (Conchon, 1986). Interestingly, this implies that glaciers did not occupy cirques during the Younger Dryas (11–10,000 ^{14}C years). However, despite detailed mapping and stratigraphical study, the geochronology of the overall glacial sequence has not been firmly established (Hewitt, 2002).

VII The Alpes Maritimes

The highest massif of the Alpes Maritimes, Argentera (3297 m), is situated less than 50 km from the Mediterranean coast at Monte Carlo (Figure 5). This massif supports six glaciers and seven glacierets with a present-day ELA of *c.* 2800 m and these glaciers are the most southerly of the European Alps (Finsinger and Ribolini, 2001). The lower discontinuous permafrost boundary occurs at *c.* 2600 m (Ribolini, 2001) and represents the threshold for permafrost creep which is important in rock glacier formation. Lichenometric dating of recently deglaciated glacier forelands has shown that during the Little Ice Age glaciers extended 100–150 m lower than present (Federici and Stefanini, 2001). It is clear, however, that ice cover was much more extensive than this during the cold stages of the Pleistocene, and during the last glacial maximum the Ghiacciaio di Entraque extended down to an altitude of 790 m with an ELA of *c.* 1710 m (Federici and Pappalardo, 1991).

During the Würmian Stage, the Alpes Maritimes were covered by ice that was contiguous with the main Alpine ice sheet, which extended over an area of *c.* 126,000 km^2 (Ehlers, 1996). The glacial geomorphology of the Argentera area has been described by

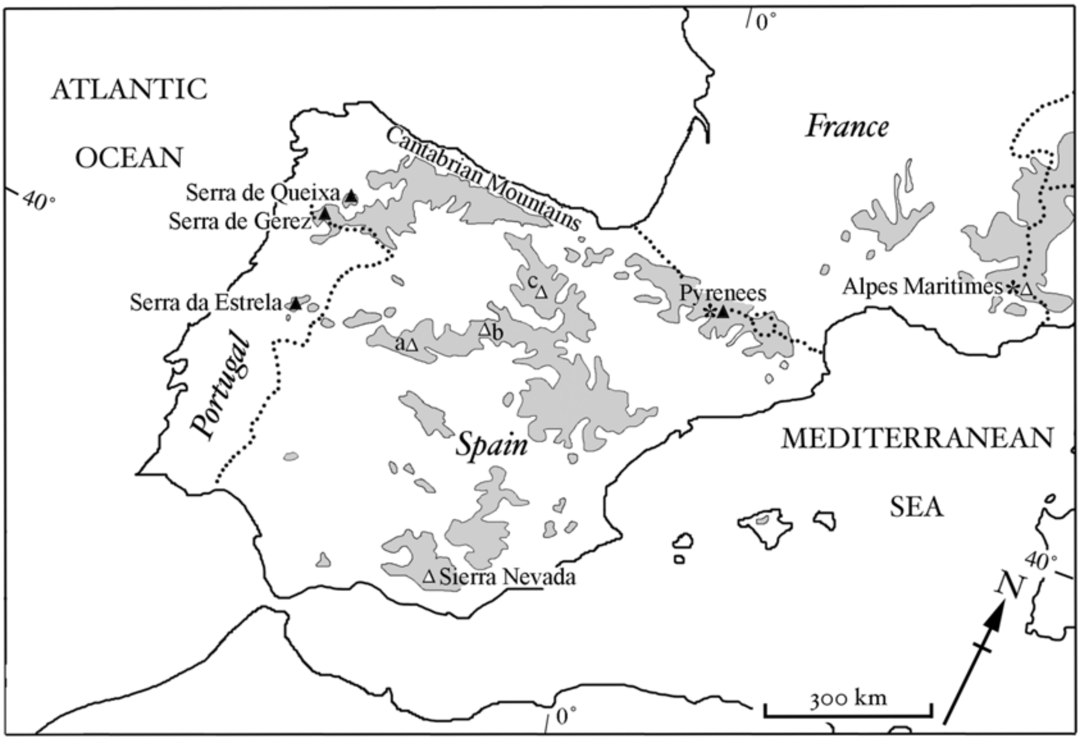

Figure 5 Location map showing some of the glaciated mountains of the Alpes Maritimes, the Pyrenees and the Iberian peninsula. Areas depicted by letters are: (a) Sierra de Gredos; (b) Sierra de Guadarrama; (c) Sierra de Cebollera/Sierra de la Demanda. A key is provided in Figure 2. Areas over 2000 m are not depicted due to scale

Ribolini (1996). The valleys of this area are deeply scoured, and large moraines were deposited in the lower parts of the valleys. The Würmian glacial maximum in the Alps occurred between 28,000 and 20,000 ± 1800 ^{14}C years BP in the northern Alpine foreland (Florineth and Schlüchter, 2000) and between 24,000 ± 120 and 17,700 ± 360 ^{14}C years BP in the southern Alpine forelands (Orombelli, 1974; Fliri, 1989). It is therefore reasonable to assume that the glacial maximum in the Alpes Maritimes occurred at a similar time during the Late Würmian, and lacustrine sediments at Lac Long Inférieur in a glaciated cirque (2090 m) have been dated to 14,190 ± 130 ^{14}C years BP (Ponel *et al.*, 2001), indicating that ice had retreated by this time. However, in the Argentera massif, Finsinger and Ribolini (2001) document evidence for glacial advances during both the Oldest and Younger Dryas Chronozones of the Lateglacial Substage.

During the Younger Dryas Chronozone, glaciers in the Alpes Maritimes are thought to have had a mean ELA of 2500 m and the lower discontinuous permafrost boundary, corresponding with the occurrence of rock glacier fronts, occurred between 2300 and 2400 m (Finsinger and Ribolini, 2001). The reconstructed glacier ELAs and altitude of the lower discontinuous boundary for the Younger Dryas compare with altitudes of *c.* 2300 m and 1850 m for glacier ELAs and lowest rock glacier fronts during the same period further south in the central Italian Apennines

(Dramis and Kotarba, 1994; Giraudi and Frezzotti, 1997). While the glacier ELAs are similar, the positions of the discontinuous permafrost boundary differ by over 450 m. Given that the lower discontinuous boundary generally corresponds to the –2°C mean annual isotherm (Belloni *et al.*, 1988; Carton *et al.*, 1988, Brazier *et al.*, 1998), this implies that mean annual temperatures during the Younger Dryas were significantly higher in the Alpes Maritimes compared with the central Italian Apennines. This is perhaps contrary to what would be expected given that the Alpes Maritimes are nearly 2° further north, and therefore until more robust dating frameworks are available such correlations must be viewed as tentative.

VIII The Pyrenees

The Pyrenees (Figure 5) were extensively glaciated during the Quaternary, a fact recognized in pioneering research in the early nineteenth century by Penck (1885). Today, only small glaciers exist on the highest massifs in the central Pyrenees, such as Maladeta (3404 m). Here, six small glaciers are present, covering a total area of around 2 km^2 with ELAs of *c.* 3000–3100 m (Julián *et al.*, 2001). Further west on the peaks of Balaïtous (3144 m) and Vignemale (3298 m) the glaciers extend down as low as *c.* 2400 m. However, in the eastern Pyrenees, glaciers are absent, despite the presence of some of the highest peaks such as Pic d'Estats (3143 m) (Calvet, 2004). Most modern glaciers in the Pyrenees exist in localities marginal for glaciation and their development and morphology are strongly influenced by factors relating to topography, especially aspect and shade (Chueca and Julián, 2004). This is characteristic of most modern glaciers in the Mediterranean region.

The snowline in the Pyrenees during the glacial maximum of the Würmian Stage varied from region to region. The snowline increased in altitude from west to east, probably tracking a marked precipitation gradient from the Atlantic to the Mediterranean coasts. In the Pays-Basque region of the western Pyrenees, Würmian Stage snowlines are estimated at 1200–1300 m, while in some areas of the eastern Pyrenees snowlines lay above 2300 m. However, the most marked asymmetry occurred between the north- and south-facing slopes, with glaciers on the southern Spanish slopes located at much higher elevations than on the French slopes to the north (Calvet, 2004).

The largest and most powerful Pleistocene glaciers in the Pyrenees occurred on the northern slopes in France (Calvet, 2004). For example, in the Ariège valley, glaciers extended 65 km to an altitude of 370 m (Hérail *et al.*, 1986). The chronology of the last glaciation in the French Pyrenees is based on sedimentological and palynological studies and radiocarbon dating of lacustrine sediments near former glacier margins. This approach has indicated that during the last glaciation the glacial maximum occurred before 38,000 ^{14}C years BP in the French Pyrenees (Hérail *et al.*, 1986; Jalut *et al.*, 1992) similar to the situation in the Vosges of Alsace (Seret *et al.*, 1990). However, dating control is limited across both the French and Spanish Pyrenees, and intersite correlation is largely based on morphostratigraphical position.

In the Spanish Pyrenees, most glacial deposits are thought to have formed during the last glaciation, although some isolated glacial deposits have been attributed to earlier glaciations (Calvet, 2004). However, as is the case in France, the geochronology of the glacial sequence in the Spanish Pyrenees is poorly defined. Correlations have often been made on the basis of morphostratigraphical comparisons, and even delimiting the maximum extent of the last glaciation remains one of the most significant problems of Pyrenean Quaternary geology (García-Ruiz *et al.*, 2003). Nevertheless, there is evidence that the maximum extent of ice during the last glacial stage occurred significantly earlier than the maximum extent of the major ice sheets of Britain and Scandinavia, which reached their maximal extents between 21,000 and 18,000 ^{14}C years BP (Sibrava *et al.*, 1986). Sedimentological and palynological analyses and an accelerator mass spectrometry ^{14}C chronology, based on minimum ages from glacial lake sediments, suggest that the maximum extent of glaciation during the last glacial phase occurred before 30,000 ^{14}C years BP (García-Ruiz *et al.*, 2003), similar to findings in the French Pyrenees to the north. Subsequent retreat was characterized by a phase of upper valley glaciation between 16,000 and 15,000 ^{14}C years BP and then by a phase of cirque glaciation between 14,000 and 13,000 ^{14}C years BP (Bordonnau 1992). The last stage of Pleistocene glaciation in the Pyrenees is represented by moraines and rock glaciers close to the cirque backwalls and may date to the Younger Dryas between 11,000 and 10,000 ^{14}C years BP (Serrat, 1979), as is the case in the Alpes Maritimes and the Italian Apennines.

In many valleys, Würmian Stage glaciers appear to have removed much of the older glacial deposits. However, in some locations, traces of older, more extensive, glacial deposits do exist and may relate to the Rissian Stage (MIS 10–6). In addition, in the eastern Pyrenees, strongly weathered tills extend to lower elevations than those ascribed to the Rissian Stage and are considered to have formed during the early Middle Pleistocene (Calvet, 2004). However, since these deposits are undated, the geochronology of the pre-Würmian record is yet to be defined and this is a key issue across much of the Mediterranean region.

IX Iberia

Quaternary glaciation occurred in many of the high mountain areas of Iberia (Figure 5). Small modern glaciers have been reported in the Picos de Europa (2651 m), the highest massif of the Cantabrian Mountains, where González-Suárez and Alonso (1994) attributed their existence to high precipitation and shading. However, Frochoso and Castañón (1995) argued that these features represent fossil ice bodies inherited from the Little Ice Age and that only perennial snow patches and sporadic permafrost occur today. The lowest Pleistocene snowlines occurred in the northwestern mountains of Galicia and the highest were located in the southern mountains of the Sierra Nevada in Andalucia (Schmitz, 1969) (Figure 5). However, apart from a few localities, the geochronology of most glacial sequences outside of the Pyrenees is unknown and, despite a century and a half of research, many areas are yet to be studied in detail (Pérez Alberti *et al.*, 2004).

The highest mountains of Iberia occur in the Sierra Nevada of Andalucia in southern Spain (Figure 5). Until recently, these mountains contained the southernmost modern glacier in Europe. Glacier ice was observed in the Corral Veleta up until the beginning of the twentieth century and, according to Messerli (1967), this glacier was 'the sensation of [the] Sierra Nevada'. Messerli (1967) recognized three distinct phases of glaciation in this area. He argued that the uppermost moraines, formed by glaciers with a snowline of between 2700 and 3000 m, existed during the Würmian Lateglacial Substage. Valley glaciers up to 9.5 km long with snowlines between 2300 and 2400 m are thought to have formed during the Late Würmian glacial maximum. However, the oldest and most extensive glacial deposits extend up to 4 km beyond the end moraines of the Würmian glaciers with a snowline around 200 m lower. Messerli (1967) considered these deposits to have formed during the Rissian Stage, although evidence from radiometric dating is not available to test this hypothesis.

Glaciers also formed in many of the central Spanish mountains during the Pleistocene including Peñalara (2428 m) in the Sierra da Guadarrama (Palacios and Sánchez-Colomer, 1997) and in the Sierra de Gredos. In the latter mountain range, the largest glaciers occurred on the northern slopes and were more than 14 km long, down to an altitude of 1450 m. In contrast, glaciers on the southern slopes extended less than 3 km in length, down to an altitude of only 1660 m. It is likely that the south-facing glaciers were higher than those on northern slopes because of greater ablation and much shorter because of the steeper slope gradient (Marcos and Palacios, 1995; Martínez de Pisón and Palacios, 1998).

Further north, in the Picos de Europa, the highest massif of the Cantabrian Mountains (Figure 5), Gale and Hoare (1997) argued that at least five former glacial episodes can be recognized. Uranium-series dating of speleothems has been employed to estimate long-term rates of fluvial incision in parts of this area, yielding rates of 0.3 m per 1000 years (Smart, 1986). Gale and Hoare (1997) used these data to estimate the time elapsed since the most extensive phase of glaciation where fluvial action has incised into a glaciated U-shaped valley. They derived a minimum age of 850,000 cal. years for the glacial valley and argued that this constitutes evidence of Early Pleistocene glaciation in the Picos de Europa. While the age of this glacial phase is far from certain, Gale and Hoare (1997) have suggested that the long-term preservation of landforms in the Picos de Europa may be the result of the karstic nature of the bedrock resulting in negligible surface runoff and limited surface erosion. Well-preserved glacial landforms in karst terrains have been recognized in many other Mediterranean mountain areas, albeit for younger moraines, where the limestone bedrock is highly karstic and surface runoff particularly low (eg, Woodward *et al.*, 2004).

Some geochronological control is available to the west of the Picos de Europa, in the Redes Natural Park. Here, recent work by Jiménez-Sanchez and Farias (2002) provided the first numerical age determinations (using radiocarbon dating) to establish the chronology of glacial phases in this region. The most extensive glacial phase here was characterized by an ice field with outlet glaciers extending up to 5 km in length, descending to *c.* 950 m with snowlines at *c.* 1550 m. A radiocarbon date of 28,990 ± 230 ^{14}C years BP was obtained for this glacial phase from a core retrieved from ice-dammed lacustrine deposits, which 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 last glacial maximum phase in the nearby Comella basin of the Picos de Europa, yielded an age of 40,480 ± 820 ^{14}C years BP. Both 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 prior to the global LGM, which occurred at *c.* 18,000 ^{14}C years BP (Martinson *et al.* 1987). Jiménez-Sanchez and Farias (2002) do not, however, suggest a specific age for the maximum glaciation, only that it occurred prior to 28,990 ± 230 ^{14}C years BP and 40,480 ± 820 ^{14}C years BP in the mountains of the Redes Natural Park and Picos de Europa, respectively.

The only directly dated glacial sequences in Iberia are those in the Serra de Queira and Serra de Gêrez in Galicia and northern Portugal (Figure 5). Here, Fernandez Mosquera *et al.* (2000) applied ^{21}Ne cosmogenic dating to glacially polished surfaces and push-moraine boulders. The results showed that three glacial phases can be identified. The oldest glacial phase was dated to before *c.* 238,000 cal. years BP, the intermediate phase to *c.* 130,000 cal. years BP and the youngest to *c.* 15,000 cal. years BP. This sequence of three major glaciations is comparable to the geochronologies established for glacial deposits in Italy and Greece (Giraudi and Frezzotti, 1997; Kotarba *et al.*, 2001; Woodward *et al.*, 2004; Hughes, 2004) although the oldest glacial phase is younger than that recorded in Greece and may correspond to a glaciation during the early Rissian (MIS 8). However, the dates presented by Fernandez Mosquera *et al.* (2000) are minimum ages and adjustments are necessary to take into account assumptions of zero cover and long-term erosion rates.

Further south, in the Serra da Estrela of Portugal (1991 m), glacial features were first described by Vasconcelos Pereira Cabral (1884, cited in Vieira *et al.*, 2001). More detailed analysis of glacial landforms and former glacier extent was presented by Lautensach (1929; 1932) and later by Daveau (1971). Glaciation in this region was extensive and was characterized by a plateau ice cap which fed diffluent glaciers, the longest of which was 13 km long. Daveau (1971) distinguished the following series of glacier phases:

1) a short-lived advance;
2) a long period of stabilization and the development of well-developed lateral moraines;
3) kame terraces and a series of stages of recession, marked by successive loops of frontal moraines.

The maximum extent of glaciation in the Serra da Estrela was attributed to the Würmian Stage by Daveau (1971) although no dates were available to confirm this. However, the retrieval of a radiocarbon-dated lacustrine sequence spanning only the Holocene inside former glacial limits at Lagoa Comprida (Janssen and Woldringh, 1981) provides some support for this assumption. More recent work in this region has involved sedimentological analyses of the glacial deposits in the Serra da Estrela (Vieira and Ferreira, 1998) and fluvioglacial deposits have been dated using thermoluminescence techniques (Vieira *et al.*, 2001). In the latter study, ages of between 16,600 ± 2500 and 10,600 ± 1600 cal. years BP from fluvioglacial units suggest glacial activity during the Lateglacial. Vieira and Ferreira (1998) also highlighted the potential for obtaining cosmogenic exposure dates from granite surfaces in future work. This would offer valuable comparisons to the findings of Fernandez Mosquera *et al.* (2000) from similar glaciated granite terrain to the north.

Glacial features have also been reported from numerous other mountain areas in Iberia including the Sierra Cebollera and Sierra de Demanda (García-Ruiz, 1979; Ortigosa, 1986; Lemartinel, 2004; Figure 5) and several other high mountain ranges (cf. Pérez Alberti *et al.*, 2004). However, geochronological control is not available for the glacial sequences in these areas. Future progress in Iberia will hinge on developing detailed geomorphological and stratigraphical surveys combined with multi-method radiometric dating programmes in different mountain areas. This will allow comparisons to be made between the timing and extent of glaciation within Iberia and the rest of the Mediterranean.

X Discussion

It is clear from this review that many Mediterranean mountains were glaciated during the Pleistocene and periglacial activity extended down to much lower altitudes than is the case today. It is also apparent, however, that the majority of glacial and periglacial sequences are poorly dated and the paucity of good chronological control remains the biggest obstacle to understanding the glacial and periglacial history of the region. Until the number of well-dated sites increases, it is difficult to provide meaningful comparison of ELAs or snowlines across the Mediterranean (cf. Messerli, 1967).

Glacial sediments are rarely directly dated and most studies employ indirect approaches based on associated sediments such as Uranium-series dating of secondary calcite cements and radiocarbon dating of lacustrine deposits inside former glacier limits. The latter has been shown to provide useful insights into the timing of the last glaciation (eg, Jiménez-Sanchez and Farias, 2002; García-Ruiz *et al.*, 2003). However, the radiocarbon method is limited to dating organic material deposited in the last 40,000 years or so and only provides a minimum age for glacier retreat. Uranium-series dating, with a range up to 350,000 cal. years BP, has the potential to provide minimum ages for cemented glacial deposits of Middle Pleistocene age and has been successfully applied in Italy and Greece (Kotarba *et al.*, 2001; Woodward *et al.*, 2004; Hughes, 2004; Hughes *et al.*, 2006). This technique is particularly useful in limestone terrains, which are widespread throughout the Mediterranean region.

Cosmogenic exposure dating is particularly useful to date erosional bedrock surfaces and moraine boulders where they have been exposed to cosmic rays since ice retreat. This method can be applied to a range of lithologies and, while there are problems concerning assumptions of integral exposure-time, it has been successfully applied in glaciated granite areas (eg, Fernandez Mosquera *et al.*, 2000; Hewitt, 2002).

Luminescence dating can also be applied to date a variety of sediments associated with glacial climates including glaciofluvial deposits and aeolian deposits, such as coversands. The technique measures the buildup of metastable electrons within minerals, which takes place once sediments are buried and no longer exposed to sunlight. However, there can be major problems regarding assumptions of bleaching (exposure to sunlight) since burial. For example, many glaciofluvial deposits, especially those deposited sub- and englacially, will never have been exposed to sunlight and, therefore, the buildup of metastable electrons is not representative of the time elapsed since burial. Nevertheless, this technique has been applied to glaciofluvial deposits with some success in the Serra da Estrela, Portugal by Vieira *et al.* (2001).

In Greece, Italy and Iberia glacial deposits of Middle Pleistocene age have been recognized through radiometric dating (Table 2). In all these regions at least one major glaciation has been identified that took place before the last interglacial. In Greece, two separate Middle Pleistocene glaciations have been identified, one dated to before the last interglacial prior to *c.* 127,000 cal. years BP and a more extensive glaciation before 350,000 cal. years BP. The latter glaciation is likely to have

Table 2 Advanced phase studies of glacial sequences in the Mediterranean showing region with radiometric dates and chronostratigraphical relationships. All dates are minimum ages for the glacial deposits. The methods of dating are shown in brackets

Marine isotope stage	Alpine/northern Europe stratigraphy	Region and approximate age of glacial units
2	Würmian/Weichselian	Italy: >22,000 ^{14}C years BP[1] (radiocarbon) Pyrenees: >38,000 ^{14}C years BP[2,3] (radiocarbon) Iberia: >29,000 ^{14}C years BP[4] (radiocarbon) >15,000 cal. years BP[5] (^{21}Ne cosmogenic)
6	Late Rissian/Saalian	Greece: >120,000 cal. years BP[6,7] (U-series) Italy: >130,000 cal. years BP[8] (U-series) Iberia: >130,000 cal. years BP[5] (^{21}Ne cosmogenic)
8	Early Rissian/Saalian	Iberia: >230,000 cal. years BP[5] (^{21}Ne cosmogenic)
12	Mindelian/Elsterian	Greece: >350,000 cal. years BP[6,7] (U-series)

[1]Giraudi and Frezzotti (1997), [2]Jalut *et al.* (1992), [3]García-Ruiz *et al.* (2003), [4]Jiménez-Sanchez and Farias (2002), [5]Fernandez Mosquera *et al.* (2000), [6] Hughes (2004), [7]Woodward *et al.* (2004), [8]Kotarba *et al.* (2001).

taken place during a cold stage that is equivalent to the Elsterian Stage and MIS 12, a period of major glaciation in the Alps and northern Europe (Hughes, 2004; Woodward *et al.*, 2004; Hughes *et al.*, 2006). It is also likely that undated glacial deposits in areas such as the Italian Apennines and the Pyrenees, described as early Middle Pleistocene in age (Giraudi, 2004; Calvet, 2004), are of similar age to those dated in Greece. Future progress in understanding the glacial history of these areas and the rest of the Mediterranean will hinge on the development of sound and detailed stratigraphical frameworks supported by geochronology.

In some areas, Pleistocene snowlines were depressed to as low as 1300 m and the variability in former snowline altitudes correspond broadly to current precipitation patterns. For example, some of the lowest Pleistocene snowlines occurred in the western Balkans in the Adriatic coastal ranges–areas that are today characterized by precipitation totals in excess of 5000 mm (Furlan, 1977). Conversely, the highest glaciers occurred in the southwestern Atlas Mountains and in eastern Turkey where today mean annual precipitation values do not exceed 500 mm (Messerli, 1967; World Meteorological Organization, 1998).

Evidence of former glaciers in Italy and eastern Turkey suggests that during the last glacier maxima in these areas, precipitation totals were close to modern values (Wright, 1962; Giraudi and Frezzotti, 1997). In Greece, glacier evidence suggests precipitation in excess of 2000 mm (Hughes, 2004), although here comparison with modern values is difficult because of the lack of high-altitude precipitation gauging stations. These findings are at odds with palaeobotanical evidence from long lacustrine sequences in Italy and Greece (eg, Tzedakis, 1999; Allen *et al.*, 2000) since these records indicate a dry steppic environment during the height of glacial cycles. However, arboreal species were able to survive in wetter mountain refugia (cf. Tzedakis, 1993; 1994), although even these areas are considered to have been much drier than at present (cf. Tzedakis *et al.*, 2002). The paradox of moist and dry environments posed by glacier and palaeobotanical records, respectively, is likely to stem from asynchronies between former glacier maxima in the uplands and the most severe arid phase of climate indicated in palaeobotanical sequences. In addition, atmospheric cooling over perennial mountain snowfields and increased adiabatic lapse rates under a more continental climate would have produced pronounced precipitation gradients between mountain and lowland areas.

The small glaciers in the Mediterranean mountains would have responded rapidly to climate change, in contrast to the extensive ice sheets that covered the Alps and northern Europe. The small mountain glaciers of the Mediterranean are likely, therefore, to have grown and decayed much faster and reached their maximum extent before the large ice sheets. The rapid response of mountain glaciers to climate change and increased aridity in southern Europe around the time of global glacial maxima may explain the evidence for an early glacial maximum in areas characterized by mountain glaciation during the last glacial stage. This concept is not new since Messerli (1967: 220) suggested that the glacial forms of the Mediterranean 'point to an early-to-maximum Würm with richer precipitation and to a maximum-to-late Würm with low precipitation'. Geochronological evidence from more recent studies of locally glaciated European mountain areas supports this theory. For example, evidence for an early Würmian glacial maximum has been documented in the Cantabrian Mountains of Spain (Jiménez-Sanchez and Farias, 2002), the Pyrenees (Jalut *et al.*, 1992; García-Ruiz *et al.*, 2003), the Massif Central (Etlicher and de Goer de Hervé, 1988), the Vosges (Seret *et al.*, 1990), the Italian Apennines (Giraudi and Frezzotti 1997) as well as in the Pindus Mountains, Greece (Macklin *et al.*, 1997). Similarly, more extensive glaciations attributed to the earlier Middle Pleistocene are also unlikely to have coincided with the global glacial maxima and the most severe arid phase of glacial cycles indicated in pollen records.

Mediterranean mountain glaciers are likely to have formed and reached maxima during *intermediate* rather than severe phases of glacial cycles–during periods of moist yet cold conditions. As noted above, these conditions are likely to have preceded global glacial maxima. Furthermore, given their potential for rapid response to climate change, Mediterranean mountain glaciers are likely to have oscillated in response to millennial to interannual climate changes as a result of short-term perturbations in North Atlantic circulation (cf. Chondrogianni *et al.*, 2004). However, major obstacles to understanding the dynamics of former glacial and periglacial activity stem from the limited precision of available dating techniques, inherent in the minimum age dating usually applied, and the fragmentary nature of the glacial sedimentary record.

XI Conclusions

The mountains of the Mediterranean have been glaciated on multiple occasions during the Quaternary. Glacial deposits record glaciation during the Middle Pleistocene, and possibly earlier, with the most recent glacial deposits dating from the last cold stage (Würmian Stage) and the Holocene. While only a limited number of small cirque and valley glaciers exist today, periglacial processes are still active and represent an important geomorphological agent in high mountain regions. In some areas, glacial and periglacial activity through the Quaternary has formed erosional and depositional landscapes that are have been very well preserved. Consequently, glacial and periglacial processes in conjunction with fluvial systems, in particular, can be considered an integral part of Mediterranean upland geomorphology. Many studies have identified glacial and periglacial features but only recently, through the application of geochronological techniques, has the number and timing of major glaciations become apparent. In little over a decade, these developments have revolutionized our understanding of glacial geomorphology and Pleistocene glacier dynamics in the Mediterranean mountains since it was previously widely assumed that most glacial deposits formed during the last cold stage. Continued progress is reliant upon detailed geomorphological and stratigraphical study of these glaciated regions and the wider application of existing and new geochronological techniques. This will allow glacial and periglacial records across the Mediterranean mountains to be compared to high-resolution climate records in the region, especially those from lacustrine sequences, and ultimately to other records of global change.

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