Pleistocene glaciation in the mountains of Greece

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Introduction

Much of mainland Greece lies south of 41°N and is predominantly a landscape of upland plateaus and rugged mountains. In his volume *The Mountains of Greece*, Sfikas (1979) indexes over twenty mainland peaks that exceed 2000 m and eight of these (including Crete) are higher than 2400 m. Many of the highest peaks such as Olympus (2917 m), Smolikas (2637 m) and Tymphi (2497 m) are found in Northern Greece, close to 40°N, and these mountains are associated with some of the most extensive and best preserved evidence for the activity of Pleistocene glaciers (Bailey *et al.*, 1990; Lewin *et al.*, 1991; Woodward *et al.*, 1992; 1995; Smith *et al.*, 1997; Boenzi & Palmentola, 1997; Smith *et al.*, 2000). At present, however, field sites in Greece where detailed modern studies of glacial sediments and landforms have been carried out are few in number, and any attempt to review this work is further hampered by the fact that robust age frameworks are not yet available for the glacial sequences. In addition, those studies which have been conducted over the last decade or so have involved contrasting aims and objectives, and a range of approaches has been employed including the lithological analysis of till sediments (Woodward *et al.*, 1992), detailed field-based landform mapping and glacial sedimentology (Smith *et al.*, 1994; 1997), satellite remote sensing for landform recognition and relative age dating (Smith *et al.*, 1998; 2000), and the estimation of Equilibrium Line Altitudes on a local and regional scale (Palmentola *et al.*, 1990; Mastronuzzi *et al.*, 1994; Boenzi & Palmentola, 1997). The aim of this contribution is to briefly review some of the recent literature on glaciation in Greece and to present new data on the age of the glacial deposits on the southern flanks of Mount Tymphi in Northwest Greece. We present the first radiometric (uranium-series) ages obtained for glacial sediments in Greece (Macklin *et al.*, 1998) and discuss the wider implications of this new chronostratigraphic framework. To the authors' knowledge, these are also the first radiometric ages for glacial sediments in the wider Eastern Mediterranean region.

Mountain glaciation in Greece and regional Pleistocene snowlines

In his review of Pleistocene glaciation in the Mediterranean region, Messerli (1967) reported several sites in Greece

with evidence for Pleistocene glacial activity and eight of them are listed in Table 1. Despite the absence of detailed morpho- and lithostratigraphic investigations of the glacial sequences at the time, Messerli (1967) assigned them to the Würmian and snowlines were plotted for this period for the entire Mediterranean basin. The principal Greek sites included on Messerli's (1967) map are shown on Fig. 1, yet, for some of these areas, glacial *deposits* have not been recorded on the 1:50,000 geological sheets produced by the Greek Institute for Geological and Mineral Exploration (IGME). This is probably due to the fact that, in some of these localities, the evidence for glacial activity is equivocal (see Pechoux, 1970), or is in the form of small-scale erosional features such as small cirques, nivation hollows and ice-moulded bedrock - with only limited evidence for landforms produced by the movement and deposition of glacial sediments down valley. Boenzi & Palmentola (1997) report that glacial features are only present on those Greek mountains that exceed 2200 m. In fact, the main sites in the country with extensive spreads of glacial sediments and landforms can be identified by examining the 1:500,000 geological map of Greece (IGME, 1983) (Table 1). This map also shows that glacial deposits are important landscape features on some of the highlands in the Southern Pindus Mountains (but to the North of 39.5°), including Mount Peristeri (2295 m) southwest of Metsovo, and further south around Mount Kakarditsa (2429 m) (Sestini, 1933) (Table 1).

Today winters are harsh and snowfall is heavy in the Greek mountains and extensive snow patches are common in the early summer on the highest peaks and ridges. 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 (Woodward *et al.*, 1995). Boenzi & Palmentola (1997) have calculated Equilibrium Line Altitudes for mountains in Greece, Albania and southern Italy and these are shown in Fig. 1. The ELAs were determined using Kurowski's method and this is based on the mean of the maximum elevation of the source area basin and the minimum elevation of each frontal moraine (Boenzi & Palmentola, 1997 p. 22). These workers have collected data for the mountains (except Olympus) shown on Fig. 1 and these data were "either personally gathered or from bibliographic sources." In common with earlier workers, while they do not provide any radiometric dates for the glacial sediments, Boenzi & Palmentola (1997) have

Fig. 1. Map of Greece, Albania and southern Italy showing the sites used in the estimation of regional Equilibrium Line Altitudes by Boenzi & Palmentola (1997). The dotted lines show the ELAs for the maximum extent of glacial activity at each site. The eight numbered sites in Greece are listed in Table 1. Note that dating control is lacking for most of these sites.

assumed that all of the glacial features on these mountains date to the last cold stage:

"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 (Würm)." Boenzi & Palmentola (1997, p. 21).

In fact, for the glacial sequences on Mount Tymphi in Epirus (Fig. 1), they have computed ELA values for four (Würmian) Lateglacial retreat stages – again without any absolute dating control. For this part of the Mediterranean basin, Boenzi & Palmentola (1997) have identified an increase in ELA of about 100 m per degree of latitude moving southwards from Albania across Greece to Crete. From a palaeoclimatic perspective, it is interesting to note that in the Pindus Mountains of Greece glacial landforms are only present on peaks higher than 2200 m whereas in the Southern Apennines of Italy, traces of glacial activity are found on mountains >1900 m. This observation may reflect regional contrasts in Pleistocene climates (humidity and/or temperature) and in the origin of precipitation-bearing air masses.

The glaciation of Mount Olympus

Background

The most detailed work to date on glacial sequences in Greece has been carried out in the Mount Olympus area by an American team led by Geoffrey Smith from the Department of Geological Sciences at Ohio University. 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. 1). Smith *et al.* (1994; 1997) have argued that previous work in the Mount Olympus area had significantly underestimated the extent of glacial activity since deposits on the eastern piedmont of the massif – that were previously classified as fluvial sediments – are, in fact, glacial diamictos. 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 (as is also the case for the rest of Greece), although the implication was that glaciation was restricted to the latest Pleistocene or Würm (Messerli, 1967).

Fig. 2. A) The glacial deposits and landforms of the Mount Olympus upland (Bara Plateau) (after Smith et al., 1997). Much of the terrain shown here is above 2000 m. B) The glacial deposits and landforms in the headwaters of the Xerolakki and Mavroneri rivers on Mount Olympus (after Smith et al., 1997).

Table 1. Mountains in Greece where evidence for significant glacial activity has been reported. The ELA values for sites in the Pindus Mountains are taken from Boenzi & Palmentola (1997) and for Mount Olympus from Smith *et al.* (1997).

Massif and Region	Peak Elevation	Latitude	ELA*	Reference	Glacial deposits marked on the 1,500,000 IGME map
1. Olympus, Pieria	2917 m	40°05'N	1030 m	Smith <i>et al.</i> (1997)	✓
2. Smolikias, Epirus	2637 m	40°05'N	1750 m	Boenzi <i>et al.</i> (1992)	✓
3. Tymphi, Epirus	2497 m	40°00'N	1700 m	Woodward <i>et al.</i> (1995)	✓
4. Peristeri, Epirus	2295 m	39°50'N	1925 m	Sestini (1933)	✓
5. Kakarditsa, Epirus	2429 m	39°45'N	1925 m	Sestini (1933)	✓
6. Parnasos, Sterea	2457 m	38°30'N	1800 m	Pechoux (1970)	✗
7. Helmos, Achaia	2341 m	38°00'N	2000 m	Mastronuzzi <i>et al.</i> (1994)	✗
8. Taigetos, Messinia	2404 m	36°56'N	1950 m	Mastronuzzi <i>et al.</i> (1994)	✗

The glacial sedimentary sequences on Mount Olympus

The stratigraphic record of Pleistocene and Holocene events on Mount Olympus is most clearly preserved on the eastern piedmont within the valleys of the Mavrolongus and Mavroneri rivers which drain to the Aegean coast (Fig. 2). Extensive moraine complexes have been mapped in the Mavroneri valley to the west and southwest of the town of Katerini, with thick proglacial (outwash) sediments present on the valley floor (Fig. 2A). 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 to 3) have been identified in the area and each is capped by a distinctive soil. The deposition of these sediments and the subsequent phases of pedogenic weathering reflect periods of glacial and non-glacial activity, respectively, in the region (Smith *et al.*, 1997, p. 809). The deposits of the eastern piedmont comprise a range of glacial, glaciofluvial, fluvial and alluvial fan sediments and each of the three main sedimentary units can be related to a period of glacial activity in the uplands (Smith *et al.*, 1997).

During the glacial phases that led to the deposition of unit 1 and unit 2 sediments, cirque glaciers developed to a size that permitted them to spread from their basins to form a continuous cover of ice on the upland (Smith *et al.*, 1997). The Bara Plateau is part of the Mount Olympus upland (a few kilometres south of the 2917 m Mytikas summit) and its glacial geology is shown in Fig. 2B. 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. 2B). Thirteen cirques have been identified on the Bara Plateau which have floor elevations ranging from 2180 to 2510 m above present sea level. On the Plateau of the Muses (which includes the Mytikas summit), eleven cirques range in elevation from 2200 to 2660 m above sea level (Smith *et al.*, 1997).

The glacial and proglacial sedimentary sequences in the Mount Olympus area constitute a potentially important record of environmental change to the east of the Pindus

Mountains and one that could be usefully compared to the long pollen record at Tenaghi Phillipon c. 160 km to the northeast (Wijmstra, 1969). However, the development of a geochronological framework for the glacial sequences has been hampered by the scarcity of suitable samples for radiometric dating. As Smith *et al.* (1997) have stated:

"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. As a result, emphasis has been placed on study of the soils that occur on top of, and within, the Mount Olympus deposits." (Smith *et al.*, 1997, p. 820).

Soil development and relative age dating

Pedogenic maturity indices have been determined for the soil profiles on units 1 to 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 resulted in the tentative correlation put forward by Smith *et al.* (1997), shown in Table 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 (no upland ice) and glaciers extended to mid-valley positions (Smith *et al.*, 1997).

While Smith *et al.* (1997) present this correlation as tentative, it is 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 Fuller *et al.*, 1998; Macklin *et al.*, 1997; 2002), and it can be argued that it does not form a reliable yardstick for regional correlation (Table 2). In addition, it is often difficult to make valid inter-site comparisons of soil profile development when sites are located at different altitudes in contrasting geomorphological settings. In such

Table 2. A tentative correlation of the Olympus Piedmont soils with the Pleistocene soils developed in alluvial sediments on the Larissa Plain studied by Demitrack (1986) (after Smith *et al.*, 1997).

Larissa Plain Soil Name	Depositional phase	Olympus Piedmont Soil Name	Marine Isotope Stage
Pinios Group	<200 years	Unit 3 surface soils	1
Deleria soil	Historical		
Girtoni soil	6-7 ka		
Non-calcareous brown soil	10-14 ka		
Gonnoi Group soils	14-30 ka		
Agia Sophia soil	27-42 ka	Unit 3 truncated (buried) soils	3
Rodia Group soils	≥54-125 ka	Unit 2 soil	5
Deep red soil	≤210 ka	Unit 1 soils	7

cases, establishing the long-term constancy of important soil forming factors such as parent material and local climate can be especially problematic (Birkeland, 1984).

Cosmogenic dating of the Olympus moraines

More recently, an attempt to develop an improved temporal framework for the glacial deposits of Mount Olympus has involved the application of cosmogenic dating of unit 1 boulder surfaces using Chlorine 36. Manz (1998) reports cosmogenic dates from two sites within large (unit 1) recessional moraine complexes on the eastern piedmont of Mount Olympus. Limestone boulders at Site 1 (immediately north of the town of Litochoro) have yielded ^{36}Cl ages within the range 32-49 ka. Site 2 is located in the Mavroneri catchment to the west of Katerina (Fig. 2B), and the sampled boulders (igneous, metamorphic and carbonate lithologies) yielded ages ranging from 43-56 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 evidence of an earlier glacial phase. Manz (1998) argues that the Site 2 ages are to be preferred because silicate rocks are more reliable when using this technique. The tentative age model for units 1 to 3 proposed by Smith *et al.* (1994; 1997) and shown in Table 2 would need to be radically revised if these ages for the unit 1 sediments are accepted. Indeed, it is difficult to reconcile these ages with the extent and thickness of the Pleistocene sediments comprising units 1 to 3 - the ^{36}Cl 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 2. The deep red soil developed on these [unit 1] sediments is thought to record an extended interval, probably of interglacial duration, during which substantial pedogenesis occurred (Smith *et al.*, 1997 p. 811). Manz (1998) concludes that:

"Although the ages of the sedimentary packages (units 1 to 3) on the eastern Olympus piedmont appear to postdate the last interglacial period, additional ^{36}Cl measurements on deposits on the piedmont and upland areas of the mountain

may reveal evidence of earlier glacial episodes." (Manz, 1998 p. 56).

In summary, at present the glacial sediments and landforms of Mount Olympus and the adjacent uplands lack a firm, internally consistent chronological base and, as Smith *et al.* (1997) have pointed out, the sequence of events proposed in Table 2 "can easily be shifted backward or forward in time." Thus, the correlation of glacial phases and periods of soil development on and around Mount Olympus with other sites in Greece and the wider Mediterranean zone is not yet possible.

The glaciation of the southern and southeastern flanks of Mount Tymphi, NW Greece

Background

Mount Tymphi (or Gamila) is located in Epirus in Northwest Greece approximately 15 km to the southwest of Mount Smolikis (Fig. 1). Its several peaks and ridges form part of the high watershed between the catchments of the Voidomatis (384 km²) and Aoos (665 km²) rivers. Tymphi has been described as both the most extensive and the most majestic of the Greek mountains (Sfikas, 1979), and includes a series of jagged limestone peaks, the highest of which exceed 2400 m (Fig. 3). The northern side consists of a range of cliffs and cirques and has been dissected by steep ravines. On the southern slopes of Mount Tymphi an extensive tableland is cut by the Vikos Canyon (Figs 3 and 4). A limited area of glacial deposits has also been mapped by IGME (1968) in the western corner of this plateau area (Fig. 3), but these features have not been studied by the authors.

Below the eastern ridges of Mount Tymphi, near the villages of Tsepelovon (39°54'N 20°49'E: c. 1100 m a.s.l.) and Skamnelli (39°55'N 20°51'E: c. 1200 m a.s.l.), extensive spreads of glacial deposits are marked on the 1:50,000 geological sheet (IGME, 1970; Fig. 3). This area contains an impressive array of glacial landforms and

Fig. 3. The drainage network, major physiographic units and solid geology of the Voidomatis River basin (after Lewin et al., 1991 and Hamlin et al. 2000 and based on the geological sheets produced by IGME (1968; 1970)). Mount Tymphi forms the highest part of the catchment and its peaks and ridges form the northeastern section of the watershed.

Fig. 4. SPOT satellite image of the glaciated terrain on the southern flanks of Mount Tymphi in the headwaters of the Voidomatis River basin. The Vikos Canyon is also shown. The image covers an area of approximately 25 x 15 km. See Fig. 3 for location.

sediments with perhaps some of the most well preserved glacial terrain on any of the Greek mountains. The cirques and major moraines in this area have been studied by Palmentola *et al.* (1990) as part of their work on central Mediterranean Pleistocene snowlines and their map is shown in Fig. 5. Seven major cirques face to the southwest and a series of 12 small and one large cirque (Manuli) face northwards and northeastwards into the Aaos River basin (Fig. 5).

Reconnaissance field 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 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 glacial landforms and sediments dominate the terrain on the southeastern flanks of Mount Tymphi and this area is shown on the SPOT satellite image (Fig. 4). This image also shows the two main gorges at the upstream end of the Vikos Canyon where glacial meltwaters and glacially-

derived sediments were fed into the Voidomatis River (Woodward, 1990; Woodward *et al.*, 1995; Bailey *et al.*, 1997; Macklin *et al.*, 1997). The glacial deposits south of Tsepelovon reach down to the valley floor of the Voidomatis River to an elevation of between 850 and 900 m above sea level (Fig. 3) (Woodward *et al.*, 1995).

The glacial sediments and landforms

In common with many of the glaciated mountains on the Balkan Peninsula and wider Mediterranean region, hard limestones are the dominant lithology (Menkovic and Markovic, this volume) (Fig. 3). Extensive areas of flysch rocks are present at lower elevations, but these are mainly beyond the limits of glacial erosion (Bailey *et al.*, 1997). Some outcrops of flysch are present within the glaciated area, but all fractions of the till sediments are dominated by limestone (Woodward *et al.*, 1995). The assemblage of glacial landscape features includes cirques of various

Fig. 5. The cirques and moraines on Mount Tymphi (after Palmentola *et al.*, 1990).

sizes and geometries (Figs 5 and 6A), deep ice-scoured troughs with stepped long profiles (Fig. 6B), ice-scoured limestone bedrock pavements (Fig. 6C), and lateral and terminal moraine complexes (Fig. 6D). Steep limestone cliffs and thick talus deposits are also important landscape features (Fig. 6B). As mentioned above, glacial depositional landform assemblages are especially well preserved on the mountain slopes around the villages of Tsepelovon and Skamnelli (Figs 4, 5, and 7). Palmentola *et al.* (1990) have identified the major moraines in this area. Their map is shown in Fig. 5 and some of their site names are used below.

Remote sensing of glacial landforms and sediments

As limestone is the dominant rock type the spectral characteristics of the glacial sediments and landforms on Mount Tymphi cover only a limited range. This has posed particular problems for attempts to establish the nature and extent of landforms and sediments related to glacial activity using satellite remote sensing because contrasting geomorphological features such as, for example, scree slopes and rocky moraine surfaces, commonly have similar spectral signatures (Smith *et al.*, 1998). In view of the complexity of the glaciated landscape and the low spectral

Fig. 6 A) The cirque close to Tsouka Rossa col on Mount Tymphi ridge. Photograph taken by Graham Smith in June 1997. B) View of the glaciated limestone terrain looking upvalley towards the Mount Tymphi ridge that separates the Voidomatis and Aaos river basins. Photograph taken by Graham Smith in June 1997. C) Glacially-planed limestone pavement with well-developed clints and grikes on the southern flanks of Mount Tymphi. Photograph taken by Jamie Woodward in June 1998. D) A sharp-crested lateral moraine above the village of Skamnelli with an extensive glacio-karst ice-scoured bedrock pavement in the middle background. Unmetalled tracks for scale. Photograph taken by Jamie Woodward in June 1998.

variability within much of the limestone-dominated study area, the effectiveness of three remotely sensed datasets (air photographs, SPOT and TM imagery) and several digital image processing procedures (see Smith *et al.*, 1998; 2000) has been examined. These approaches have been tested for their ability to:

- 1) determine the spatial extent of landforms on Mount Tymphi and
- 2) differentiate between glaciated landscape features on the basis of both their genesis and age

One example is given here using Landsat Thematic Mapper (TM) imagery with 30 x 30 m pixels. 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 (Smith *et al.*, 1998). A portion of the TM image (c. 70 km²) covering much of the glaciated terrain was selected for analysis. Prior to the MLC exercise, the five most important terrain classes were identified from field observations and air photograph analysis as:

1. Sharp-crested ("fresh") moraines
2. Weathered and eroded moraines
3. Scree formations
4. Slopes in flysch bedrock
5. Ice-scoured bedrock and limestone pavement

The results of this procedure are shown in Fig. 8 and Table 3. Given the 30 x 30 m resolution of the TM imagery, the MLC output provides a good representation of the geomorphology of the target area and the overall extent of the glacial deposits. However, some misclassification is evident, perhaps most notably in the overestimation of the extent of weathered and eroded moraines, and several sharp-crested moraines were actually misclassified as limestone bedrock (Smith *et al.*, 1998). Vegetation density and soil development generally increase with decreasing elevation and this is also an important influence on the spectral characteristics of the landscape classes. Nonetheless, the results of the MLC were evaluated in the field and from air photographs and the moraine complex to the north of Skamnelli was correctly classified as being dominated by

Table 3. Supervised Maximum Likelihood Classification results for the portion of the TM image covering the glaciated terrain and adjacent flysch basins shown in Fig. 8. The image covers an area of c. 8.2 x 8.5 km and areal estimates in km² of each terrain class are also given.

Terrain Class	% of TM image	km ²
1. Sharp-crested moraines	15.77	10.99
2. Weathered/degraded moraines	19.80	13.80
3. Limestone scree formations	05.21	03.63
4. Slopes on flysch bedrock	32.89	22.92
5. Ice-scoured limestone bedrock and pavement	26.33	18.35
Total	100.00	69.70

sharp crested moraines and the landforms near the village of Tsepelovon were correctly classified as weathered and degraded moraines. This approach is still under development, but it is clear that any relative-age information derived from the MLC can be evaluated against the geochronological data obtained from both the radiometric dating programme (uranium series) and data from soil development indices (e.g. Woodward *et al.*, 1994; Smith *et al.*, 1997). Some of these relative age data from the MLC outputs are discussed further below.

Smith *et al.* (1998; 2000) have shown that satellite imagery offers the potential to improve our understanding of glaciated Mediterranean mountain landscapes and can be a valuable aid in reconnaissance mapping studies. However, for glaciated limestone environments – which are common in the Mediterranean region – it has been shown that the value of such an approach and the accuracy of terrain mapping will increase as a function of both the spatial and spectral resolution of the imagery employed (Smith *et al.*, 1998; 2000).

The impact of Pleistocene glaciation on the long-term behaviour of the Voidomatis River

The middle and lower reaches of the Voidomatis River, some 15 to 30 km downstream of the glaciated terrain described above, contain perhaps the best documented and well-dated Pleistocene alluvial sequence in the Eastern Mediterranean region (Bailey *et al.*, 1990; Lewin *et al.*, 1991; Woodward *et al.*, 1992; Woodward *et al.*, 1994; Macklin *et al.*, 1997; Hamlin *et al.*, 2000; Woodward *et al.*, 2001). The nature of this record will not be repeated in detail here, but it is significant because it demonstrated for the first time in the Mediterranean region that the glaciation of some of the most southerly mountains in mainland Europe exerted a major influence on Pleistocene river behaviour and sediment transfer (Bailey *et al.*, 1990; Lewin *et al.*, 1991; Woodward *et al.*, 1992; Woodward *et al.*, 1995; Macklin *et al.*, 1997). This work involved detailed lithostratigraphic and pedostratigraphic investigations supported by a range of relative and absolute dating

methods (see Macklin *et al.*, 1997). The most recent phase of fieldwork in the Voidomatis River basin has shown that uranium series dating of calcretes formed within coarse-grained fluvial gravels can provide excellent age control for Middle and Late Pleistocene sequences which is in good agreement with other methods such as Electron Spin Resonance and Thermoluminescence (Macklin *et al.*, 1998; Hamlin *et al.*, 2000). In conjunction with an extension of the earlier mapping programme, this has allowed the development of a more detailed sub-division of the sequence of Pleistocene coarse-grained alluvial sediments deposited in the lower part of the catchment (Macklin *et al.*, 1998; Hamlin *et al.*, 2000; Hamlin, 2000).

Uranium-series isochron dating of calcretes in the Mount Tymphi tills

Deep sections in the glacial sediments are present where the depositional zone on the lower slopes is traversed by mountain tracks or by the Tsepelovon to Skamnelli road (Fig. 9). Such exposures in the Mount Tymphi tills show that the glacial sediments are commonly matrix supported and rich in sands, silts and clays derived from the comminution of the hard limestone bedrock (Woodward *et al.*, 1995). Sub-rounded boulders, cobbles and gravels are also common and at some locations, the road and track cuttings have exposed cavities within the till matrix where carbonate precipitation has taken place. In some places the fine sediment matrix has been washed away creating interclast voids that have been partially or completely filled with calcite. These calcretes often form a skin on the surface of cobble- and boulder-sized limestone clasts (accreting roughly parallel to the host surface) and, in some cases, they completely fill interclast voids. Calcrete development has been observed within a few metres of the moraine surface and the carbonates are probably derived from corrosion of the fine calcareous till matrix (see Ford & Williams, 1989).

The term calcrete is used here in a broad sense to describe the products of secondary carbonate formation (including a variety of morphologies) in a near surface

A

B

Fig. 7 A). Air photograph of the moraine complex at an elevation of c. 1600 m (above the village of Skamneli) on the southern flanks of Mount Tymphi. The locations of calcrete samples B and C listed in Table 4 are shown.
B) Crest of the large end moraine complex on the southern slopes of Mount Tymphi above the village of Skamneli. Photograph taken by Jamie Woodward in June 1998.

Table 4. Uranium-series ages from calcretes collected from glacial sediments on the southeastern slopes of Mount Tymphi. Sample locations are shown on Fig. 3 and discussed in the text. The errors associated with each U/Th age are given at 2 sigma probability and represent a measure of counting uncertainties in the determination of nuclide concentrations (see Hamlin, 2000). Note that Site F comprised a sequence of glacial and glacio-fluvial sediments exposed on the present valley floor of the Voidomatis River. This scheme will be revised and extended as more dates and field data become available. Marine isotope stages after Martinson *et al.* (1987). Note that these ages provide only a minimum age for the host sediments (see text for discussion).

Site	Uranium-series age of calcrete sample	Elevation of sample location	Marine Isotope Stage associated with calcrete formation
A.	>350,000	1750 m	11 or earlier
A.	321,500 $\pm$ 35,650	1750 m	9
A.	121,400 $\pm$ 21,000	1750 m	5e
B.	80,450 $\pm$ 15,100	1750 m	5a
C.	131,250 $\pm$ 19,250	1800 m	6
C.	81,700 $\pm$ 12,900	1800 m	5a
D.	71,100 $\pm$ 8,700	1290 m	5a/4
E.	105,730 $\pm$ 21,450	1210 m	5c
F.	96,250 $\pm$ 15,500	850 m	5c

terrestrial environment (see Dixon, 1994; Kelly *et al.*, 2000). Macklin and Woodward collected calcretes from several exposures on the southern slopes of Mount Tymphi in May 1998 (Figs 3 and 7A) and these materials have been dated by the U/Th isochron method by Dr Stuart Black (see Kelly *et al.*, 2000; Hamlin, 2000). This approach involves the measurement of ^{230}Th ingrown from the decay of authigenic ^{234}U and, indirectly, ^{238}U , the uranium having been co-precipitated from solution with the carbonate (Kelly *et al.*, 2000). This approach employs an isochron method (see Bischoff & Fitzpatrick, 1991) to determine the authigenic radionuclide components in each calcrete sample (see Kelly *et al.*, 2000). Nine U/Th ages from six sites on the southern slopes of Mount Tymphi are listed in Table 4. The errors on the age determinations are quoted at 2 sigma probability and are determined as a measure of counting uncertainties in the radionuclide measurements. It is important to recognise that these U/Th ages provide *minimum* ages for the host glacial sediments as the calcretes were formed sometime after deposition. Each sample site (A to F) is listed in Table 4 and shown on Fig. 3 and described in detail below:

Site A: This sample was collected from an exposure in a body of till sediments that was preserved down-valley of a low bedrock protrusion on the eastern side of the main moraine complexes above the village of Skamnelli (Fig. 10A). In contrast to the other five sites discussed below, the fine sediment matrix (where present) showed some evidence of weathering. The section at Site A revealed sub-rounded limestone glacial clasts with horizons of clast supported material where the fine matrix had been winnowed away by percolating waters allowing calcretes to fill the interclast voids (Fig. 10A). This sample had three clearly different types of calcite present (Fig. 10B) and each

has been sub-sampled and dated by uranium series. Several generations of calcite growth were evident (Dr Stuart Black, personal communication) and the oldest of these was beyond the range of uranium-series dating (>350 ka). The two other calcrete samples yielded ages of 321,500 $\pm$ 35,650 and 121,400 $\pm$ 21,000 and indicate further phases of calcrete development during the interglacial conditions of MIS 9 and MIS 5e respectively (Table 4). The presence of several stages of calcite growth at this site indicates that this section has been stable for an extended period of time (>350 ka). Despite the limited extent of this deposit, the oldest uranium series assay provides the first direct dated evidence of Middle Pleistocene glacial activity in Greece and the wider Mediterranean region before c. 350 ka.

Site B: This site was exposed in a section along a vehicle track in the easternmost lateral moraine above the village of Skamnelli. This part of the glaciated terrain (Vracachi complex, see Fig. 5) contains two well-preserved lateral moraines that can be traced up valley to the easternmost cirque shown on Fig. 5. A calcrete sample yielded a uranium series age of 80,450 $\pm$ 15,100 years BP (Table 4). This provides a minimum age for this moraine system and indicates that the last major phase of glacial activity in this upland valley took place before MIS 4. This uranium series age is discussed further below in relation to the evidence from Site C (Fig. 7A).

Site C: A calcrete sample was collected from a section exposed in the track on the western side of the major arcuate lateral and terminal moraine complex on the slopes high above the village of Skamnelli. This landform and the sample location are shown in the aerial photograph of this part of the southern slopes of Mount Tymphi (Fig. 7A). This calcrete sample contained evidence of two generations

Fig. 8. Supervised Maximum Likelihood Classification of the TM image of the glaciated headwaters of the Voidomatis River (southern slopes of Mount Tymphi). The image covers an area of approximately 8.2 x 8.5 km (after Smith *et al.*, 1988). Elevations: Tsepelovon (c. 1100 m) and Skamnelli (c. 1200 m). Compare with geological map (Fig. 3) and SPOT image (Fig. 4).

of calcite growth and each has been dated giving uranium-series ages of $131,250 \pm 19,250$ and $81,700 \pm 12,900$ years BP respectively. The older of the two ages provides a minimum age for this large moraine complex and suggests that the glacial phases to which it relates took place during MIS 6 although an earlier date is possible (Table 4). The similar size, form and degree of preservation between the closely spaced moraines shown in Fig. 7A (associated with Sites B and C) strongly suggests that they relate to the same phase of glacial activity. While the calcrite at Site B has yielded a younger age, the freshness of the topography (sharp-crested moraines shown on the TM imagery and in Fig. 7A) and the uranium series ages from Site C indicate that this moraine complex was probably formed during MIS 6. These ages demonstrate that the glacial sediments and landforms in this part of Mount Tymphi are much older than the global Last Glacial Maximum of MIS 2.

Site D: A calcrite sample was collected from a section revealing limestone-dominated till sediments to the north of Tsepelovon at an elevation of c. 1290 m on the margin of the Laccorponi valley system mapped by Palmentola *et al.* (1990) (Fig. 5). This material yielded a uranium series age of $71,000 \pm 8,700$ years BP. This age falls close to the

boundary of MIS 4 and 5a (Martinson *et al.*, 1987). Given the quoted uncertainty associated with this age, the glacial phase could not have taken place later than the early part of MIS 4 and could have taken place during an earlier cold stage.

Site E: The road from Tsepelovon to Skamnelli cuts across several lateral moraines and provides a series of excellent exposures in till sediments that are typical of those found across the southern slopes of Mount Tymphi (Fig. 9). In the first major exposure on this road outside Tsepelovon (see Woodward *et al.*, 1995), cemented till sediments were present at the base of the section just above the level of the road. A calcrite sample from this horizon yielded a uranium-series age of $105,730 \pm 21,450$ years BP. This moraine is a major landscape feature and is part of a spread of glacial deposits that extend down to the valley floor of the Voidomatis River (Fig. 3) (Woodward *et al.*, 1995). This calcrite formed during MIS 5 (possibly during MIS 5c) and forms a minimum age for the deposition of this feature. This moraine forms part of the "weathered and eroded moraines" category identified on the TM imagery (see Smith *et al.*, 1998 and Fig. 8).

Fig. 9. A road cut section in a large moraine outside the village of Tsepelovon (Photograph taken by John Lewin in August 1986).

In contrast to the sharp-crested moraines at Sites B and C above Skamnelli (whose upper sections are not weathered), exposures in this (Site E) moraine complex have revealed a thick soil with strongly weathered A and B horizons (Woodward and Smith, unpublished) that are similar to those identified on terraced alluvial surfaces in the middle reaches of the Voidomatis River (Woodward *et al.*, 1994). The degraded form of this moraine and the evidence for an extended period of pedogenic weathering indicate that it relates to a phase of glacial activity that took place before the formation of the moraine complex above Skamnelli. The multiple phases of calcrete development evident at Sites A and C demonstrate that calcretes can form a long time after the deposition of the primary glacial sediments and it is important to appreciate that the uranium series age from Site E represents a minimum age for its host glacial sediments. Thus, if the moraines above Skamnelli (Sites B and C) were deposited during MIS 6, the glacial sediments at Site E could relate to an earlier phase of glacial activity during MIS 6 or an earlier (pre-MIS 6) cold stage. It is worth pointing out that Site E is located further down the Laccorponi valley system (than Site D) mapped by Palmentola *et al.* (1990) (Fig. 5) and the above discussion would suggest that the glacial sediments at Site D are much older than the uranium series age of $71,000 \pm 8,700$ years BP.

Site F: Glacial and glacio-fluvial sediments are exposed on the present valley-floor of the Voidomatis River to the south of Tsepelovon (Fig. 3) at an elevation of approximately 850 m above sea level. A sample of calcrete was collected from a cemented glaciofluvial unit that lay between 5 to 6 m above the modern channel within a much thicker sequence of glacial and glaciofluvial deposits. This sample yielded a uranium series age of $96,250 \pm 15,500$ (Table 4). In common with the sample from Site E, this age

lies within the MIS 5 complex and may have formed during MIS 5c, with the phase of primary coarse sediment deposition taking place during the preceding cold phase (MIS 5d) or earlier.

Towards a new chronostratigraphic framework for glaciation in Greece

While more uranium-series ages and more extensive and detailed field mapping are needed to develop and refine the age model for the Mount Tymphi sequences presented here, it is nonetheless possible to make some important observations about landscape development and glacial history in the mountains of Greece. Furthermore, the geochronological data presented in this paper and the arguments outlined below have significance for our understanding of Pleistocene glacial activity in the wider Mediterranean region. Apart from Site C, the uranium series ages indicate that calcrete development took place during warm periods and, where a suite of ages is available, the oldest ages for a particular deposit can be used to infer glacial activity during a previous cold stage. Additional information from, for example, geomorphological mapping and relative-age dating criteria (e.g. soil development and moraine degradation indices) can be synthesized to develop a chronostratigraphic framework for the Pleistocene glaciation of the Pindus Mountains.

The sediments exposed at Site A contrast with the other exposures discussed above because of the high proportion of clast-supported, matrix free sediment. In addition, unlike the other locations, this body of sediment is not part of an extensive and well-preserved moraine complex and these characteristics are in good agreement with the very old uranium-series ages we have obtained (Table 4). Each of the ages from Sites B to F are from contexts which relate to

A

B

Fig. 10. A) The section exposed at Site A showing the zone of calcrete formation between the two large clasts to the left of Mark Macklin's head and chest.

B) Close up of the sampled calcrete between the boulders showing distinctive layering, well developed columnar calcite crystals and multiple phases of development. The lens cap has a diameter of 6 cm. Photographs taken by Jamie Woodward in June 1998.

distinctive and extensive glacial depositional (and glacio-fluvial in the case of Site F) features on the southern flanks of Tymphi, and they range in age from $131,250 \pm 19,250$ (MIS 6) to $71,000 \pm 8,700$ (MIS 5a/4).

Work on the cemented alluvial sediments downstream in the Voidomatis gorges and Konitsa basin (Fig. 3) has shown that calcretes can form relatively quickly following deposition of the host gravels. However, the multiple phases of calcrete development at sites A and C demon-

strate that it is important to obtain several assays from each suite of glacial sediments and landforms as, under certain conditions, calcrete development can also take place a considerable time *after* the deposition of the parent glacial sediments. Thus, while the ages obtained for Sites E and F (which are located in the "weathered and eroded moraine" category used in the MLC classification of the TM imagery) are younger than the oldest age from Site C, the primary glacial sediments at Sites E and F could be much

older. In fact, the presence of deep and strongly weathered soil horizons on the moraine surface down valley of Tsepelovon indicates that the sediments at Site E are considerably older than those at Sites B and C in the "sharp-crested moraine" complex above the village of Skamnelli.

The uranium-series ages discussed above indicate that most of the glacial sediments and landforms in the headwaters of the Voidomatis River basin are much older than the global Last Glacial Maximum (MIS 2) and relate to glacial activity during MIS 6 and earlier cold stages. There is also evidence of glacial activity in the Pindus Mountains before c. 350 ka. The evidence for several stages of calcrete growth at two sites (A and C) is highly significant and cautions the development of chronostratigraphic frameworks based on a small number of dates. The multi-phase calcretes at Sites A and C show that these bodies of sediment and their associated landscape features have been stable for an extended period of time and >350 ka in the case of Site A and at least $131,250 \pm 19,250$ at Site C. These periods span glacial-interglacial cycles and the data from Site C in particular demonstrate 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).

It is not yet clear whether ice build up and glacier development took place in Northern Greece during the cooler phases of the MIS 5 complex. The ages from Sites B, D, E and F relate to the Last Interglacial (Table 4), but it is important to remember that each of them represent minimum ages. A larger suite of uranium series ages in conjunction with a detailed mapping programme is required to address this issue. Detailed analysis of the pollen records for these sub-stages would allow a broader picture of the associated regional palaeoenvironments (e.g. humidity and temperature) to be produced.

The bulk of the glacial sediments and major glacial depositional landforms in this area are much older than the global LGM of MIS 2 and this is a very significant outcome of the uranium series dating programme. Glacial deposits of this period do not appear to be extensive, although further mapping and uranium-series dating work is in progress and sediments of this period may be present at higher elevations (Fig. 5). The excellent preservation of the sharp-crested moraines above the village of Skamnelli (Fig. 9A) may be the result of free-draining limestone-rich till sediments and the extensive areas of scree sediments and glacially-scoured limestone pavement that limit surface runoff and erosion by fluvial processes and mass wasting. There is little evidence of soil development on these moraines (Woodward and Smith, unpublished) and it is not yet clear if this is due to very slow rates of pedogenic weathering at this elevation or whether the apparently fresh moraines are eroding slowly and uniformly across their surfaces, thus preventing the development of a marked weathering profile.

As we have mentioned above, the uranium-series method has been used successfully to develop a chronostratigraphic framework for the coarse-grained alluvial units at lower elevations in the Voidomatis River basin

(Macklin *et al.*, 1998; Hamlin *et al.*, 2000) providing ages that are in good agreement with other methods such as ESR, TL (Lewin *et al.*, 1991) and radiocarbon (Woodward *et al.*, 2001). It is interesting to note that the Pleistocene alluvial sequence in the Voidomatis River contains evidence for major phases of aggradation (also dated by uranium-series methods) shortly before $113,000 \pm 6000$ and $80,000 \pm 7000$ (Macklin *et al.*, 1998; Hamlin *et al.*, 2000). In the southern part of the Konitsa basin, where the river emerges from the confines of the Lower Vikos Gorge (Fig. 3), these terrace surfaces lie approximately 15.5 and 12.75 metres above the present channel (Hamlin *et al.*, 2000). These are the thickest limestone-dominated coarse-grained alluvial units yet identified in the Voidomatis basin and represent major phases of sediment transfer and deposition. The uranium-series ages listed in Table 4 strongly suggest that large glaciers and active moraine complexes were present in the headwaters of this river system during MIS 6 and are in good agreement with the geomorphological implications of the alluvial record. The issue of glacial activity in the Mediterranean during the cold sub-stages of MIS 5 (5d and 5b) is an intriguing one and further work is required to confirm this. Interestingly, in a recent Mediterranean-wide review of Middle and Late Pleistocene river behaviour, Macklin *et al.* (2002) have identified major periods of valley-floor sedimentation across the Mediterranean region during MIS 6 and the cooler phases of MIS 5 – i.e. during 5d and most notably at the 5b/5a boundary. Most of the river basins considered in their analysis drain mountainous headwater catchments and, during phases of cooler climate, increases in sediment supply and flood frequency promoted widespread aggradation throughout many river valleys. Indeed, as Macklin *et al.* (2002) suggest, these appear to have been important periods of landscape development and sediment transfer in many Mediterranean mountain catchments.

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 available dated evidence from Mount Tymphi, glacial activity was not as extensive during the Last Glacial Maximum (Late Würmian or MIS 2). However, it is worth pointing out that all of the uranium-series ages listed in Table 4 are significantly older than almost all of the ^{36}Cl 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. If this is the case, it would be difficult to reconcile the extensive pre-Würmian 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 above, in the light of the 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 2). It is important to appreciate that, in common with the uranium series data from the calcretes 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 to 56 ka (and this could have been during MIS 4 or earlier, depending on the geomorphological history of the dated boulders), while the outlier of 146 ka may represent glacial activity during 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 (ideally using a range of methods) are needed from both regions.

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. However, there is still a need for detailed field mapping in many areas to establish the precise spatial extent and style of glacial activity in the Greek mountains. The morphological and sedimentological evidence for glaciation is less extensive and less well preserved in central and southern Greece. At present, the only glaciated terrain in Greece where detailed field-based mapping and lithostratigraphic assessment have been carried out is on Mount Olympus and the surrounding piedmont zone (Smith *et al.*, 1997). However, the absence of a reliable and internally consistent chronology for this work limits its value as a source of palaeoclimatic information and prevents detailed comparison with data from Mount Tymphi and with the long pollen sequences in Greece and other records of proxy climate.

Even though most of the sequences have not been dated, a number of workers have assumed that the glacial sediments and landforms in Greece date to the most recent cold stage (Würmian) of the Pleistocene (Boenzi & Palmentola, 1997) and the global Last Glacial Maximum (MIS 2). The Mediterranean region is 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. Further work is needed

to build on these findings and to address whether glacial activity also took place during the cold sub-stages of MIS 5.

Regional comparisons of Equilibrium Line Altitudes in the Mediterranean should *not* assume that fresh glacial landforms relate to the latter part of the most recent cold stage. Indeed, the timescales involved in the preservation and reworking of glacial landforms and sediments in limestone mountain environments is also a key issue as our data from Mount Tymphi suggest that apparently fresh glacial landforms may be much older than previously thought.

There is little doubt that the glacial sediments and landforms in the mountains of southern Europe form an important record of environmental change. Where appropriate samples are available, uranium series methods may provide the best means of developing good chronological control for sedimentary sequences in glaciated limestone terrains and can provide the necessary age control to develop models of ice build up and decay that may aid palaeoclimatic reconstruction. Future work on the chronology and palaeoclimatic implications of the glacial sequences of the Pindus Mountains will allow detailed comparisons to be made with the region's fluvial records to establish the nature of the interactions between ice build up and decay and coarse and fine sediment inputs to the fluvial system (Woodward *et al.*, 1995; Macklin *et al.*, 1997; Hamlin *et al.*, 2000). Robust chronological frameworks are needed to improve our understanding of long-term landscape development, glacial palaeoclimates, and sediment fluxes in glaciated Mediterranean mountain catchments.

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Note: A detailed geomorphological mapping programme is currently underway on Mount Tymphi and Mount Smolikis by Philip Hughes as part of his PhD project (2001 to 2004) supervised by Dr P. L. Gibbard

(Cambridge) and Dr J. C. Woodward (Leeds). The U/Th dating programme is also being extended by this team with support from the UK Natural Environment Research Council (NERC).

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