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Relict rock glaciers as indicators of Mediterranean palaeoclimate during the Last Glacial Maximum (Late Würmian) in northwest Greece

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ABSTRACT: Relict rock glaciers have been identified and mapped in the high cirques of Mount Tymphi, in the Pindus mountains of northwest Greece. They are periglacial forms and represent the most recent cold-stage landforms in an area that displays widespread evidence of Pleistocene glaciation. It is likely that these features formed during the Last Glacial Maximum (Late Würmian) as talus rock glaciers, and beneath small cirque glaciers as debris rock glaciers. Comparisons with modern rock glacier–climate relationships suggests mean annual temperatures of ca. 8–9 °C lower than present at their time of formation. This temperature reconstruction is in good agreement with recent palaeoclimatic reconstructions for the northern Mediterranean based on a general circulation model. Moreover, as rock glaciers are typical of cold and relatively dry mountain regions, their presence is consistent with palaeobotanical and lake-level data suggesting a cold and relatively dry climate for the Last Glacial Maximum in Greece. However, the presence of small cirque glaciers above some rock glaciers suggests that although precipitation must have been low enough to preclude glacier extension down to lower altitudes, it was not so low as to inhibit glacier formation entirely. Copyright © 2003 John Wiley & Sons, Ltd.

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KEYWORDS: Greece; rock glaciers; temperatures; palaeoclimate; Last Glacial Maximum; Late Würmian; periglaciation.

Introduction

The climate in northwest Greece and the wider Mediterranean at the Last Glacial Maximum (LGM) during the Late Würmian Substage has been the subject of much debate (Bailey *et al.*, 1983; Prentice *et al.*, 1992). Pollen evidence for this period suggests that in much of the Balkans the predominant vegetation consisted of an *Artemisia*-Chenopodiaceae steppe which is thought to represent rather drier climatic conditions than present (Bottema, 1974; van Zeist and Bottema, 1991; Tzedakis, 1993; Willis, 1994). However, elevated lake beach deposits, dated to 20 800 ± 810 and 20 200 ± 480 ^{14}C yr BP at the Kastritsa rockshelter near Lake Pamvotis (Ioannina), have been used to suggest a higher lake-level at this time and a pluvial LGM (see Higgs *et al.*, 1967; Bailey *et al.*, 1983) (Fig. 1). Prentice *et al.* (1992) attempted to reconcile this conflict using a combined water-balance and biome model. They proposed an increase in *seasonality* with a prolonged summer drought inhibiting tree growth and stormier and wetter winters producing high lake-levels. However, more recently Galanidou *et al.* (2000) have suggested that evidence of higher lake-levels at Ioannina may be purely an artefact of tectonic uplift of the Kastritsa ridge—an idea first proposed by King and Bailey (1985). They also provide a revised chronology of the deposits used in the model of Prentice *et al.* (1992) showing that they are not of LGM age, as previously thought, but formed during a period of intermediate rather than extreme conditions *prior* to the LGM.

The most severe temperature depression in the region occurred around 21 000–22 000 ^{14}C yr BP, coeval with Heinrich Event 2 in the North Atlantic (Galanidou *et al.*, 1999). This is prior to the time of maximum global ice volume at ca. 18 000 ± 1000 ^{14}C yr BP. Ostracoda evidence during the coldest phase indicate a distinct lowering of lake-levels during this period (Frogley, 1997). The case for a higher lake stand at Ioannina during the LGM is therefore open to question and is also at odds with evidence from other lakes in Greece. At Lake Xinias, for example, Digerfeldt *et al.* (2000) found evidence of a low lake-level from ca. 32 000 yr BP through to ca. 15 000 yr BP, in accordance with the pollen evidence for arid steppe vegetation. Similarly, at Lake Kopais, Okuda *et al.* (2001) propose that the lake-level was low during the full-glacial period on the basis of the presence of

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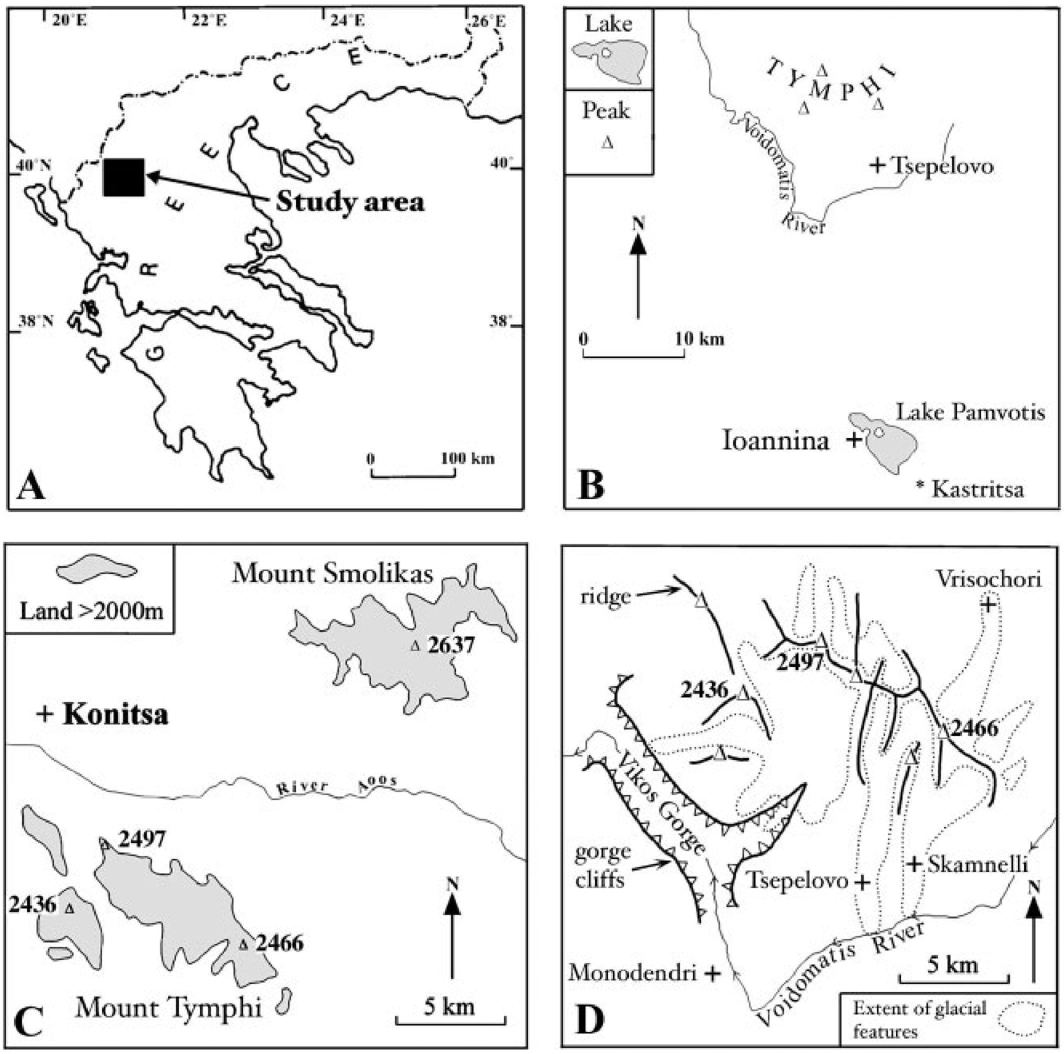

Figure 1 (A) Location map of the field area within Greece. (B) Mount Tymphi in relation to Ioannina and the Kastritsa rockshelter. (C) The Mount Tymphi area. (D) The extent of glacial features on Mount Tymphi and the upper reaches of the Voidomatis River

lignite lenses, indicative of swamp development and therefore lower lake-levels, throughout the core horizons dated to this period. More recently, estimates of LGM temperatures and precipitation for the Ioannina region have been provided by Tzedakis *et al.* (2002) using data from a nested global general circulation model developed by E. J. Barron and D. Pollard. At 21 000 yr BP, the model suggests that mean January and July temperatures were 10 °C and 7 °C lower than present, respectively, and also mean annual precipitation values ca. 545 mm lower.

This paper documents a series of relict rock glaciers on Mount Tymphi (2497 m), which are located around 40 km northeast of the Ioannina basin in Epirus, northwest Greece (Fig. I). The mountain is part of the Pindus chain, which was formed by the Pindus thrust from mid-Eocene until Oligocene times (Clews, 1989). Relict rock glaciers allow palaeoclimatic reconstruction based on analogy with the modern relationship between rock glaciers and climate (e.g. Girauldi and Frezzotti, 1997). The presence of such features in the Pindus Mountains therefore provides a powerful proxy for reconstructing glacial climate in Greece. The genesis of modern rock glaciers is contentious, however—especially with regard to whether they represent debris-covered glaciers or true periglacial forms consisting largely of debris with only interstitial ice (Barsch, 1988, 1996). This paper describes the relict rock glaciers of Mount Tymphi and discusses their mode of formation as well as the implications of this new proxy data on the LGM climate in the eastern Mediterranean.

Study area

Geology

Mount Tymphi comprises a series of uplifted fault blocks and faulted escarpments and is formed largely of Palaeocene–Eocene limestone, but includes Senonian–Jurassic dolomites and limestones on the northern scarp and in the Vikos gorge to the south (Fig. 1). The limestones are pure, resistant, crystalline rocks typical of the wider Epirus region (Woodward *et al.*, 1992) and karstic features are evident throughout the area (Waltham, 1978). The lower slopes are dominated by younger flysch rocks (Late Eocene to Miocene), which consist of thin beds of graded sandstones (10–20 cm) intercalated with softer, fissile siltstones (Bailey *et al.*, 1997).

Climate

The modern climate of Epirus is transitional between those of central Europe and the Mediterranean and local variations in climate are considerable, largely reflecting relief. At Ioannina (484 m above sea-level (a.s.l.)), annual precipitation is ca. 1200 mm with 176 mm of this falling in December and 29 mm falling in August. Mean January and July temperatures are 4.9 °C and 24.9° respectively (National Statistical Service of Greece, 1981). Annual precipitation values are higher in the mountains, reaching 1702 mm in Tsepelovon (1100 m a.s.l.) (Hamlin *et al.*, 2000) and greater than 2000 mm in the central massifs of Smolikas and Tymphi (Furlan, 1977). Mean January and July temperatures of −5 °C and +15 °C are typical of the higher mountains (Bailey *et al.*, 1997) and consequently much of the winter precipitation falls as snow—patches of which persist until late June on the highest mountains.

Glacial history

Glacial deposits are extensive and well preserved on Mount Tymphi and extend to altitudes as low as 850 m a.s.l. (Fig. 1). The impressive moraines of Tymphi have been noted by many workers (e.g. Messerli, 1967; Waltham, 1978; Bailey *et al.*, 1990; Palmentola *et al.*, 1990; Lewin *et al.*, 1991; Woodward *et al.*, 1992, in press; Smith *et al.*, 2000), although it is only recently that the sedimentology and chronology of these features have been investigated in any great detail (Hughes *et al.*, unpublished data). Glaciation is also clearly in evidence on nearby Mount Smolikas (2632 m a.s.l.), across the Aoos valley to the north (Niculescu, 1915; Boenzi *et al.*, 1992; Hughes *et al.*, unpublished data). Here, glacial deposits extend down to similar altitudes as on Mount Tymphi and work is in progress to understand the detailed chronology and correlation of the deposits with relation to those on Mount Tymphi.

The glacial deposits of Mount Tymphi have been dated via the U-series dating of calcite cements (calcretes). Woodward *et al.* (in press) have shown that the most extensive glacial deposits do not belong to the Late Würmian Substage as assumed by Palmentola *et al.* (1990). Woodward *et al.* (in press) and Hughes *et al.* (unpublished data) suggest that the most extensive deposits belong to earlier glacial events, before marine oxygen isotope stage (MIS) 5 (Table 1). This is consistent with the tentative chronology developed for Mount Olympus in eastern Greece by Smith *et al.* (1997). These workers recognise three phases of glaciation on Olympus, the oldest and most extensive belonging to at least MIS 8, an intermediate phase assigned to MIS 6 and a phase of small cirque and mid-valley glaciation above 2000 m correlated with the Middle to Late Würmian (MIS 4–2). As on Mount Olympus, the most recent glacial and periglacial deposits on Mount Tymphi occur in the highest cirques, where they are characterised by small moraine ridges and relict rock glaciers. The latter are the focus of this paper. Relict rock glaciers have been noted in other parts of the Pindus, such as at Mount Parnassus (Pechoux, 1970), although their significance for our understanding of late Pleistocene palaeoclimate has not, until now, been fully appreciated.

Table 1 The glacial chronology of Mount Timfi based on U-series dating of calcite cement (calcrete) formed within tills and the morphostratigraphical position of glacial deposits. Both sets are at 2-sigma error. The dates of Woodward *et al.* and Hughes represent minimum ages for the glacial deposits and are from different laboratories

U-series dates from tills	Marine oxygen isotope stage	Glacial characteristics
>350 000 yr BP[a]	**12**	Extensive valley glaciers and a small ice-field existed on Mount Tymphi
131 250 ± 19 250 yr BP[a] 103 328 ± 4849 yr BP[b] 96 250 ± 15 500 yr BP[a] 81 450 ± 15 100 yr BP[a] 71 000 ± 8700 yr BP[a]	**6**	Valley glaciers and glaciers that reached mid-valley positions
	2	Cirque moraines and *rock glaciers*

[a] From Woodward *et al.* (in press).
[b] From Hughes *et al.* (unpublished data).

Rock glacier genesis

Rock glaciers are masses of coarse angular debris that can have the external appearance of small glaciers and, owing to their large non-ice component, retain much of their morphology long after they were active. They commonly display steep fronts and transverse surface ridges, possibly the product of differential movement of discrete layers of debris (Loewenherz *et al.*, 1989). The origin of rock glaciers has been a particularly contentious issue in mountain geomorphological research, the traditional view being that these features are periglacial forms with movement explained via a model of creeping permafrost (Barsch, 1978, 1988, 1996; Haeberli, 1985). Rock glaciers are therefore indicative of at least discontinuous permafrost in high mountain and polar regions. However, some workers distinguish between rock glaciers of glacial origin and periglacial origin. For example, Martin and Whalley (1987) and Whalley and Martin (1992) recognised ice-cored rock glaciers, which are essentially debris-covered glaciers, and ice-cemented rock glaciers, which are essentially periglacial features. However, this generalisation does not always hold because some ice-cored rock glaciers can form by the periglacial deformation of recently deglaciated ice-cored moraines (e.g. Barsch, 1971).

It has been shown that some rock glaciers are debris-covered glaciers, as evidenced by glacier ice exposures in rock glaciers in the Colorado Front Range, USA (Outcalt and Benedict, 1965; White, 1975), Yukon Territory, Canada (Johnson and Lacasse, 1988) and in Iceland (Whalley *et al.*, 1994). Ice-cored rock glaciers may be produced by climatic amelioration and the overloading of a retreating glacier (Morris and Olyphant, 1990). However, the evidence supporting a role for permafrost is considerable. The main evidence tends to be from geophysical investigations (e.g. Barsch, 1973; Fisch *et al.*, 1977; Haeberli, 1985; Barsch and King, 1989; Evin and Fabre, 1990) and drilling operations (Barsch *et al.*, 1979; Vonder Mühll and Haeberli, 1990) and does seem to show the presence of interstitial ice (ice-cemented) rather than an ice-core in many modern rock glaciers. Morris and Olyphant (1990) suggest that ice-cemented rock glaciers form when conditions are sufficiently cold and wet to produce an ice matrix within rockfall debris but insufficient to promote positive mass balance. It is also generally accepted that in some contexts both kinds of ice can be present in rock glaciers, as noted earlier where ice-cored rock glaciers can form by the periglacial deformation of recently deglaciated ice-cored moraines. However, it is important to appreciate that measurements and observations show that permafrost is *always* associated with rock glaciers (Evin and Fabre, 1990).

Rock glaciers can be classified following the approach of Barsch (1996) who recognised *debris* rock glaciers and *talus* rock glaciers. This approach is by no means exclusive and several different models have been proposed in explaining rock glacier formation in different localities. Indeed it is often difficult, especially with regard to relict rock glaciers, to be certain of the exact mode of formation. What is important when reconstructing palaeoclimates on the basis of rock glacier evidence is that climatic assumptions hold even where different modes of formation can be envisaged.

Debris rock glaciers often form below glaciers (Fig. 2A). According to Barsch (1988), during times of maximum glacial advance the deposited moraines act as a 'rooting zone' for a rock glacier, which develops from this debris below the glacier. This type of rock glacier can be identified where the cirque basin displays erosional evidence and a distinct morainic lobe (the rock glacier) has formed on the distal side of the moraine and the lip of the cirque. A modern example of this type is the rock glacier in the Cirque de Marinet in the French Alps (Evin and Fabre, 1990, fig. 8). Debris rock glaciers can also form where a glacier retreats into a high-walled cirque and becomes buried owing to high debris supply resulting from frost-shattering of the surrounding rockwalls (Johnson, 1980, 1987; Morris and Olyphant, 1990; Benn and Evans, 1998, pp. 257–258). In this case the rock glacier has evolved as a result of both glacial and periglacial processes and the fossil rock glacier will not necessarily represent the most severe stage of climate. *Talus rock glaciers* form below talus slopes and are built up by layers of coarse colluvial debris. Their ice content is derived from snowmelt as well as from avalanches, which are incorporated into the rock glacier (Fig. 2B).

Rock glaciers of Mount Tymphi—the field evidence

Most of the relict rock glaciers on Mount Tymphi occur in the north-facing cirques, although one isolated example occurs on the southern slopes. The rock glacier localities are numbered on Fig. 3 and are described in numerical order below.

1 In the vast amphitheatre containing the Tsouka Rossa cirques, a well-developed lobate fossil rock glacier is preserved extending down to a height of 2000 m a.s.l. (Fig. 4). The feature has a steep distal scarp and its surface is characterised by boulder-covered transverse ridges. In the four higher subsidiary cirques, end moraines are evident and it would appear that the landform below is a former debris rock glacier. The moraines of the small cirque glaciers possibly provided the 'rooting zone' of this rock glacier. In this model, the small cirque glaciers continually add debris to the rooting zone and the debris moves downslope owing to the action of permafrost (cf. Barsch, 1988, 1996). As cirque moraines exist above the rock glacier and appear to have been the debris source, it is probable that the cirque glaciers and rock glacier existed contemporaneously.

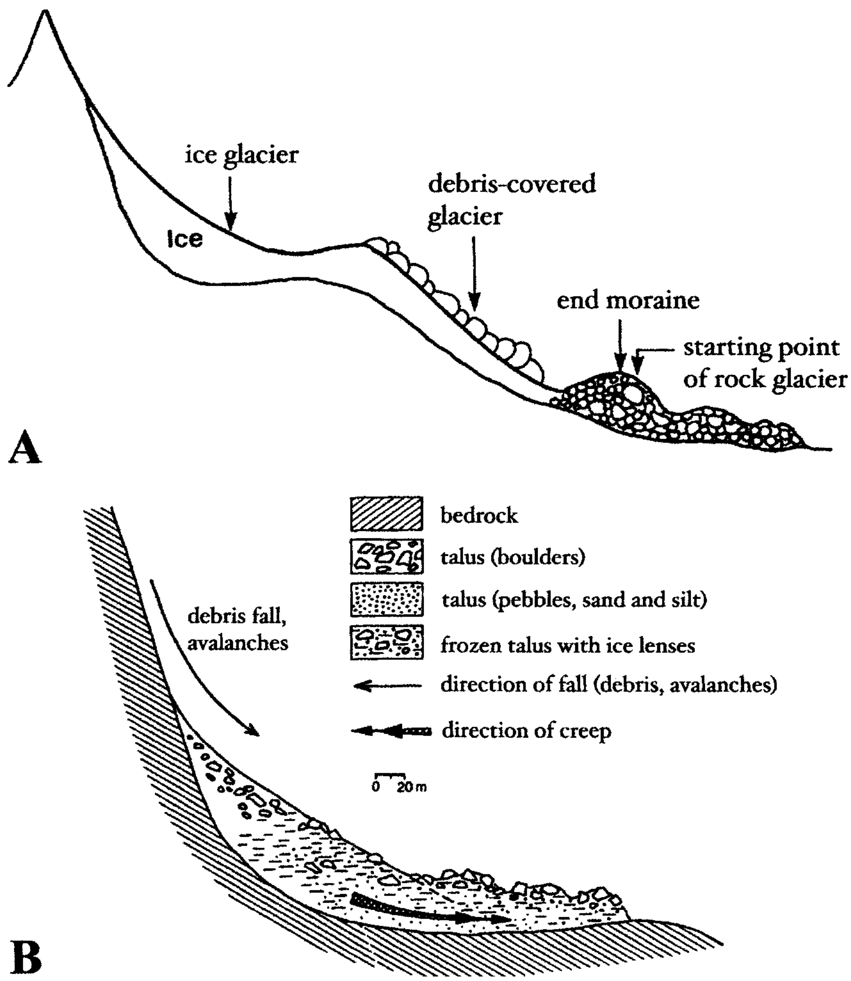

Figure 2 The formation of debris rock glaciers is illustrated in A and the formation of talus rock glaciers in B. Both are periglacial forms. (Adapted from Barsch 1988)

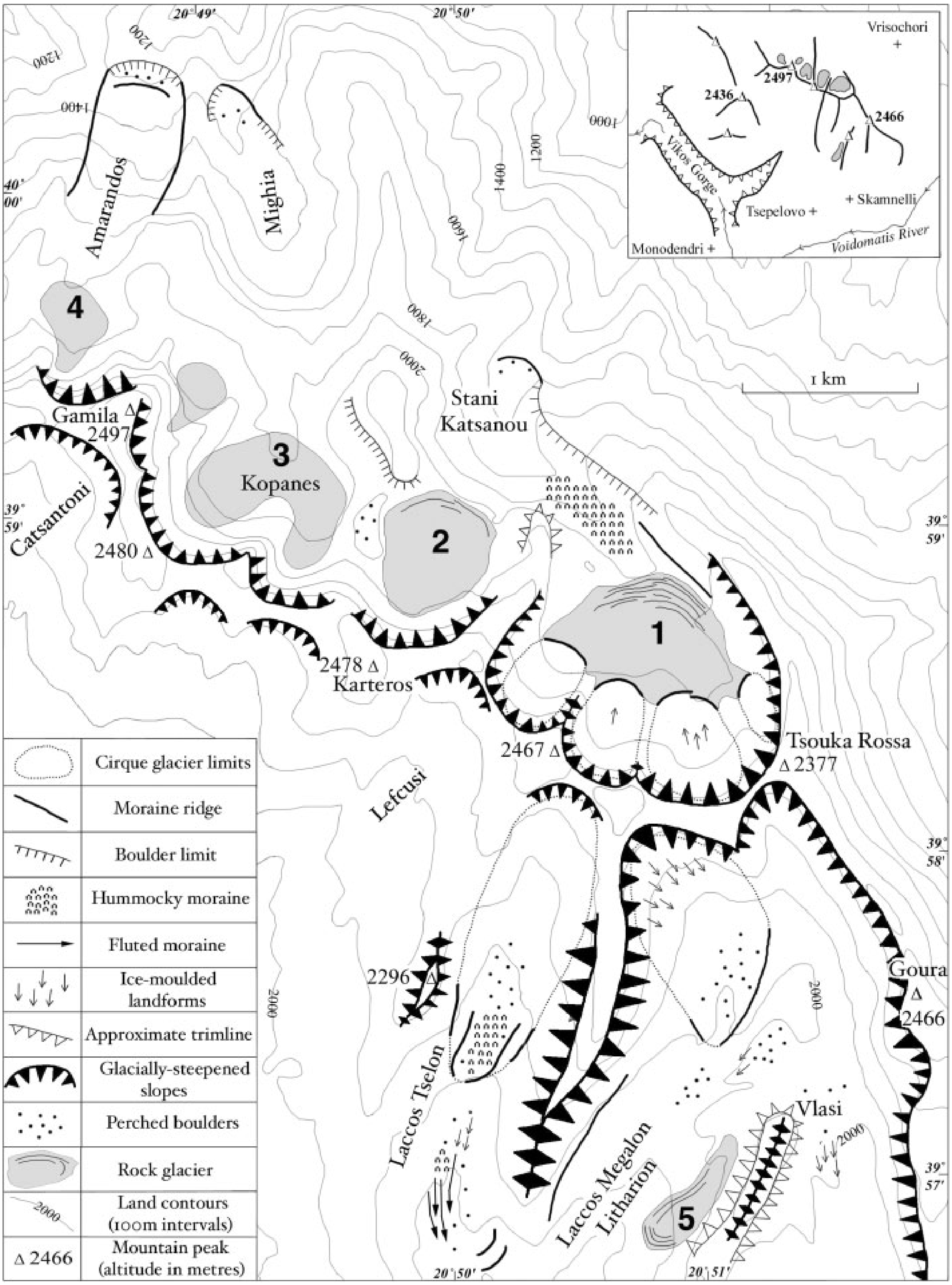

Figure 3 Geomorphological map of the main ridge of Mount Tymphi showing the locations of the rock glaciers (numbered 1 to 5) described in the text. The base maps were ex-Soviet Edition 1 : 50 000 topographic sheets

2 The Karteros cirque also contains evidence of a fossil rock glacier in the form of a boulder-covered lobe with a steep distal scarp extending down to ca. 2020 m a.s.l. Transverse ridges are not as well developed as in the Tsouka Rossa cirques although they can still be discerned. Moreover, no glacial moraines are evident in the upper parts of the cirque. The landform extends from the base of extensive scree slopes and it would therefore appear likely that the feature is a talus rock glacier (cf. Barsch, 1988, 1996). The surface clasts are larger and more angular than those on the Tsouka Rossa rock glacier, reflecting the different origin of the debris material—directly from talus rather than from glacially derived sediments.

3 In the Kopanes cirques angular boulder lobes, with steep distal slopes, are evident extending from the base of scree slopes. They are interpreted as talus rock glaciers and occur down to ca. 1900 m a.s.l. A slightly higher rock glacier is also evident in the small cirque to the northeast of the Gamila peak (2497 m a.s.l.). Again, this feature extends as a lobate tongue from the base of a scree slope and is most

Figure 4 Part of the Tsouka Rossa rock glacier 1 viewed from the north. (Photograph taken by P. D. Hughes, July 2001)

likely to have formed as a result of debris creep owing to permafrost.

4 In the upper cirque of the Amarandos valley, a boulder lobe is present and is similar to the talus rock glaciers of the Kopanes and Karteros cirques. This feature extends down to ca. 1800 m a.s.l. and as cirque moraines are absent the field evidence suggests that this is also a talus rock glacier.

5 A relict rock glacier is present on the western slopes of the subsidiary peak known as Vlasi, on the south side of Mount Tymphi (Fig. 5). Several boulder ridges are present and the proximal planform morphology is lobate extending down to ca. 1850 m a.s.l. The whole feature is dominated by coarse angular debris and it has also retained much of the original form, indicating that the original feature was debris-dominated rather than merely a debris-covered glacier. The position of the landform at the base of a steep sidewall indicates that the sediments are of colluvial origin. The well-developed transverse ridges, the steep lobate front and the fact that the feature appears morphologically distinct from downslope glacial deposits precludes the possibility that the feature could represent recessional moraines. Also, the short distance from the backwall would not have accommodated a glacier of sufficient size to produce such large marginal moraine ridges. If ice had been present then we would expect to find a much larger and deeper depression behind the moraine ridges.

Elsewhere on Mount Tymphi, cirque moraines are evident in the upper reaches of the Laccos Tselon and Laccos Megalon Litharion valleys. These moraines occur at ca. 2000 m a.s.l. and are probably contemporaneous with the cirque moraines of the Tsouka Rossa cirques and the rock glaciers described in this paper. In total, there is evidence for six cirque glaciers in the central part of the Mount Tymphi massif—four of which existed directly above the Tsouka Rossa rock glacier (rock glacier 1). Pronival ramparts (cf. Shakesby, 1997) are also evident at lower altitudes at the base of the great northeastern escarpment of Goura (2466 m a.s.l.) and Tsouka Rossa (2377 m a.s.l.).

The age of the rock glaciers

The rock glaciers we have described represent the most recent large-scale cold-climate landforms on Mount Tymphi. In this section we argue that these landforms, and the associated climatic conditions described below, represent those of the last major cold period in Greece—the Last Glacial Maximum (LGM) during the Late Würmian Substage. The coldest phase of climate during this period may have occurred slightly before the global LGM, at ca. 21 000–22 000 ^{14}C yr BP and may equate to Heinrich Event 2 in the North Atlantic (Galanidou *et al.*, 1999). It could be argued, however, that they formed within the Late-glacial period or during the earlier part of the Würmian, but the existing evidence points to a LGM age. The arguments in favour of this are presented below:

1 If the rock glaciers and associated moraines belong to the Late-glacial, then this would leave a major hiatus in the Late Pleistocene record on Mount Tymphi. Similarly, if the features formed during the earlier Würmian then it would leave an unlikely absence of cold climate landforms during MIS 2. The glacial terrain immediately downslope on Mount Tymphi is characterised by very well-preserved moraine complexes that pre-date the global LGM by at least 60 kyr and a suite of U-series dates from cemented tills (Table 1) has shown that they were deposited before MIS 5 (Woodward *et al.*, in press; Hughes *et al.*, unpublished data). Marine oxygen isotope stage 2 is represented by a severe climatic deterioration in all the long pollen records in Greece (Tzedakis *et al.*, 1997) and by a major episode of alluviation in the Voidomatis River driven by an increase in

Figure 5 The Vlasi rock glacier 5 viewed from the south. (Photograph taken by P. D. Hughes, April 2002)

sediment supply (Macklin *et al*., 1997). These facts suggest an LGM age for the rock glaciers.

2 At present, there is no clear agreement regarding the climatic severity of the Younger Dryas in the eastern Mediterranean. Moreover, it can be argued that this period was of insufficient duration to allow the formation of the large-scale rock glaciers on Mount Tymphi described above. According to Bottema (1995), the Younger Dryas event is poorly represented in the eastern Mediterranean pollen records and cannot be discerned as a severe deterioration in climate. Rossignol-Strick (1995), on the other hand, argues for a cold and arid Younger Dryas on the basis of sea–land correlations of pollen records in the eastern Mediterranean. Some evidence of climatic deterioration during the Younger Dryas is also provided in the rockshelter sediments of Theopetra in Thessaly, Greece (Karkanas, 2001). However, even if marked cooling did characterise the Younger Dryas in Greece, the rock-glacier-based temperature reconstruction presented below would imply that the period of rock glacier formation was as cold as that suggested for the Last Glacial Maximum.

Palaeoclimatic implications

In the Swiss and Italian Alps, active modern rock glaciers indicate the presence of discontinuous mountain permafrost and are found only in areas where the mean annual temperature is less than −2 °C (Fisch *et al*., 1977; Barsch, 1978; Belloni *et al*., 1988; Carton *et al*., 1988). This fact was utilised in reconstructing palaeotemperatures from relict rock glaciers by Kerschner (1978, 1983) in the Tyrolean Alps, Austria, and by Girauldi and Frezzotti (1997) in the Italian Appennines at a latitude of 42°50′N. A similar approach was used in this study on Mount Tymphi and a mean annual temperature of −2 °C can be estimated for the lowest altitude of the rock glaciers at the time of their activity.

The rock glaciers of Tymphi all occur above 1800 m a.s.l. in the high cirques of Mount Timfi. In the Tsouka Rossa cirque, it is assumed that they formed below cirque glaciers and it is likely that all of the Tymphi rock glaciers were coeval with the most recent small cirque glaciers that formed in the Laccos Tselon and Megalon Litharion cirques (Fig. 3). The altitudes of the Tymphi rock glaciers are similar to the other documented rock glacier in Greece found on Mount Parnassus, (ca. 200 km to the southeast), which has its terminus just beneath the 2000 m contour (Pechoux, 1970). If these rock glaciers are contemporaneous, this implies similar climatic conditions throughout the Pindus range.

The reconstructed temperature at the lowest altitude of the relict rock glaciers (ca. 1800 m) can be compared with the modern-day mean annual temperatures. At nearby Ioannina, at an altitude of 484 m a.s.l., the modern mean annual temperature is 14.4 °C (National Statistical Service of Greece, 1981). During the LGM, if the mean annual temperature at 1800 m was ca. −2 °C then at 484 m a.s.l. (the altitude of Ioannina) the mean annual temperature would have been ca. 6 °C assuming a lapse rate of 0.6 °C per 100 m. This implies an 8–9 °C depression of mean annual temperature compared with the present at the time of rock glacier formation. However, this is derived using a standard lapse rate for the troposphere (Barry and Chorley, 1996; Whiteman, 2000) and a range of environmental lapse rates are possible under periglacial conditions. As a result, temperature reconstructions can only be viewed as approximate.

The mean annual temperature reconstruction given above, where temperatures were 8–9 °C lower than present, sits within the 7–10 °C depression during the LGM as determined by the nested climatic model used by Tzedakis *et al*. (2002). This temperature reconstruction is also similar to the estimate for the Italian Appennines during the Late Würmian using a similar technique to that adopted in this paper (cf. Girauldi and Frezzotti, 1997). Based on the presence of rock glaciers, correlated with glacial moraines dated to the Last Glacial Maximum, Girauldi and Frezzotti (1997) derived palaeotemperatures of 7.3–8.3 °C lower than present. These Italian rock glaciers occur at a minimum altitude of 1660 m, 130 m lower than the minimum altitude on Mount Tymphi, as would be expected given that they are 2°30′ further north. In addition, a further two generations of rock glacier are also evident in the Italian Appennines; the latter occur at higher altitudes and are attributed to the Würmian Late-glacial. Equivalent features are absent from Tymphi probably because of lower elevations and the more southerly latitude.

As well as providing information on palaeotemperatures, the presence of rock glaciers indicates a continental climate where precipitation values are lower than 2500 mm (Haeberli, 1985; Belloni *et al.*, 1988). If precipitation levels were higher then glaciers would form. Glaciers often form above rock glaciers, where temperatures are lower, offsetting low rates of accumulation. This is the reason why glaciers on Tymphi provided the moraine 'root' from which the rock glacier in the Tsouka Rossa cirque formed (rock glacier 1). The fact that small cirque glaciers existed above the Tsouka Rossa rock glacier and in the uppermost reaches of the Laccos Tselon and Laccos Megalon Litharion valleys indicates that although precipitation must have been low enough to preclude glacier extension down to lower altitudes, it was not so low as to inhibit ice build-up entirely. This implies that climate was characterised by moderate rather than severe aridity. This is illustrated by the fact that aboreal populations are preserved during the LGM at Ioannina (Tzedakis, 1993). Climate modelling presented in Tzedakis *et al.* (2002) suggests that precipitation, although being 545 mm less than today, was still above 600 mm with an equable distribution throughout the year. However, the fact that the LGM glaciers of Mount Tymphi were much less extensive than those during previous Pleistocene glaciations, where glaciers extended down to 850 m a.s.l. (Woodward *et al.*, in press; Hughes, unpublished data), indicates that earlier glacial phases were probably characterised by greater winter precipitation and/or lower temperatures during the ablation (summer) season.

Conclusions

The presence of relict rock glaciers in the high cirques of Mount Tymphi in the Pindus mountains of northwest Greece provides information regarding Late Pleistocene climates in this area. The features are of periglacial origin and can be classified, according to Barsch (1988, 1996), as talus and debris rock glaciers. Analogy with modern rock-glacier–climate relationships implies a depression of mean annual temperature at the time of formation of 8–9 °C compared with that of today. The rock glaciers are likely to have formed during the Last Glacial Maximum and the temperature reconstruction compares favourably with results of climatological models, and rock glacier evidence in the Italian Appennines. Similarly, the fact that rock glaciers tend to form in cold and relatively dry mountain environments is in good agreement with palaeobotanical and lake-level evidence for a cold and relatively arid climate at the Last Glacial Maximum during the Late Würmian Substage in Greece. The presence of small glaciers above the rock glaciers implies that although there was not sufficient winter accumulation to enable extension of these glaciers to lower altitudes, it was sufficient to enable limited glaciation of the highest cirques.

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