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Chapter 15

Glaciation in Greece: A New Record of Cold Stage Environments in the Mediterranean

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15.1. INTRODUCTION

In his seminal review of glaciation in the Mediterranean region, Messerli (1967) reported evidence for Pleistocene glacial activity in several areas of upland Greece and assigned all the glacial phenomena to the last (Würmian) cold stage. Messerli's overview brought together some of the earliest work on glaciation in Greece including Niculescu's pioneering (1915) study of Mount Smolikas in northwest Greece and Sestini's (1933) observations on the mountains of southern Epirus. Figure 15.1 shows how the Pindus Mountains, aligned roughly NNW-SSE, extend along the length of mainland Greece and dominate its topography. Much of this mountain chain lies over 1000 m a.s.l., and many peaks exceed 2000 m. Evidence for glacial activity has been identified throughout the Pindus Mountains from Mount Grammos (2523 m) on the Albanian border to Mount Taygetos (2407 m) in the southern Peloponnese. The principal sites in Greece included on Messerli's (1967) map for which there is additional published information on Pleistocene glaciation are shown in Fig. 15.1. Table 15.1 provides summary data for each of the sites shown in Fig. 15.1 and lists the key references in each case.

In general terms, during Pleistocene cold stages, the glaciers of Greece decreased in size with decreasing latitude, although climatic and topographic controls could be locally important. Well-preserved glaciated terrains of Pleistocene age have been observed in the highest parts of the northern Peloponnese (Mastronuzzi et al., 1994), and Fig. 15.2 shows a range of glacial landforms on the high limestone peaks of Mount Chelmos (2341 m) which lies just south of 38°N. The evidence for glacial activity on the mountains

of Crete is less clear cut, and further research is needed. Nemec and Postma (1993) have argued that the White Mountains were glaciated during the Pleistocene, and on Mount Idi (also known as Ida or Psiloritis at 2456 m), Fabre and Maire (1983) have reported a circue with moraines at an altitude of just ca. 1945 m. This claim is out of step with the evidence from mainland Greece. Boenzi and Palmentola (1997), for example, have argued that evidence for glaciation is only present in Greece on mountains that exceed 2200 m. Several publications on the White Mountains of Crete (e.g. Poser, 1957; Bonnefont, 1972; Boenzi et al., 1982) do not report any evidence for the action of glaciers. At some of the Greek sites discussed in Messerli's (1967) review, the evidence for glacial activity is rather limited in areal extent-being confined to the highest peaksand modern investigations have not yet taken place (Table 15.1). In some of these cases, cirques, ice-steepened cliffs and ice-scoured bedrock surfaces account for most of the evidence for the action of former glaciers, with only very limited evidence for the transport and deposition of glacial sediments to lower elevations. Thus, in some of the localities shown on Messerli's (1967) map and Fig. 15.1, glacial deposits have not been marked on the later 1:50,000 geological sheets produced by the Greek Institute for Geological and Mineral Exploration (IGME).

Recent reviews of glaciation in the mountains of the Mediterranean (Hughes et al., 2006a, Hughes and Woodward, 2009) have shown how the history of research can be broadly classified into three stages of development (either Pioneer, Mapping or Advanced stages) as defined in Table 15.1. The published literature on Pleistocene glaciation in Greece shows that all three of these stages are represented (Table 15.1). By far, the most detailed work



FIGURE 15.1 Topographic map of Greece highlighting mountain landscapes above 2000 m. Most of the published evidence for Pleistocene glacial activity in the mountains of Greece comes from the 10 locations indicated (Table 15.1). Pleistocene snowlines for the Pindus Mountains are also shown (based on Hagedorn, 1969). Glaciers do not exist today in the mountains of Greece, but snowfall is heavy and extensive snow patches are common in the early summer on the highest peaks and ridges. Winters are severe in the mountains and evidence of periglacial processes is widespread. There are marked variations in precipitation across Greece with values in excess of 2000 mm in the northwest and central uplands, falling to < 500 mm in the lowland coastal zone of the southeast.

TABLE 15.1 Geographical Data for Each of the Glaciated Mountains Shown in Fig. 15.1							
Massif and Region	Elevation (m)	Latitude (approx.)	ELA (m)	References	Phase ^a		
1. Grammos, Epirus	2523	40°34′N	1800	Louis (1926)	(P)		
2. Smolikas, Epirus	2637	40°05′N	1800	Niculescu (1915)	(P)		
				Boenzi et al. (1992)	(M)		
3. Olympus, Pieria	2917	40°05′N	1030	Faugères (1969)	(M)		
				Smith et al. (1997)	(M)		
				Manz (1998)	(M/A)		
4. Tymphi, Epirus	2497	39°97′N	1600	Palmentola et al. (1990)	(M)		
				Smith et al. (1998)	(M)		
				Woodward et al. (2004)	(A)		
				Hughes et al. (2006b)	(A)		
5. Peristeri, Epirus	2295	39°68′N	1750	Sestini (1933)	(P)		
6. Kakarditsa, Epirus	2429	39°46′N	1750	Sestini (1933)	(P)		
7. Oeta, Sterea	2160	38°75′N	2150	Mistardis (1952)	(P/M)		
8. Parnassos, Sterea	2457	38°52′N	2200	Pechoux (1970)	(P/M)		
9. Chelmos, Achaia	2341	37°96′N	2150	Mastronuzzi et al. (1994)	(M)		
10. Taygetos, Messinia	2404	36°95′N	2150	Mastronuzzi et al. (1994)	(M)		

The ELA values for Mount Olympus are from Smith et al. (1997) and the rest are from Hagedorn (1969) as shown in Fig. 15.1.

^a The letter in brackets after the reference refers to the scheme of Hughes et al. (2006a) for Pioneer, Mapping and Advanced phases of research. Pioneer phase refers to locations where evidence of glaciation has been observed but not mapped. The Mapping phase refers to locations where detailed geomorphological maps of glacial phenomena, and related landforms have been produced but without radiometric dating control. The Advanced phase refers to sites where systematic mapping and detailed stratigraphical assessments have taken place in conjunction with a programme of radiometric dating that has led to the development of a robust chronological framework for the glacial record.

on Pleistocene glaciation has been carried out in northern Greece on Olympus and Tymphi (Fig. 15.1), which both lie close to 40°N. This chapter will therefore review the glacial records from these two areas in detail. A key feature of recent work in Greece has been the development of a dating framework for the glacial record in tandem with systematic geomorphological mapping and formal stratigraphical appraisal of the glacial geology. In the 1960s, when Messerli (1967) produced his synthesis, radiometric dates were not available for any of the glacial records in the Mediterranean and this situation remained largely unchanged for over 30 years. The past decade, however, has seen major advances in geochronology with dating frameworks based on a range of methods (including uranium-series, cosmogenic radionuclides, OSL and tephrostratigraphy) emerging for glacial records across the Mediterranean (e.g. Kotarba et al., 2001; Woodward et al., 2004; Vidal-Romaní and Fernández-Mosquera, 2006; Pallàs et al., 2007; Akçar et al., 2008; Kuhlemann et al., 2008; Sarıkaya et al., 2008, 2009; Lewis et al., 2009; Chapter 30). Research in Greece, using uranium-series dating, has been at the forefront of these developments (Hughes et al., 2006b; Woodward

et al., 2008; Hughes and Woodward, 2009). This new chapter builds on an earlier contribution to the first edition of this volume (Woodward et al., 2004) and reports some key advances in our understanding of Pleistocene glaciation in Greece. It can be argued that these findings have important implications for the study of Pleistocene glacial records in upland environments not only across the Mediterranean region but also in glaciated mountain terrains around the world.

15.2. THE GLACIAL RECORD ON MOUNT OLYMPUS, NORTHEAST GREECE

Olympus is the highest mountain in Greece (2917 m) and is located to the east of the main Pindus Mountain chain in the northeast corner of peninsular Greece, close to the Aegean coast (Fig. 15.1). The most recent research on the glacial record on Olympus was conducted by an American team led by the late Geoffrey Smith from the Department of Geological Sciences at Ohio University. Smith and his co-workers (1994, 1997, 2006) argued that the earlier studies in the Mount Olympus area had significantly underestimated the extent of glacial activity, as deposits on the



FIGURE 15.2 Glaciated topography on the upper slopes of Mount Chelmos in the northern Peloponnese (Number 9 in Fig. 15.1). The upper photograph shows moraines and glacially steepened limestone back-wall cliffs behind the dried out lake basin of Mavrolimni. The lower photograph shows a large moraine and active scree slopes in a large circue on the northwest slopes of Mount Chelmos at an elevation of ca. 1900 m. Note the figure on the moraine crest for scale.

eastern piedmont of the massif—that were previously classified as fluvial sediments—are, in fact, glacial diamictons. As Smith et al. (1997) have pointed out, the early investigations on Mount Olympus did little to establish the sequence and timing of glacial events in the area although the implication was that glaciation was restricted to the latest Pleistocene or Würmian Stage (Messerli, 1967).

15.2.1. The Glacial Sedimentary Sequences on Mount Olympus

The stratigraphic record of Pleistocene and Holocene events on Mount Olympus is most clearly observed on the eastern piedmont within the valleys of the Mavrolongus and Mavroneri Rivers which drain to the Aegean coast (Fig. 15.3). Extensive moraine complexes have been mapped in the Mavroneri valley to the west and southwest of the town of Katerini, and thick proglacial outwash sediments are well preserved on the valley floor (Fig. 15.3A). The deposits in this valley represent the convergence of valley ice from Mount Olympus (to the south) and the High Pieria Mountains (to the north). Three discrete sedimentary packages (units 1–3) have been identified in the area—each capped by a distinctive soil. The deposition of these sediments and the subsequent phases of pedogenic weathering reflect periods of glacial and nonglacial activity, respectively (Smith et al., 1997, p. 809). The deposits of the eastern piedmont comprise a range of glacial, glaciofluvial, fluvial and alluvial fan sediments. Smith et al. (1997, 2006) have argued that each of the three main sedimentary units can be related to a period of glacial activity in the uplands.

During the glacial phases that led to the deposition of the unit 1 and unit 2 sediments, circue glaciers developed to a size that allowed them to spread out from their basins to form a continuous cover of upland ice (Smith et al., 1997, 2006). The Bara Plateau is part of the Mount Olympus upland that lies a few kilometres south of the Mytikas summit (2917 m). The glacial geology of the plateau is shown in Fig. 15.3B. Here, the unit 2 sediments are the most extensive in this area and can be traced for almost 2 km from the headwaters of the Mavratza River across the Bara Plateau to the head of the Mavrolongus valley (Smith et al., 1997; Fig. 15.3B). Thirteen cirques have been identified on the Bara Plateau with cirque floor elevations ranging from 2180 to 2510 m above present sea level. On the Plateau of the Muses, which includes the Mytikas summit, 11 cirgues range in elevation from 2200 to 2660 m a.s.l. (Smith et al., 1997, 2006).

The glacial and proglacial sedimentary records in the Mount Olympus area constitute a potentially important archive of landscape change to the east of the Pindus Mountains and one that could be usefully compared to the long pollen record at Tenaghi Philippon ca. 160 km to the northeast (Wijmstra, 1969; Tzedakis et al., 2006). However, a robust geochronological framework for the glacial sequences on the Olympus massif is still lacking. Smith et al. (1997, p. 820) have conceded that the lack of radiometric dates on deposits of Mount Olympus and the adjacent piedmont precludes the establishment of a numerical chronology for Pleistocene events in this area. Attention was therefore directed towards the study of the weathering profiles associated with soils on the Mount Olympus deposits to develop a relative-age dating framework and to allow comparisons with other Quaternary records in northeast Greece.

Pedogenic maturity indices have been determined for the soil profiles on units 1–3 in an attempt to correlate the deposits of the Olympus piedmont with the sequence of soils developed on dated alluvial sediments in the Larissa Basin immediately to the south (Demitrack, 1986; van Andel et al., 1990). This approach led to the tentative correlation put forward by Smith et al. (1997), shown in Table 15.2. This model places the unit 1 sediments before 200 ka within marine isotope stage (MIS) 8 and the unit 2 deposits within MIS 6. On the basis of this age model, the nature of the unit 1 soil suggests that the last major glaciation of the Olympus massif took place at some time during the last cold stage (MIS 2 or 4) but was restricted to valley heads and glaciers extended to mid-valley positions (Smith et al., 1997).

Smith et al. (1997) presented this correlation as tentative because of the absence of radiometric dates. It is also important to point out that the chronological control for the alluvial sequence and soils of the Peneios River in the Larissa Plain, studied by Demitrack (1986), is relatively poor by the standards of more recent investigations (see Macklin et al., 2002; Macklin and Woodward, 2009) in the Mediterranean, and it can be argued that it does not form a reliable yardstick for regional correlation (Table 15.2). It is often difficult to make valid intersite comparisons of soil profile development when sites are located at different altitudes in contrasting geomorphological settings. In such cases, establishing the long-term constancy of important soil forming factors such as parent material and local climate can be especially problematic (Birkeland, 1984).

To improve the age control for the glacial deposits of Mount Olympus, cosmogenic dating of unit 1 boulder surfaces using chlorine-36 (³⁶Cl) was attempted. This was one of the earliest efforts to use cosmogenic exposure dating in the Mediterranean. Manz (1998) reports cosmogenic dates from two sites within large (unit 1) recessional moraine complexes on the eastern piedmont. Limestone boulders at Site 1 (immediately north of the town of Litochoro) yielded ³⁶Cl ages within the range 32–49 ka. Boulders at Site 2 in the Mavroneri catchment to the west of Katerina (Fig. 15.3B) yielded ages ranging from 43 to 56 ka. One boulder at Site 2 gave an age of 146 ka (MIS 6), and this outlier has been attributed to either previous exposure or



FIGURE 15.3 Geomorphological maps of the glaciated uplands of Mount Olympus in northeast Greece showing the landscape near the village of Katerini (A) and the circues and glacial deposits close to the summit (B) (modified from Smith et al., 1997).

evidence of an earlier glacial phase. Manz (1998) argued that the Site 2 ages were more reliable because silicate rocks are better suited to this method. The tentative age model for

units 1–3 proposed by Smith et al. (1994, 1997, 2006) and shown in Table 15.2 would need to be radically revised if the 36 Cl ages for the unit 1 sediments are accepted. Indeed,

TABLE 15.2 A Tentative Correlation of the Olympus Piedmont Soils with the Pleistocene Soils Developed in Terrace
Alluvial Sediments on the Larissa Plain Studied by Demitrack (1986) (after Smith et al., 1997)

Depositional	Olympus Piedmont	Marine Isotope Stage
Phase	Soil name	
<200 years	Unit 3 surface soils	1
Historical		
6–7 ka		
10–14 ka		
14–30 ka		
27–42 ka	Unit 3 truncated (buried) soil	3
≥54–125 ka	Unit 2 soil	5
\leq 210 ka	Unit 1 soils	7
	Depositional Phase < 200 years Historical $6-7$ ka $10-14$ ka $14-30$ ka $27-42$ ka $\geq 54-125$ ka ≤ 210 ka	DepositionalOlympus PiedmontPhaseSoil name $<$ 200 yearsUnit 3 surface soilsHistorical -7 ka $6-7$ ka -14 ka $10-14$ ka -14 ka $14-30$ kaUnit 3 truncated (buried) soil $27-42$ kaUnit 3 truncated (buried) soil $\geq 54-125$ kaUnit 1 soils

Note that the marine isotope stages shown represent warm periods conducive to weathering and soil development. Soil formation began in the marine isotope stage indicated.

it is difficult to reconcile these ages with the extent and thickness of the Pleistocene sediments comprising units 1–3 because the ³⁶Cl ages demand much faster rates of soil development and landscape change in this area than those put forward by Smith et al. (1997) in Table 15.2. The deep red soil developed on the unit 1 sediments is thought to record an extended interval, probably of interglacial duration, during which substantial pedogenesis took place (Smith et al., 1997, p. 811). Manz (1998, p. 56) concluded that additional ³⁶Cl measurements on deposits on the piedmont and upland areas of the mountain might reveal evidence of earlier glacial episodes even though the ages of the deposits (units 1–3) on the eastern Olympus piedmont appear to postdate the last interglacial period.

The work of Manz (1998) represents a pioneering application of the cosmogenic dating method in the Mediterranean. In common with more recent examples of this approach in the region, it highlighted the potential for considerable noise in such datasets and the need for much more extensive sampling and dating programmes. In conclusion, the glacial sediments and landforms of Mount Olympus and its adjacent uplands lack a firm, internally consistent chronological framework and, as Smith et al. (1997, p. 822) pointed out, the sequence of events proposed in Table 15.2 "can easily be shifted backward or forward in time."

15.3. THE GLACIAL RECORD ON MOUNT TYMPHI, NORTHWEST GREECE

Mount Tymphi is located in Epirus in northwest Greece approximately 15 km southwest of Mount Smolikas and 40 km south of Mount Grammos on the Albanian border (Fig. 15.1). The several peaks and ridges of Mount Tymphi

form part of the high watershed between the catchments of the Voidomatis (384 km^2) and Aoos (665 km^2) rivers (Fig. 15.4). With its series of jagged limestone peaks, the highest of which exceed 2400 m, Tymphi has been described as both the most extensive and the most majestic of the Greek mountains (Sfikas, 1979). Figure 15.5 is an oblique air photograph that portrays very clearly this distinctive upland landscape and its impressive array of glacial landforms. It also shows some of the major topographic elements of the Voidomatis River basin (see Bailey et al., 1997) that are labelled in Fig. 15.4. The northern side of the Tymphi massif includes a magnificent set of cirques and limestone cliffs dissected by steep ravines. To the south, an extensive tableland is cut by the 900-m-deep Vikos Canyon. Mount Tymphi boasts the most extensive and best preserved glacial terrain on any of the Greek mountains. In common with many of the glaciated mountains on the Balkan Peninsula and wider Mediterranean region, hard limestones are the dominant lithology and the effects of karstic processes are widespread (Waltham, 1978; Lewin and Woodward, 2009).

South of the eastern ridges of Mount Tymphi, around the villages of Tsepelovo (ca. 1100 m) and Skamnelli (ca. 1200 m), extensive spreads of glacial deposits are marked on the 1:50,000 geological sheet (IGME, 1970). Here, numerous moraine ridges are especially well defined as shown in the lower left portion of Fig. 15.5. The glacial deposits south of Tsepelovo reach down to the valley floor of the Voidomatis River to an elevation of around 850 m a. s.l. (Fig. 15.4) (Woodward et al., 1995, 2004; Smith et al., 1998; Hughes et al., 2006b). It is only very recently, however, that the glacial record in this area has been mapped in detail and radiometrically dated. Reconnaissance field



FIGURE 15.4 Map of the Voidomatis River basin of northwest Greece. This basin drains the glaciated limestone uplands of Mount Tymphi (Number 4 in Fig. 15.1). The Pleistocene fluvial record in this basin is particularly well preserved in the lower part of the basin (Reaches I and III) (see Woodward et al., 2008). Flysch rocks are widespread at lower elevations in the Voidomatis River basin and mainly beyond the limits of glacial action (Woodward et al., 1992; Bailey et al., 1997; Hughes et al., 2006b).

studies of this area were conducted in the mid-1980s as part of the first phase of fieldwork investigating the Pleistocene history of the Voidomatis River (Fig. 15.4) and the principal alluvial sediment sources in the basin (Bailey et al., 1990; Lewin et al., 1991; Woodward et al., 1992). This work confirmed that the southern flanks of Mount Tymphi were dominated by glacial sediments and landforms (Woodward, 1990; Woodward et al., 1995; Bailey et al., 1997; Macklin et al., 1997; Woodward et al., 2008).

The assemblage of glacial landscape features on Mount Tymphi includes cirques of various sizes and geometries (Fig. 15.5), deep ice-scoured troughs with stepped long profiles (Fig. 15.6A), limestone bedrock pavements (Fig. 15.6B) and lateral and terminal moraine complexes (Figs. 15.6B, D, and F). Steep limestone cliffs and thick talus deposits are also important landscape features (Fig. 15.6E). As mentioned above, glacial depositional landforms are especially well preserved on the slopes around Tsepelovo and Skamnelli (Fig. 15.5). Good-quality exposures are commonly present in the glacial sediments where the depositional zone on the lower slopes is traversed by mountain tracks or by the Tsepelovo to Skamnelli road. A good example is shown in Fig. 15.6D where a road-side quarry revealed a deep section in till sediments in the large moraine immediately to the east of Tsepelovo (Fig. 15.4). Such exposures in the Mount Tymphi tills show that the glacial sediments contain subrounded limestone boulders, cobbles and gravels commonly dispersed in a fine-grained matrix rich in sands, silts and clays derived from the comminution of the hard limestone bedrock (Fig. 15.7A) (Woodward et al., 1992, 1995, 2004; Hughes et al., 2006b).

During the mid- to late 1980s when Lewin, Macklin and Woodward worked on the alluvial record in the Voidomatis basin, Italian researchers mapped the glacial landforms on



FIGURE 15.5 An oblique air photograph of Mount Tymphi looking to the south and southwest. This image shows the steep limestone cliffs and cirques on the northern face of the mountain and the extensive glaciated landscapes that drain southwards to the Vikos Canyon and the upper reaches of the Voidomatis River (Fig. 15.4). Photograph taken by Giannis Tsouratzis in June 2009. T = T sepelovo and S = S kamnelli.

Tymphi and Smolikas (Palmentola et al., 1990; Boenzi et al., 1992). Geomorphological maps of the major moraines were drawn and, despite the absence of any dating control, it was argued that all the phases of glacial activity took place during the Late Würmian. The next phase of work in the area saw Smith et al. (1998) employ Landsat Thematic Mapper satellite imagery to map the extent of the glacial sediments and landforms on Mount Tymphi. A supervised image classification of the TM scene (using bands 1 to 5 and 7) was carried out using the maximum likelihood classification (MLC) decision rule. The MLC results were evaluated using air photographs and field checking and were shown to provide a good approximation of the geomorphology of the target area. The moraine complex to the north of Skamnelli was correctly classified as being dominated by sharp crested moraines, and the landforms near the village of Tsepelovo and southwards to the Voidomatis River were correctly classified as weathered and degraded moraines (Smith et al., 1998). This contrast in moraine form can be seen in Fig. 15.5.

From this analysis, it became clear that the glacial record on Mount Tymphi consisted of at least two major phases of glaciation, and this pointed towards a more complex Pleistocene history than that proposed just a few years earlier by Palmentola et al. (1990). Indeed, the clear contrasts in weathering depth and landform style suggested that the most extensive moraines were much older than those at

higher elevations. Without radiometric dates, however, it was not possible to quantify the difference in age or to establish whether or not the two groups of moraines formed during the same cold stage.

15.4. THE FIRST URANIUM-SERIES AGES FOR THE GLACIAL RECORD IN GREECE

The first radiometric dating programme on Mount Tymphi began in May 1998 when secondary carbonate samples were first recognised in the glacial deposits. At some locations, the road and track cuttings expose cavities within the till matrix where carbonate precipitation has taken place often in association with subrounded boulders, cobbles and gravels. In places, the fine sediment matrix has been completely removed to leave interclast spaces that have been partially or completely filled with calcite. These secondary carbonates often form a skin on the surface of cobble- and boulder-sized limestone clasts accreting roughly parallel to the host surface (Fig. 15.7b). These secondary carbonates can be dated using uranium-series methods.

The first secondary carbonate samples were collected from five exposures in the glacial sediments on the southern slopes of the Tymphi massif and these yielded nine uranium-series ages (see Woodward et al., 2004 for a detailed discussion of these sites and ages). These ranged in age from 71.1 to >350 ka. In each case, because these ages were obtained from secondary carbonates, they provided *minimum* ages for the host glacial sediments. This set of uranium-series ages lead to a major reinterpretation of the Pleistocene glacial record, not only in Greece but also across the Balkan Peninsula and the wider Mediterranean region. They showed, for the first time, that the most extensive phases of glaciation in Greece took place during the Middle Pleistocene during a cold stage before 350 ka. They also showed that a major phase of glaciation took place before the last interglacial during MIS 6. The nine uranium-series ages published in Woodward et al. (2004) showed that most of the glacial sediments and landforms in the headwaters of the Voidomatis River basin were Middle Pleistocene in age and therefore much older than the last cold stage. Further, two sites revealed multiphase secondary carbonate development demonstrating that the host





FIGURE 15.6 Glaciated landscapes on the slopes of Mount Tymphi in northwest Greece. (A) Limestone pavements and glacially steepened cliffs looking up-valley towards the high circues between the peaks of Gamila (2497 m) and Goura (2466 m). (B) Well-developed clints and grikes on an elevated limestone pavement with Vlasian Stage moraines in the middle ground.

sediments and their associated landscape features had been stable for an extended period of time. The bulk of the glacial sediments and major glacial depositional landforms in this area are much older than the global Last Glacial Maximum (LGM) of MIS 2, and this was a very significant outcome of the first uranium-series dating programme.

These dates showed that it is unwise to assume that apparently fresh moraines in Mediterranean mountain environments must date to the most recent cold stage (see Palmentola et al., 1990; Boenzi and Palmentola, 1997). Glacial landform stability appears to be a feature of high limestone landscapes especially where secondary carbonate formation (cementation) is widespread. Despite these advances, a major programme of field mapping was still needed to establish the extent of glacial action on Mount Tymphi and the dimensions of the former ice masses during the cold stages of the Middle and Late Pleistocene.



FIGURE 15.6 (C) Large glacially transported boulders on the western side of Tymphi. (D) A deep section in Skamnellian Stage glacial sediments exposed in a quarry on the Tsepelovo to Skamnelli road showing the rounded form of the oldest moraines on Mount Tymphi (MIS 12) and the limestone-rich till sediments.



FIGURE 15.6-cont'd (E) Glaciated terrain and well-developed screes immediately up-valley of Skamnellian Stage end moraines. (F) A Skamnellian Stage moraine crests on the southern slopes of Mount Tymphi.

15.5. TOWARDS A FORMAL STRATIGRAPHICAL FRAMEWORK FOR THE GLACIAL RECORD IN GREECE

It quickly became apparent that the full potential of this glacial record could not be realised without detailed mapping of the entire massif (including the high-level cirques and associated moraines and rock glaciers) allied to a more extensive uranium-series dating programme. This work was completed during the course of a PhD project (Hughes, 2004) and led to a series of papers on the stratigraphy and geochronology of the glacial deposits on Mount Tymphi (Hughes et al., 2006b) and the palaeoclimatic significance of the glacial record (Hughes et al., 2006c, 2007a,b). This latest phase of research on Mount Tymphi is summarised below. The new record is based on systematic field mapping of the glacial landforms, section logging and sedimentological investigations, detailed examination of soil profiles on moraine surfaces, allied to the most comprehensive programme of uranium-series dating yet conducted on glacial deposits anywhere in the world. Figure 15.8 provides a useful illustration of the kinds of data that have been compiled to develop a new model of Pleistocene glacier behaviour in Greece. It shows a geomorphological map of the southern slopes of Mount Tymphi detailing a wide range of erosional and depositional features. It also shows 21 of the uranium-series ages and the respective sample locations. This work has led to the formal identification of three glacial phases on Mount Tymphi. Figure 15.9 shows the geography of the ice masses during



FIGURE 15.7 (A) A road-side exposure in till sediments on the north side of Mount Tymphi. Note the abundant limestone-rich fine sediment matrix and the wide range of boulder sizes.



FIGURE 15.7-cont'd (B) An exposure in till on Mount Tymphi showing examples of secondary carbonates that have been sampled for uranium-series dating.

each glacial phase. These stages (Skamnellian, Vlasian and Tymphian) have been formally defined by Hughes et al. (2006b) and correlated with the long lacustrine record from Lake Ioannina that lies about 40 km south of Mount Tymphi (Fig. 15.4). The Mount Tymphi record provides a glacial

stratigraphical framework for the Pindus Mountains and is now underpinned by 28 uranium-series ages on secondary carbonates. Based on Hughes et al. (2006b) and Woodward et al. (2008), each phase of glaciation is described in turn below.



FIGURE 15.8 Geomorphological map of part of the southern slopes of Mount Tymphi showing a range of glacial landforms and 21 uranium-series ages obtained from secondary carbonates formed in limestone-rich till (modified from Hughes et al., 2006b). Figure 15.4 shows the location of Tsepelovo and Skamnelli in the Voidomatis River basin.

FIGURE 15.9 The extent of glaciation during the Middle and Late Pleistocene on Mount Tymphi (based on Hughes and Woodward, 2009). The rock glaciers on Mount Tymphi and the major meltwater routes to the Voidomatis River are also shown.

15.5.1. The Skamnellian Stage

As Fig. 15.9 shows, the earliest and most extensive phase of glacial activity took place before 350 ka and saw the formation of large ice fields and valley glaciers on the southern slopes of Mount Tymphi and across the Astraka-Gamila plateau. The moraines from this glaciation have deeply weathered soil profiles with profile development indices (PDIs) ranging from 51.8 to 61 (Hughes et al., 2006b).

The glaciers extended beyond the villages of Tsepelovo (1100 m) and Skamnelli (1200 m) down to about 850 m a.s.l. (Fig. 15.4). In this area of Mount Tymphi, these glacial deposits are well exposed on the right bank of the modern Voidomatis River (Woodward et al., 1995; Hughes et al., 2006b). Excellent exposures also exist down to altitudes as low as 1000 m in the Vadulakkos valley on the northern slopes of Mount Smolikas (Hughes et al., 2006d). Ice cover on Mount Tymphi during the Skamnellian glaciation

approached 60 km² at its maximum extent, and the mean equilibrium line altitude (ELA) was ca. 1741 m a.s.l. (Hughes et al., 2007b). The oldest secondary carbonates from sediments associated with this phase of glaciation are beyond the range of uranium-series dating and six samples yielded ages > 350 ka (Fig. 15.8 and 15.10) (Woodward et al., 2004; Hughes et al., 2006b). The oldest secondary carbonates have been correlated with MIS 11, and the Skamnellian Stage glacial deposits are correlated with the Elsterian Stage of northern Europe and MIS 12 (Hughes et al., 2006b).

15.5.2. The Vlasian Stage

During the Vlasian glaciation, the maximum extent of ice cover (ca. 21 km²) extended over about one-third of the area that was glaciated during the earlier Skamnellian glaciation. At this time, most of the Astraka-Gamila plateau was ice free while glaciers advanced to mid-valley positions above Tsepelovo and Skamnelli (Figs. 15.8 and 15.9). During the maximum extent of this glaciation, the mean ELA was ca. 1862 m a.s.l (Hughes et al., 2007b). Eight uranium-series ages have been obtained from sediments belonging to this

FIGURE 15.10 The uranium-series ages for the Pleistocene glacial record on Mount Tymphi plotted in relation to the vegetation record (AP pollen percentages) from Tenaghi Philippon (top) and the S06 δ^{18} O benthic composite marine isotope record from sites in the equatorial East Pacific (see Tze-dakis et al., 2006 for sources). The uranium-series ages are from Woodward et al. (2004) and Hughes et al. (2006b) and have been plotted in relation to their respective glacial stratigraphical units (see Hughes et al., 2006b). The pollen and marine isotope time series come from Tzedakis et al. (2006). See text for discussion.

phase of glaciation. These range in age from 80.45 ± 15.1 to 131.25 ± 19.25 ka and indicate that this phase of glacial activity took place *before* the last interglacial during MIS 6. The Vlasian Stage is correlated with the late Saalian Stage of northern Europe and MIS 6 (Hughes et al., 2006b). It is quite likely that glaciers also developed during the cold stages between the Vlasian and Skamnellian Stages (i.e. during MIS 8 and MIS 10), but deposits from these periods have not been preserved. It appears likely that they were less extensive than the Vlasian Stage glaciers and were overrun and reworked by glaciers during this cold stage.

15.5.3. The Tymphian Stage

The most recent phase of glacial activity took place during the last cold stage, and this is known as the Tymphian Stage. The glacial deposits and landforms of this period are younger than those of the Vlasian (MIS 6) glaciation because they are found at much higher elevations and well within the limits of the Vlasian Stage deposits (Fig. 15.9). Soils on moraine surfaces also show only very limited evidence of pedogenic weathering (PDIs of 7.8-9.0) (Hughes et al., 2006b). However, due to the absence of secondary carbonates in the Tymphian Stage glacial sediments, uraniumseries ages have not been obtained. Nonetheless, following the arguments presented in Hughes et al. (2006b), the Tymphian Stage is correlated with the Weichselian/Würmian Stage of northern Europe and the Alps, respectively, and MIS 5d to MIS 2. The climate at the local glacier maximum during this stage would have been wet and cold.

Rock glaciers also formed during this cold stage and provide evidence of cold and dry conditions *after* the local glacial maximum (Hughes et al., 2003, 2006c). The period of rock glacier formation probably correlates with the global LGM around 20–22 ka. About 15 km to the northeast of Mount Tymphi on Mount Smolikas (2637 m), welldeveloped moraines have been mapped at elevations above the floors of the highest cirques on Mount Tymphi (Hughes et al., 2006e). These glacial landforms postdate the youngest moraines on Mount Tymphi, and it has been argued that they may be Younger Dryas in age, although this has not been confirmed by radiometric dating (Hughes et al., 2006e). Together these records show that, in the Pindus Mountains, climatic conditions were favourable for glacier development at various times during the last cold stage.

15.6. SECONDARY CARBONATE FORMATION AND ENVIRONMENTAL CHANGE

The 28 uranium-series ages from the glacial deposits on Mount Tymphi have been plotted in Fig. 15.10 alongside the tree pollen curve from Tenaghi Philippon and the marine oxygen isotope record. The pollen record shows very rapid expansions and contractions in tree cover during the course of the past 500,000 years (Tzedakis et al., 2003, 2006; Tzedakis, 2005) (Fig. 15.10). The uranium-series ages range from 71 to > 350 ka. As we have argued above, these represent minimum ages for the host glacial sediments because phases of secondary carbonate formation can take place long after the deposition of the primary glacial deposits. The oldest ages obtained for each formation are therefore closest in age to the cold stage in which the glacial deposits were laid down. Figure 15.10 shows that the secondary carbonates in the till sediments form in clusters, with evidence of secondary carbonate formation on Mount Tymphi during four interglacials, namely, MIS 5, 7, 9 and 11. We have obtained eight dates on secondary carbonates from the Vlasian Stage moraines-all of them are associated with calcite formation during the last interglacial (5a-e). The uranium-series database also includes eight ages from within the Skamnellian Stage moraines associated with calcite formation during the last interglacial. This was clearly a very significant period of secondary carbonate formation with prolonged periods of high rainfall, dense forest cover and active soil processes producing high concentrations of CO₂ in percolating vadose waters. The Skamnellian Stage moraines also contain 11 uranium-series ages that predate MIS 6 with six of these being > 350 ka. This earliest phase of secondary carbonate formation probably took place during MIS 11. The host glacial sediments are clearly much older than those of the Vlasian Stage moraines, and we have argued that they were deposited during MIS 12 (Hughes et al., 2006b).

The formation of speleothems and other secondary carbonates is commonly reduced or absent during cold stages but most active during warm intervals when rainfall is higher and biological productivity and soil development increase (Gascoyne, 1992). The pollen records from Ioannina and Tenaghi Philippon show that forest cover in Greece expanded and contracted very rapidly between cold and warm stages, primarily in response to changes in precipitation. These shifts would have dramatically transformed hillslope and soil profile hydrology and the flux of CO_2 in the vadose zone. The dated record of secondary carbonate formation we have assembled from the Mount Tymphi tills shows very clearly how the near-surface karst system switched from cold to warm stage modes. Within the moraines, secondary carbonate formation is influenced by several factors. The water that enters voids in the glacial sediment matrix must have passed through biologically active soil profiles where it acquires elevated concentrations of CO₂, and the ground surface must allow the free passage of soil waters. The combination of low organic productivity, lower rainfall and perhaps also frozen soils effectively shut down secondary carbonate formation during cold stages on Mount Tymphi. Vegetation responded very rapidly to climatic amelioration with a rapid expansion of tree cover at the onset of interglacials and interstadials (Fig. 15.10). This is important for the build-up of organic materials in soils and the enhanced biological productivity that allows elevated concentrations of CO_2 in soil water. The rapid decline in tree cover at this altitude during the onset of cold periods may partly explain the almost complete absence (only 1 out of 28 dates) of secondary carbonate formation during cold stages.

All the uranium-series ages predate the global LGM of MIS 2; they provide compelling evidence for the presence of large ice masses in the Mediterranean during the Middle Pleistocene (Woodward et al., 2004; Hughes et al., 2006a,b, c,d,e). There is no evidence of secondary carbonate formation in the youngest (Tymphian) glacial sediments from the last cold stage. Nor is their evidence for Holocene-age secondary carbonate formation in earlier till sediments. This may be due to the progressive filling of intraclast voids in the oldest glacial sediments and the particularly active phases of secondary carbonate formation and void closure during the last interglacial (Fig. 15.10). The youngest glacial sediments are associated with the smallest moraines on Mount Tymphi, and these sediments do not contain large amounts of finegrained limestone matrix. There is also some evidence to suggest that secondary carbonate formation is more important towards the end of interglacial periods (Fig. 15.10). It follows therefore that the Holocene may not have been long enough for the development of sufficiently mature soils, and the mid-Holocene removal of much of the tree cover may have reduced biological productivity and the CO₂ concentration of vadose waters. The Mount Tymphi record shows that there was only very limited glaciation during the cold stages that followed MIS 6. The smallest glaciers were restricted to higher elevations, and their deposits contain a much smaller proportion of finely comminuted limestone-derived fine sediments. The dissolution of this carbonate-rich material in the soil profile is the raw material for secondary carbonate accumulation at deeper levels. It may also be significant that all the secondary carbonates we have sampled formed at elevations lower than 1800 m. The Tymphian Stage moraines are all above 1800 m and commonly above 2000 m (Fig. 15.9). In this environment, secondary carbonate formation is more likely at lower elevations where a range of parameters including vegetation cover and deep soil development combined to provide more favourable conditions. These contrasts are also reflected by the PDI values for the three glacial formations (see Hughes et al., 2006b).

15.7. PALAEOCLIMATE RECONSTRUCTIONS FROM GLACIAL GEOMORPHOLOGICAL DATA

Hughes et al. (2007b) argued that the large glaciation of the Skamnellian Stage was strongly influenced by very low summer temperatures at least 11 °C lower than modern values. In the long pollen record at Tenaghi Philippon, the cold and dry interval correlated with MIS 12 was one of the most severe of the Pleistocene (Tzedakis et al., 2003). A dry climate during MIS 12 caused thick loess accumulations to form in the Pannonian basin in the northern Balkans (Marković et al., 2009). During the later Vlasian and Tymphian glaciations, climate would have been significantly warmer and wetter. However, wetter conditions were offset by the warmer summer temperatures resulting in smaller glaciers than during the Skamnellian.

A similar glacier-climate history to that in northern Greece has recently been revealed on Orjen in Montenegro. Here, the most extensive glaciation correlates with the Skamnellian glaciation in Greece during MIS 12 (ca. 480-430 ka). Later and less extensive glaciations are also recorded in the cirques and valleys of Orjen and correlate with glaciations in Greece during the Vlasian (MIS 6; 190–130 ka) and Tymphian Stages (MIS 5d-2; 110-11.7 ka) (Hughes et al., 2010). The Vlasian glaciers in Greece appear to have formed under the wettest conditions of all the three recorded major glaciations. This is in accordance with evidence of higher precipitation during MIS 6, compared with other cold stages, recorded in δ^{18} O stalagmite records in Italy and sapropel records in the Mediterranean Sea (Bard et al., 2002). For the Tymphian Stage glaciation in Greece, periglacial evidence has been used to reconstruct mean annual temperatures that were 8-9 °C cooler than present (Hughes et al., 2003)—an estimate that is supported by independent evidence from other records (e.g. Peyron et al., 1998). However, this temperature corresponds with the coldest and driest part of the last glacial cycle-close to the global LGM. Glaciers on Mount Tymphi were larger at earlier points of the Tymphian Stage, reaching their maximum between 25 and 30 ka, when climate was wetter—with precipitation > 2000 mm. In fact, glaciers are likely to have oscillated in response to millennial-scale climate fluctuations throughout this cold stage (Hughes et al., 2006c). All the palaeoclimate reconstructions described above were calculated using the Ohmura et al. (1992) regression which relates summer temperatures to values of winter balance + summer precipitation. These palaeoclimate reconstructions were rerun for Mount Tymphi and Smolikas using a degree-day model approach by Hughes and Braithwaite (2008) and produced similar findings.

15.8. RIVER RESPONSE TO GLACIATION AND THE LAST GLACIAL-TO-INTERGLACIAL TRANSITION

The new age framework for glaciation on Mount Tymphi has allowed fresh insights into the Pleistocene history of the Voidomatis River. The long-term interactions between the glacial and fluvial systems have recently been examined in detail by Woodward et al. (2008). An interesting feature of the alluvial record preserved in the middle and lower reaches (I, II and III in Fig. 15.4) of the Voidomatis River is the evidence for multiple phases of aggradation during the last cold stage. In this context, for the last cold stage at least, the alluvial record may offer a more detailed record of upstream glacial activity than the glacial record itself. The alluvial record can also offer insights into aspects of long-term glacial system behaviour that cannot be obtained

from the glacial sediments and landforms themselves. Figure 15.11 is a good example. It presents provenance data from fine-grained slackwater sediments preserved at the downstream end of the Lower Vikos Gorge (Reach II in Fig. 15.4). The lower part of the diagram shows the composition of cold stage meltwater floods towards the end of the last cold stage (Late Tymphian). The suspended load of the full-glacial river was dominated by glacially derived, finely comminuted limestone-rich sediment. The upper part of the diagram shows the composition of flood sediments preserved in Boila Rockshelter (Fig. 15.4). Boila preserves a

> FIGURE 15.11 Slackwater sediment records and suspended sediment source data from two sites in the lower Voidomatis River basin. Together they span the last glacial to interglacial transition in the Pindus Mountains (modified from Woodward et al., 2008). Boila Rockshelter and The Old Klithonia Bridge site are both located in Reach II shown in Fig. 15.4.

Late-glacial record, and these sediments show very clearly how the catchment switched rapidly during the last glacial to interglacial transition to a system dominated by rainfallgenerated floods with suspended sediments originating from lower elevation (nonglaciated) flysch terrains (Fig. 15.4). The composition of the flood sediments from Old Klithonia Bridge demonstrates that glaciers were active in the headwaters of the Voidomatis River basin towards the end of the last cold stage. This flood record provides valuable age control for these glacial processes because we do not have any uranium-series ages for the Late Pleistocene Tymphian moraines (Fig. 15.10).

15.9. THE MOUNT TYMPHI AND MOUNT OLYMPUS RECORDS

Smith et al. (1994) have argued that the first phase of glaciation on Olympus was the most extensive, with ice lobes covering part of the eastern, northern and western piedmont of the mountain. This period of glaciation was associated with a snowline as low as 1900 m above present sea level. Thus, in common with the record from Mount Tymphi, glacial activity was not as extensive during the last cold stage. All the uranium-series ages shown in Fig. 15.10 are significantly older than almost all the ³⁶Cl ages reported by Manz (1998) for the unit 1 moraine complexes on Mount Olympus. As Tymphi and Olympus are both located close to 40°N, one may expect a broad correlation between major phases of ice build-up and glacial sediment deposition. Recent work on Mount Orjen in Montenegro, for example, has produced a very similar record of Middle and Late Pleistocene glaciation to that recognised on Tymphi (Hughes et al., 2010). It is not possible to reconcile the extensive Middle Pleistocene glacial sequence we have identified on Mount Tymphi with the compressed sequence of post-MIS 5 glacial cycles and pedogenic weathering phases required on Mount Olympus if the MIS 3 cosmogenic ages preferred by Manz (1998) are accepted. In fact, notwithstanding the weaknesses discussed earlier and in view of the now substantial body of uranium-series ages from Mount Tymphi, the timescales associated with the tentative age model presented by Smith et al. (1997) would appear to be more realistic (Table 15.2). It is important to appreciate that, in common with the uranium-series data from the secondary carbonates on Mount Tymphi, the cosmogenic ages from Mount Olympus also constitute minimum ages. Thus, the cosmogenic ages from Site 2 indicate glacial activity at some time before 43-56 ka, while the outlier of 146 ka may represent glacial activity during the Vlasian Stage of MIS 6. This scenario would be much closer to the age model we have proposed for the glacial sediments and landforms on Mount Tymphi. However, before detailed correlations can be attempted, it is clear that more radiometric dates are needed from Mount Olympus.

15.10. PLEISTOCENE ELAs ACROSS GREECE

Hagedorn et al. (1969) was the first to estimate Pleistocene snowline altitudes across Greece, and these are shown in Fig. 15.1. Boenzi and Palmentola (1997) later estimated ELAs for mountains in Greece, Albania and southern Italy. In the northern Pindus Mountains, the estimates of Hagedorn and Boenzi and Palmentola closely correspond with the ELAs calculated for the most extensive Skamnellian Stage glaciers by Hughes et al. (2006c, 2007b). However, in common with earlier workers, they did not provide any radiometric dates for these glacial records. Boenzi and Palmentola (1997, p. 21) stated, "On the highest mountains of the Southern Apennines (Italy) and of the region stretching from Albania as far as Crete, many traces of glacial modelling are preserved, all attributable to the last glacial age (Würmian)." This assumption is now known to be incorrect as the Würmian Stage glaciers (Tymphian) were restricted to the highest cirques, and the ELAs estimated by Hagedorn (1969) and Boenzi and Palmentola (1997) relate to the largest Middle Pleistocene glaciations of the Skamnellian Stage (MIS12). Nevertheless, as noted for northern Greece, these estimates do represent an accurate reflection of the ELAs during the most extensive glaciation in Greece. Boenzi and Palmentola (1997) have computed an increase in ELA of about 100 m per degree of latitude moving southwards from Albania to Crete. From a palaeoclimatic perspective, it is interesting to note that, in the Pindus Mountains of Greece, glacier formation only took place on peaks higher than 2200 m, whereas in the Southern Appenines of Italy, traces of glacial activity are found at lower elevations on mountains >1900 m. This observation may reflect regional contrasts in air mass trajectories and other components of cold stage climates.

15.11. CONCLUSIONS AND FUTURE RESEARCH NEEDS

Recent work has shown that the mountains of Greece contain evidence for multiple phases of ice build-up and decay during the Middle and Late Pleistocene. Detailed field-based mapping has only been carried out in two areas: on Mount Olympus and the surrounding piedmont zone (Smith et al., 1997) and on Mount Tymphi in northwest Greece. The morphological and sedimentological evidence for glaciation is less extensive and less well preserved in central and southern Greece. The absence of a reliable and internally consistent chronology for the Mount Olympus record limits its value as a source of palaeoclimatic information and prevents detailed comparison with other sites. Recent work on Mount Tymphi has demonstrated the value of combining detailed field mapping with uranium-series dating in glaciated limestone landscapes (Woodward et al., 2004; Hughes et al., 2006b). The record on Mount Tymphi is proposed as a

formal stratigraphical framework for the glacial record in Greece and the wider region. It is quite possible that evidence of glaciation during MIS 8 and 10 has been preserved on some parts of the Pindus Mountains, but there is still a need for detailed field mapping to establish the precise spatial extent and style of glacial activity. The uranium-series ages from Mount Tymphi show that the most extensive glaciations took place during the Middle Pleistocene and not during the most recent cold stage and the global LGM (MIS 2). The alluvial record in the Voidomatis basin shows how the shift from full glacial to interglacial conditions can take place very rapidly.

Large areas of the Mediterranean region are dominated by uplifted carbonate terrains, and the glacial sediments are often cemented by carbonate materials than can be dated by uranium-series methods. The uranium-series ages reported here indicate that glaciation was extensive on Mount Tymphi during MIS 6 and earlier cold stages. We also present the first dated evidence for glacial activity in the Mediterranean region before 350 ka. Together, these ages show that many of the glacial landforms have been very well preserved and that ice build-up on Mount Tymphi (and perhaps in the rest of the Pindus Mountains) was much less extensive during the Late Würmian. Regional comparisons of ELAs in the Mediterranean should not assume that fresh glacial landforms relate to the latter part of the most recent cold stage-several reconstructions have made the mistake of using Middle Pleistocene ice limits to reconstruct ELAs for the last cold stage (e.g. Kuhlemann et al., 2008). Data from Mount Tymphi show very clearly that apparently fresh glacial landforms may be much older than previously thought.

Robust geochronologies are required to compare the timings of glaciations in the different mountain areas of the Mediterranean. At present, the geochronological framework for glacial sequences is patchy, although there has been a dramatic increase in the number of studies in the past decade-mainly utilising cosmogenic nuclide analyses to date glacial surfaces (e.g. Vidal-Romaní and Fernández-Mosquera, 2006; Pallàs et al., 2007; Akçar et al., 2008; Kuhlemann et al., 2008; Sarıkaya et al., 2008, 2009; Chapters 11 and 30). Cosmogenic isotope analyses have largely been restricted to noncarbonate lithologies (utilising ¹⁰Be, ²¹Ne and ³⁶Cl isotopes), and different studies have yielded contrasting geochronologies. In Iberia, Vidal-Romaní and Fernández-Mosquera (2006) applied ²¹Ne and ¹⁰Be analyses to date glacial landforms in granitic terrain in Spain and found evidence for Middle and Late Pleistocene glaciations, similar to that found in Greece (although at different times within the Middle Pleistocene). In other areas, such as Turkey, only Late Pleistocene glaciations have been found using cosmogenic dating (Akçar et al., 2008; Sarıkaya et al., 2008, 2009). In theory, carbonate surfaces can also be dated using ³⁶Cl, and it may be possible to develop multiple approaches for dating glacial sequences (by combining U-series and ³⁶Cl). For example, ³⁶Cl analyses have been successfully applied to date landslides on limestone rocks in the Alps (Ivy-Ochs et al., 2009). However, ³⁶Cl analyses have rarely been applied to date glaciated limestone terrains because of problems in estimating surface loss by solution—especially in wet (> 2000 mm), highly karstic, mountain regions, such as northwest Greece. Other possibilities include the dating of glaciated ophiolite surfaces, such as those on Mount Smolikas, using ³He. However, there are theoretical and practical obstacles in the effective application of these techniques to the lithologies of the mountains of northwest Greece. Uranium-series dating remains the most effective dating technique for establishing the geochronology of glacial deposits in this area.

There is little doubt that the glacial sediments and landforms in the mountains of southern Europe form an important record of Quaternary environmental change. As we have shown for northwest Greece, where appropriate samples are available, uranium-series methods may provide the best means of developing good age models for sedimentary sequences in glaciated limestone terrains. They can also provide the necessary age control to develop models of ice build-up and decay over several glacial–interglacial cycles (see Hughes et al., 2010). More robust chronological frameworks are now emerging for several parts of the Mediterranean, and this is allowing regional contrasts in glacier dynamics to be explored (e.g. Hughes and Woodward, 2008, 2009; Giraudi et al., 2011).

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