Pleistocene glacial history of Mount Olympus, Greece: Neotectonic uplift, equilibrium line elevations, and implications for climatic change

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Pleistocene glacial history of Mount Olympus, Greece: Neotectonic uplift, equilibrium line elevations, and implications for climatic change

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ABSTRACT

Evidence of former equilibrium line elevations on Mount Olympus, Greece, coupled with estimates of uplift rate, point to more extensive Pleistocene glaciation and far colder climates than previous studies have indicated. These findings are supported by the record of glacial deposition both on the mountain and across the adjacent piedmont. The data not only provide evidence of significant equilibrium line altitude depression from a present-day elevation as much as 600 m above the mountain's summit (2917 m), but also show that Mount Olympus was glaciated on several occasions, and that the first episode of glaciation significantly predated the late Pleistocene.

Piedmont sediments east and west of Mount Olympus record three discrete stages of deposition, each of which can be related to glacial activity on the mountain. Soils that separate these sedimentary units correspond to nonglacial intervals and can be correlated to a dated soil succession south of Olympus. This correlation suggests that the oldest soils correspond to the isotope stage 7 (Mindel/Riss) interglacial event (ca. 210,000 yr before present; U/Th disequilibrium) and that the oldest Pleistocene sediments record isotope stage 8 (Mindel) glaciation in the Olympus region. Subsequent stages of deposition are interpreted to record glaciation on the mountain during the isotope stage 6 (Riss) and isotope stages 4–2 (Würm) glacial events.

Sedimentary units defined on the piedmont are also recognized on the Olympus upland and within valley-head cirques, where they correspond to three stages of cirque development. The distribution of these materials, as well as the occurrence of glacial erosional and depositional landforms, indicates that Mount Olympus supported upland ice during the first and second episodes of glaciation and that the first glaciation was sufficiently extensive to produce piedmont ice lobes that covered parts of the eastern, northern, and western piedmont of the mountain.

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Uplift-corrected cirque floor elevations, coupled with the distribution of glacial sediments, indicate that the Pleistocene equilibrium line altitude during each episode of glaciation was depressed at least 1400–1500 m, to elevations of 2000–2100 m asl (present). Assuming that lowering of the equilibrium line was solely a function of temperature, this would correspond to a mean annual temperature decrease of 8–9 ∞C. This contrasts with previous studies of the Mount Olympus region, which suggest that glaciation was restricted to small valley glaciers in upland and valley-head positions, that the regional Pleistocene equilibrium line was lowered only to elevations of 2200–2400 m above present sea level (asl), and that active glaciation was restricted to the latest Pleistocene (Würm). Study of the neotectonic history of Mount Olympus suggests that uplift persisted throughout the mid-Pleistocene–Holocene at a rate of ~1.6 m/k.y

Keywords: Pleistocene glaciation, Mount Olympus, neotectonics, equilibrium line, Greece

INTRODUCTION

The reconstruction of past cold climates based on geologic evidence of former glaciation depends not only on determining the previous extent of ice in an area, but also on quantifying the degree to which the regional snow line or equilibrium line (i.e., the line above which annual snow accumulation exceeds ablation) was lowered in accord with the accompanying temperature decrease and/or increasing snowfall (e.g., Menzies, 1996). The former is achieved through the delineation and interpretation of the occurrence of features produced by glacial erosion and deposition. More detailed analysis of the morphology of these features and the stratigraphy of the deposits provides the means to reconstruct the sequence of past glacial events. However, the ability to reconstruct the magnitude of the temperature decrease that gave rise to glacial conditions is largely dependent upon the ability to reconstruct the position of the equilibrium line relative to its modern elevation during any given episode of glaciation. For small glaciers, the position of the equilibrium line is approximated by the elevation of the floors of cirque basins, the theaterlike hollows in which the glaciers developed. Thus, the ability to determine the position of a former equilibrium line for small glaciers depends on the accuracy with which cirque basins and their elevations can be mapped and measured. In areas of active tectonics, these elevations must be additionally corrected to account for any uplift and/or subsidence that have occurred since glaciation. Mapping of former equilibrium lines for more extensive glaciers is more complex (e.g., Benn and Evans, 1998) and utilizes a variety of techniques depending on the degree to which the extent of the former glacier is known. Where the three-dimensional form of the glacier can be reconstructed, the equilibrium line altitude can be determined using either the accumulation area ratio method, which assumes that the glacier's accumulation area occupied some fixed proportion of its total area, or the balance ratio method, which makes use of the fact that total accumulation above the equilibrium line must annually balance the total ablation below it. Where the extent of former glaciation is poorly constrained, as is the case in this study, equilibrium line altitudes can be approximated either from the maximum elevation of lateral moraines or by setting the elevation at some fixed ratio between the toe of the glacier and the top of the valley headwall.

Mount Olympus, the highest mountain in Greece, is particularly well suited to the study of past glacial climates. It is a relatively isolated mountain massif that is not currently glaciated, the 0 °C isotherm lying close to 3500 m above present sea level (asl) (Messerli, 1967), or nearly 600 m above the summit (2917 m). It is separated from mountains to the north (the High Pieria Mountains) and south (Mount Ossa) and is bounded on the east and west by the Aegean coastal plain and the Plains of Thessaly, respectively (Fig. 1). It is located in a maritime climate within 25 km of the Aegean coast and within 100 km of seawater over 400 m deep. It is therefore in proximity to an ample source of precipitation and would have been even in glacial times. It is also influenced by prevailing westerly storm systems from northern and central Europe. The juxtaposition of the maritime influence of the Aegean Sea and the southerly and westerly movement of weather systems from northern Europe produces a high frequency of storms and a high level of annual precipitation. Annual precipitation statistics are not available for the Olympus massif, but exceed 600 mm in Kozani on the northern flank of the High Pieria Mountains. Hence, Mount Olympus, by virtue of its topographic setting and the conditions of the local meteorology, is a logical setting for the study of former glacial conditions.

Other studies in Greece and on the adjacent Aegean continental shelf clearly indicate that glacial conditions (and related botanical changes and shifts in sedimentary depositional regimes) occurred throughout the northeastern Mediterranean region during the late Quaternary (e.g., Lewin et al., 1991; Prentice et al., 1992; Tzedakis, 1993; Bottema, 1995; Rossignol-Strick, 1995; Karkanas, 2001; Okuda et al., 2001; Hughes et al., 2003). The record of Alpine glaciation in Greece, however, is sparse, and much of the early research (e.g., Wiche, 1956a,b; Messerli, 1966a,b, 1967; Faugères, 1969) suggested that mountains such as Mount Olympus experienced glaciation of very

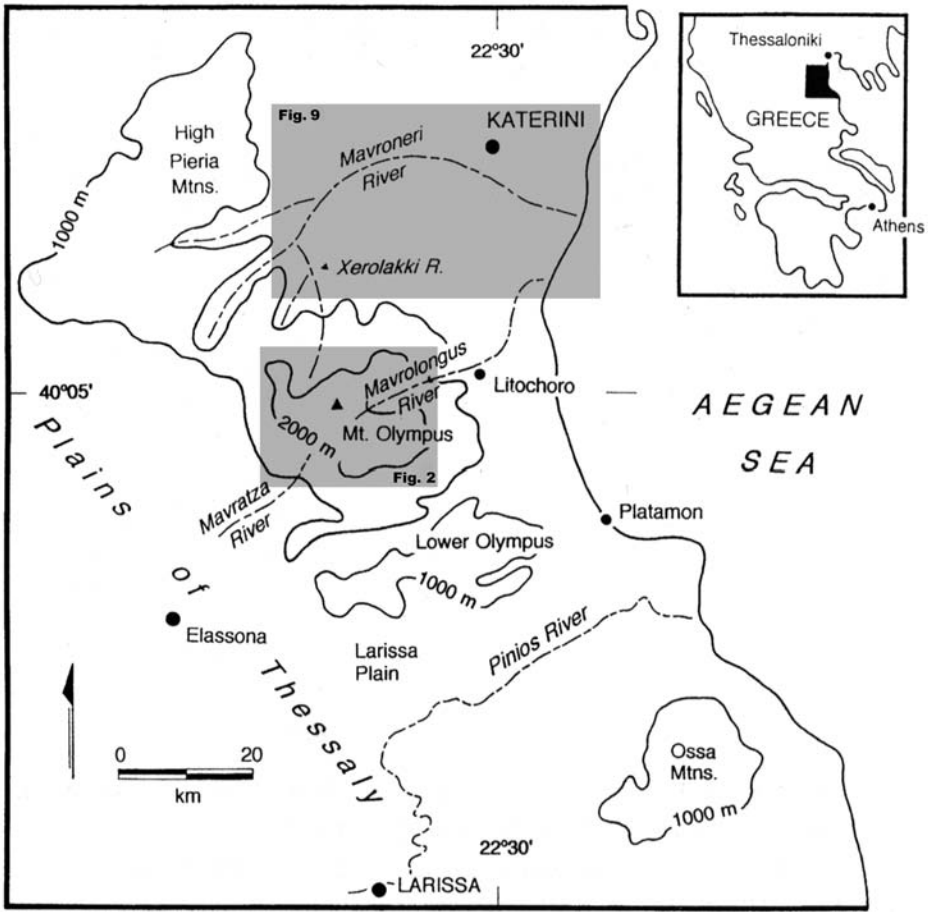


Figure 1. Location map of Mount Olympus, Greece, showing major towns and rivers. The shaded areas outline the locations of Figures 2 and 9.

limited extent during that period, and then only during the latest Pleistocene. The general lack of information on glaciation of the mountains of Greece, coupled with the unique setting of Mount Olympus, led to development of the present study. Details of the sedimentological and geomorphic evidence for the glaciation of Mount Olympus and the correlations used to establish its temporal framework accompany Smith et al. (1997). Hence, they are only briefly summarized in this article, which focuses instead on our efforts to determine equilibrium line altitudes and on their potential implications for Pleistocene climate change in the eastern Mediterranean.

PHYSICAL SETTING OF MOUNT OLYMPUS

Mount Olympus is situated in northeastern mainland Greece, ~265 km northwest of Athens and 60 km southwest of Thessaloniki. The mountain is 2917 m high and covers an area of roughly 300 km^2 at its base (Fig. 1). A succession of studies over the past three decades (e.g., Godfriaux, 1968; Barton, 1975; Schmitt, 1983; Latsoudas, 1985; Katsikatsos and Migiros, 1987; Schermer, 1990; Schermer et al., 1990) have shown that the upland massif that comprises Mount Olympus consists of a metamorphosed and deformed sequence of Triassic and Cretaceous to Paleogene continental shelf limestones deposited discontinuously between ca. 250 and 50 Ma. During the Eocene (ca. 40 Ma), these rocks were tectonically overridden by a series of thrust sheets consisting of metamorphosed continental margin sediments, basement gneisses, granites, and metamorphic rocks and also ophiolitic rocks that represent fragments of ancient ocean floor. Neogene to Holocene normal faulting over the past 20 m.y. facilitated uplift of the mountain massif and subsequently exposed the Olympus carbonates in the form of a tectonic window through the overlying stack of thrust sheets. The High Pieria Mountains, northeast of Mount Olympus, are underlain by late Paleozoic granites and metamorphic rocks generally older than 300 Ma (Yarwood and Aftalion, 1976; Nance, 1981).

The mountain upland is a broad planar surface above which rise several conical peaks and into which are incised a number of shallow basins (Fig. 2). This roughly circular plateau is tilted to the southwest so that north- and east-facing valleys are more extensively developed than south- and west-facing valleys. The morphology of these valleys reflects a complex and repeated history of glaciation, tectonic uplift, and rapid fluvial erosion that occurred in such a way that the classic U shape of glacial valley profiles is generally lacking, despite clear depositional evidence of glaciation within the valleys. The mountain upland

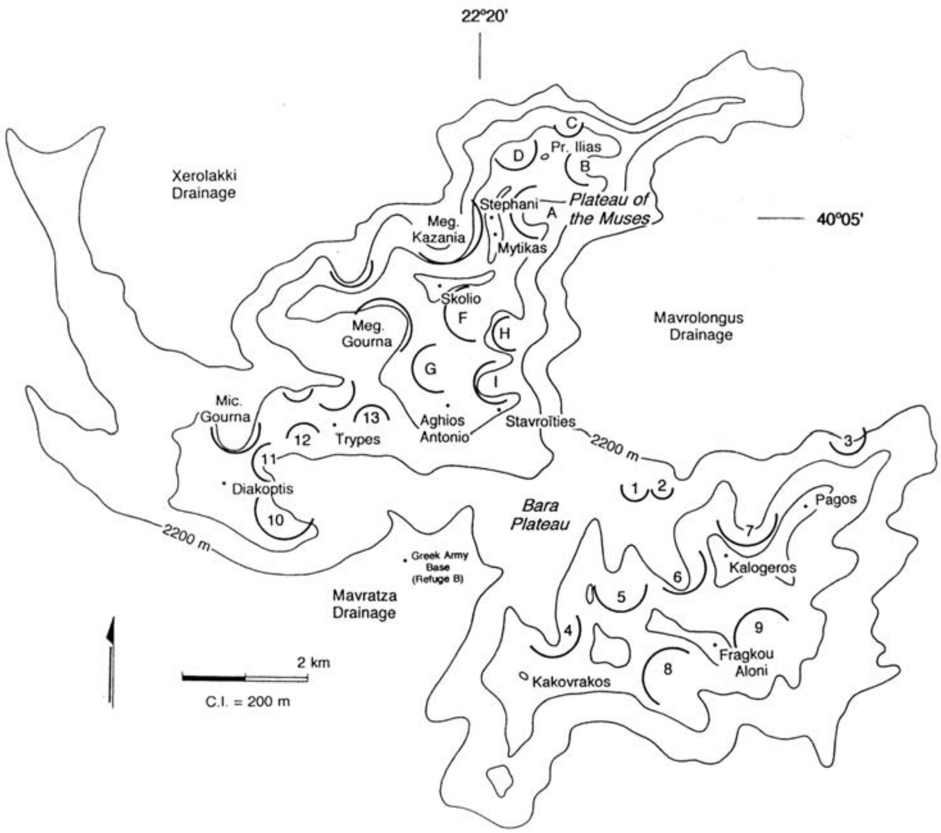


Figure 2. Geomorphic map of the Mount Olympus upland showing principal cirque basins, undissected upland areas, and major drainage systems (from Smith et al., 1997). Contour interval 200 m. See Figure 1 for location.

is surrounded by a broad piedmont slope that merges with the Aegean coastal plain on the east and extends to the Plains of Thessaly on the west. Well-developed alluvial fans dominate the geomorphology of the piedmont (Faugères, 1977; Psilovikos, 1981, 1984) and comprise a virtually unbroken alluvial apron along the eastern and western flanks of the mountain. Stream incision related to Neogene through Holocene uplift (e.g., Koukouvelas and Aydin, 2002) and changes of sea level (e.g., Lykousis, 1991) has produced a series of well-defined terraces within major valleys draining the upland.

EARLY VIEWS OF OLYMPUS GLACIAL HISTORY

Previous studies of the geomorphology and glacial history of Mount Olympus focused on both the upland plateau and the adjacent piedmont. Upland studies by Messerli (1966a,b, 1967) and Faugères (1977) indicated that Mount Olympus had been glaciated in the past. However, both concluded that glaciation of the mountain was restricted to the latest Pleistocene and that glacial ice was limited to high elevations at the heads of valleys. These conclusions place serious restrictions on the amount of equilibrium line depression that could have occurred during the Pleistocene and imply a single, rather recent, episode of glaciation in which the equilibrium line was depressed to an elevation no lower than ~2200 m asl.

Previous studies by Faugères (1977) and Psilovikos (1981, 1984), primarily on the eastern piedmont of Mount Olympus, demonstrated the occurrence of three discrete sedimentary units (units 1–3) that record deposition during the Quaternary. These units have been considered alluvial fan deposits that reflect deposition under a variety of climatic regimes, but without any direct glacial influence. The fact that the piedmont sediments were viewed in terms of fluvial processes rather than direct glacial deposition placed further constraints on both the timing and the extent of glaciation on Mount Olympus. At the very least, these studies imply that glacial ice never extended onto the eastern piedmont of the mountain.

A NEW MODEL FOR GLACIATION

These early views of the timing and extent of glaciation on Mount Olympus differ markedly from those proposed by Smith et al. (1997) based on a detailed re-examination of the mountain's upland and eastern piedmont and field reconnaissance of areas to the north and west. The results of this four-year project suggest that previous workers had failed to recognize a broad spectrum of erosional and depositional features, both on the upland and on the piedmont, that are clear testament to Pleistocene glacial activity on Mount Olympus. As a result, previous studies substantially underestimated both the areal and the temporal extent of glaciation in this region; the implication is that previous paleoclimatic reconstructions for northern Greece and the eastern Mediterranean (e.g., Emiliani, 1955; Farrand, 1971) are incorrect and need to be revised.

The principal results of this study, which are summarized later, indicate that (1) Mount Olympus was glaciated on at least three separate occasions from mid- to late Pleistocene time; (2) the glaciation was sufficiently extensive to produce ice that covered the uplands, filled major valleys, and spread as broad lobes onto the adjacent piedmont; (3) soils developed on the deposits of glaciation during each episode can be correlated with a dated soil succession south of the Olympus massif to provide a chronology for glaciation; and (4) events on Mount Olympus can be correlated with other terrestrial and marine records of Pleistocene climatic change.

Timing of Glaciation

According to Smith et al. (1997), evidence for the number of glacial episodes that have affected Mount Olympus is to be found both on the upland and on the adjacent piedmont and corroborates the three-part subdivision of sedimentary units on the eastern piedmont (units 1–3) originally defined by Faugères (1977) and Psilovikos (1981, 1984). These units can be recognized throughout the Mount Olympus area, not only on the eastern piedmont, but also on the uplands and on the northern and western piedmont slopes (Fig. 3). Furthermore, each of these units is capped by a distinctive soil (or soils) that records an interval of nondeposition and terrestrial weathering. These soils, which had not been generally recognized by previous workers, proved to be the most reliable features for establishing correlations between piedmont deposits and upland deposits and between eastern piedmont deposits and those of the southern, northern, and western piedmonts.

Smith et al. (1997) describe stratigraphic sections on the eastern, northern, and western piedmonts and on the mountain upland. In addition, measured soil profiles representing soils from each of the three sedimentary units are described at eleven localities on the eastern and northern piedmonts (Figs. 4 and 5). Establishment of a Harden profile development index (a measure of soil maturity; Harden, 1982) for each of the soil profiles (Fig. 4B) provides the basis for defining a relative sequence of the soils. It also allows for correlation of soils from one locality to those from another and constitutes the basis for dating the sediment-soil sequence.

The results of the stratigraphic studies and soil analyses described by Smith et al. (1997) indicate several points. (1) Sedimentary units record periods of active deposition under both glacial and nonglacial conditions both on the piedmont and on the upland. Direct glacial deposits can be distinguished from glacier marginal deposits, proglacial (meltwater) deposits, and nonglacial (fluvial) deposits on the piedmont on the basis of texture, sorting, fabric, and geometry. The great majority of upland sediments are direct glacial deposits. (2) Soils (and groups of soils) that record intervals of nondeposition and nonglacial weathering conditions can be associated with specific sedimentary units and can be correlated throughout the piedmont and from piedmont to upland. Based on profile development indexes, the soils (and the sediments with which they are associated) can be placed into a relative time framework (Table 1). (3) Soils and/or sediments of the eastern piedmont can be correlated with a soil sequence south of Mount Olympus dated on the basis of U/Th disequilibrium by Demitrack (1986). As a result, a tentative absolute framework for depositional and soil-forming events in the Mount Olympus region can be established (Table 1). This scale is consistent with that established for Mount Tymphi, less than 150 km west of Mount Olympus, on the basis of U-Pb series dating of calcretes (Hughes et al., 2003).

The correlation between soils of the eastern piedmont and dated soils of the southern piedmont (Larissa Plain) proposed by Smith et al. (1997) is based on two main considerations. First, a relatively young surface soil from the southern piedmont (the Rodia Narrows, Fig. 4A), dated on the basis of U/Th disequilibrium by Demitrack (1986) at ca. 54,000 yr before present (BP), yielded a profile development index (PDI = 27) that lay between the indexes for the surface soils of unit 3 (PDI = 5–13) and unit 2 (PDI = 38) of the eastern piedmont (Fig. 4B). As a result, Smith et al. (1997) concluded that the profile for the Rodia Narrows soil from the southern piedmont was equivalent to one of two buried partial soil profiles within the unit 3 sediments of the eastern piedmont. Furthermore, the date of ca. 54,000 yr BP for the soil places it in oxygen isotope stage 3 of the marine record, that is, in the middle portion of last (late Pleistocene) ice age (Würm in Alpine Europe and Wisconsinan in North America). Therefore, they suggested that the unit 3 sediments record deposition during the Würm (Wisconsinan) glaciation and that the Rodia Narrows soil and the surface soils of the eastern piedmont record interstadial (minor retreat or stillstand) and postglacial (Holocene) events associated with this glacial episode.

Second, a mature soil described by Demitrack (1986) on fan remnants of the southern piedmont proved to be very similar to the oldest soils (PDI >73) developed on unit 1 deposits of the eastern piedmont. Both soils have thick and complex profiles, they are both clay-enriched and display optimal B horizon structural development, and they are both strongly rubified (reddened); the colors of the eastern piedmont soils range between 2.5YR 3/6 and 5YR 4/4 (Smith et al., 1997). Demitrack (1986) obtained a U/Th disequilibrium age of ca. 210,000 yr BP for the soil from the southern piedmont, placing it in oxygen isotope stage 7 of the marine record, that is, in the interglacial period preceding the major glacial advance known as the Riss in Alpine Europe and the Illinoisan in North America. On the basis of this correlation, Smith et al. (1997) suggest that the unit 1 soil of the eastern piedmont represents isotope stage 7 and that the unit 1 sediments on which the soil is developed record deposition during isotope stage 8, which chronicles an even earlier (pre-Illinoisan) glaciation corresponding to the Mindel of Alpine Europe. Overlying unit 2 sediments are considered to have been

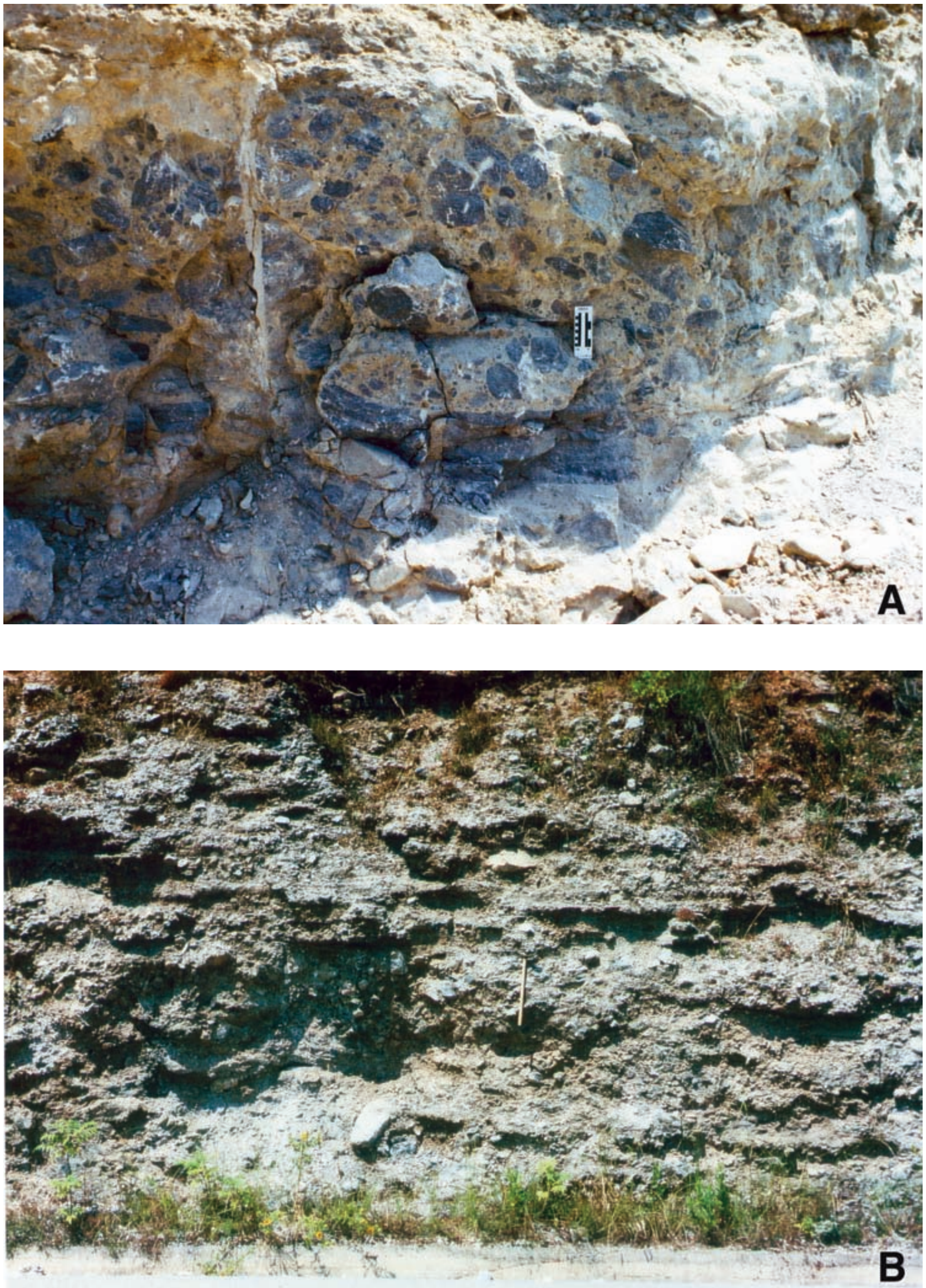
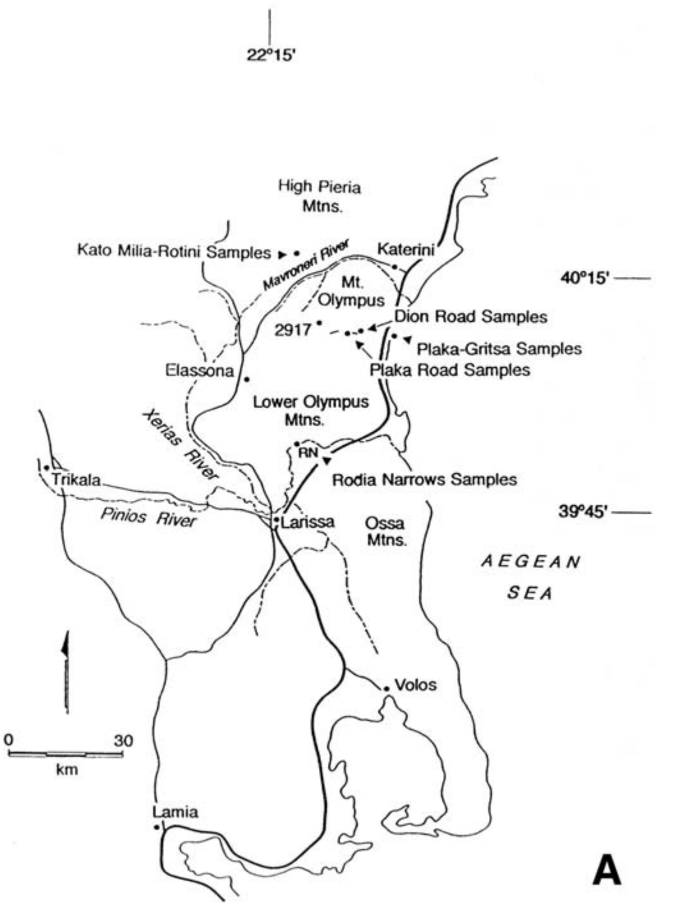


Figure 3. Pleistocene stratigraphic units of the Mount Olympus region. (A) Unit 1 deposits on the western piedmont in the vicinity of Kokkinopilos. (B) Unit 2 deposits in the Mavrolongus (Enipius) Valley north of Litochoro. (C) Unit 2 deposits on the Mount Olympus upland (Bara plateau) at the head of the Mavrolongus drainage. (D) Unit 3 deposits in the DEAL gravel pit east of Litochoro.

Figure 3. *Continued*



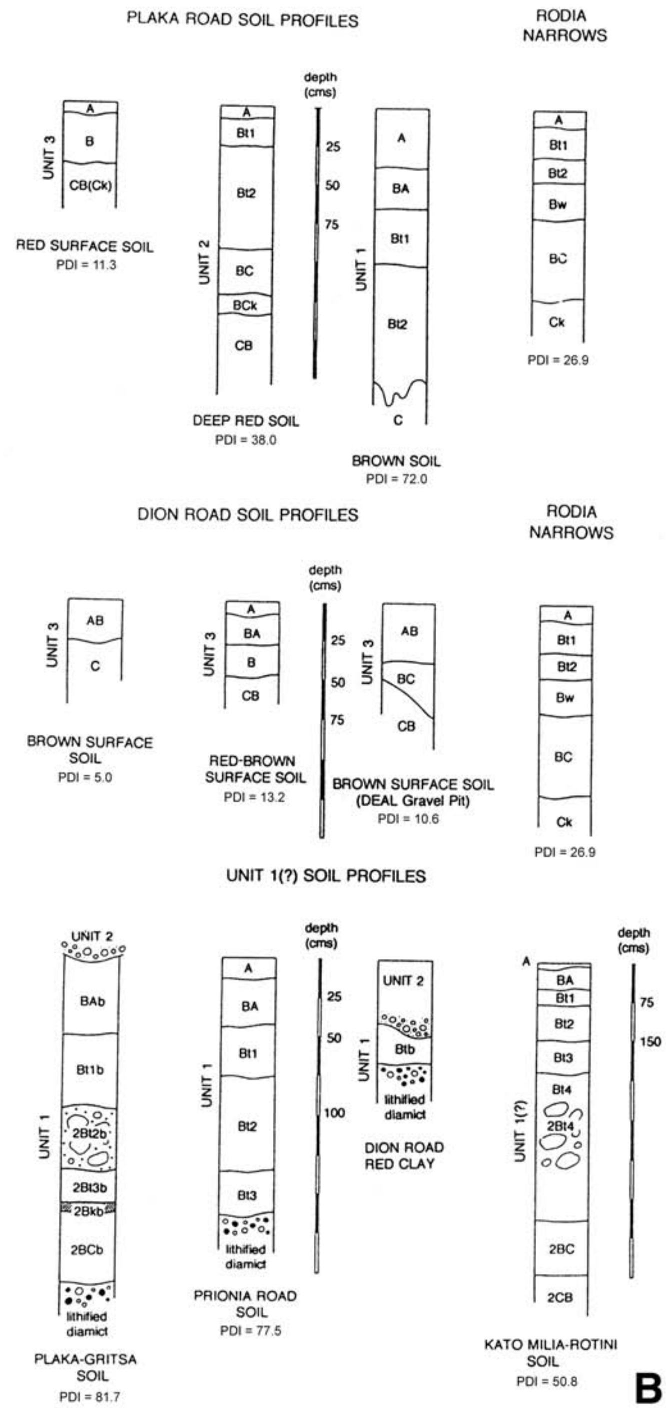


Figure 4. Soils of the Mount Olympus region (modified after Smith et al., 1997). (A) Location map. RN = Rodia Narrows. (B) Simplified soil profiles for soils of the eastern piedmont of Mount Olympus (including Plaka-Gritsa and Kato Milia–Rotini) and the Rodia Narrows (Larissa Plain). Top: Plaka Road profiles compared to Rodia Narrows (AA) profile. Center: Dion Road profiles compared to Rodia Narrows (AA) profile. Bottom: Other profiles from the eastern piedmont. PDI—soil profile development index after Harden (1982).

deposited during isotope stage 6, which records the Riss (Illinoisan) glaciation, and the soil(s) developed on these sediments are thought to have formed during isotope stage 5, the major interglacial episode that separates the glacial advances of the Riss (Illinoisan) and the Würm (Wisconsinan).

Cirque Morphology

Smith et al. (1997) further showed that the story of multiple glaciation and deglaciation recorded in the sediments and soils of the eastern piedmont is also reflected in the erosional and depositional features of the Mount Olympus upland. Upland cirques were mapped in terms of morphology (length, width, height), orientation, and basin elevation (Table 2), and their morphologic attributes were quantified according to a parameter of depth (y) to length (x)known as the k value ($y = k[1 - x]e^{-x}$; Haynes, 1968) in order to distinguish very old or very young cirques from mature cirques. Based on a consideration of all cirque characteristics, two groups of cirques are distinguished: upland cirques (subdued morphology, high basin elevation, variable orientation) and valley-head cirques (mature morphology, lower basin elevation, predominantly north and east orientation).

Figure 5. Field relations of eastern piedmont soils on (A) unit 1 (Prionia Road soil), (B) unit 2 (Plaka Brown soil), and (C) unit 3 (Dion Brown surface soil). See Figure 4 for locations, soil profiles, and profile development indexes.

Upland cirques proved to be complex features that record multiple stages of development and occupation. Younger cirques are commonly inset into older cirque basins, although some younger glaciers occupied old cirque basins without modifying the original cirque form. Sediments within cirques and over the upland surface are very similar in composition and degree of lithification to the unit 1–3 deposits described on the eastern piedmont and are considered laterally equivalent. Most are entirely coarse, poorly sorted sediments (Fig. 6) of demonstrated glacial origin and overlie glacially striated bedrock (Fig. 7).

On the other hand, valley-head cirques have a mature morphology, with well-defined headwalls and sidewalls and an

TABLE 1. ROCK AND SOIL STRATIGRAPHIES OF THE EASTERN PIEDMONT OF MOUNT OLYMPUS WITH CHRONOLOGY AND CORRELATION TO THE MARINE ISOTOPE RECORD PROPOSED BY SMITH ET AL. (1997)

Stratigraphy						
Local rock	Local soil	Local soil names	Index ranking of soils	Larissa plain soils	Age	Isotope stage
==== xxxx	Unit 3 surface soils	DEAL	11			———
		Dion Brown	10			1
		Plaka Red	9			———
		Dion Red Brown	8			
Unit 3	Unit 3 buried soils		7	Rodia Narrows “A-A”	54,000	2
‾‾‾‾ xxxx xxxx						3
						4
==== xxxx	Unit 2 surface soil	Plaka Brown	4			———
						5
						———
‾‾‾‾ xxxx	Unit 2 buried soil	Plaka Deep Red	6			
Unit 2						6
==== xxxx	Unit 1 soil	K. Milea-Rotini	5	Soil on fan remnants	210,000	———
		Prionia	3			7
		Plaka-Gritsa	2			———
		Dion Red Clay	1			
Unit 1						8

Notes: ====/xxxx indicates surface soil; ‾‾‾‾/xxxx indicates buried soil; ——— indicates interglacial period.

angularity of form that is not seen in the upland cirques. They occur at lower elevations on the mountain, and in general indicate, by virtue of morphology and basinal sediments, that they were developed and occupied by ice on only one occasion, in unit 3 time. Glacial deposits in one valley-head cirque, Megali Kazania, record glaciation during unit 1, unit 2, and unit 3 time. This cirque also contains glacial deposits that postdate those of unit 3 and are probably Neoglacial in age.

Smith et al. (1997) considered the erosional and depositional features on the Mount Olympus upland to record the fol-

TABLE 2. MORPHOLOGIC ATTRIBUTES OF CIRQUES OF THE MOUNT OLYMPUS UPLAND

		(meters asl)					
Cirque basin	Base elevation (meters asl)	Length	Width	Height	*K* value	Orientation	Designation
1	2430	700	900	260	0.749	Northwest	Upland cirque
2	2430	900	850	280	0.766	North	Upland cirque
3	2330	1000	1000	340	0.925	Northwest	Upland cirque
4	2280	850	850	400	1.100	North	Upland cirque
A	2540	640	500	160	0.849	East	Upland cirque
B	2600	510	550	80	0.272	North	Upland cirque
C	2670	410	500	80	0.205	North	Upland cirque
D	2560	440	500	130	0.364	North	Upland cirque
F	2650	750	600	160	1.376	North	Upland cirque
G	2640	760	500	120	1.058	Northeast	Valley head
H	2480	500	580	180	0.585	East	Valley head
I	2560	600	550	280	1.276	East	Valley head
Megali Kazan.	2200	1330	800	800	—*	Northwest	Valley head
Megali Gouma	2440	1260	900	360	—*	Southwest	Valley head

Source: From Smith et al. (1997).
Notes: Cirques listed are those numbered and lettered in Figure 2.
* Cirque k-values cannot be determined for these cirques, because they are composite forms that record multiple stages of occupation.

Figure 6. Glacial deposits of the Mount Olympus upland. These sediments occur at the mouth of cirque D (Fig. 2) and directly overlie the glacial striations shown in Figure 7.

lowing conditions. Glaciers developed and occupied cirques on the upland on two occasions, considered equivalent to unit 1 (isotope stage 8) and unit 2 (isotope stage 6) depositional events on the eastern piedmont. Glaciers spread over the upland surface, into major north-, east-, and west-draining valleys, and, in the case of unit 1, onto the adjacent piedmont (see subsequent discussion). In general, unit 2 cirques were developed within unit 1 cirques. Later, during unit 3 time, glaciers developed cirques at lower elevations at selected (north- and east-draining) valley heads. These glaciers were restricted to the mountain valleys and probably represent the glacial conditions described by previous workers.

Extent of Glaciation

The occurrence of glacial sediments and glacial erosional markings on the Mount Olympus upland led Smith et al. (1997) to conclude that during unit 1 time and unit 2 time, glaciers cov-

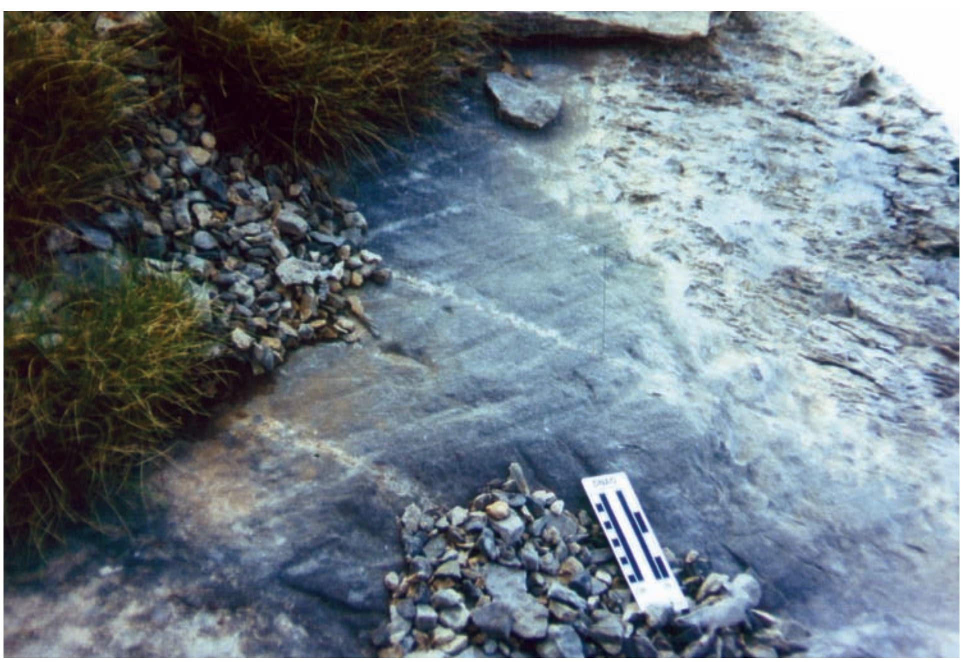


Figure 7. Glacial striations at the mouth of cirque D on the Mount Olympus upland. The striations indicate ice flow to the north, parallel to the valley axis.

ered the upland surface as a small ice cap. Ice spread from local cirque basins to merge as a coherent ice mass on plateau surfaces both north and east of the mountain summit. Upland ice fed valley glaciers that extended east, north, and west from the plateau surface. Available evidence, primarily in terms of the distribution of glacial sediments, suggests that unit 2 and unit 3 glaciers were restricted to terminal positions at valley mouth and mid-valley sites, respectively. Based on these criteria, it appears that unit 1 glaciers were much more expansive (Fig. 8).

Deposits of till (direct ice sediment) and outwash (meltwater sediment), and landforms such as moraines and outwash fans, were mapped by Smith et al. (1997) over broad areas of the eastern and northern piedmont. Of particular importance are the unit 1 deposits of the Mavrolongus (Enipius) River Valley and the Xerolakki-Mavroneri River Valley (see Fig. 1). Sediments in these localities consist of bouldery accumulations of till, sand, and gravel. The unit 1 deposits here define lobate (or elongate lobate) features that stand in topographic relief above surrounding deposits. Notably, particularly in the Xerolakki-Mavroneri Valley (Fig. 9), these lobate deposits consist of linear ridge forms that are symmetrically arranged about the axis of the present valley. These linear ridges consist of bouldery till with occasional shear planes (produced by active ice at the glacier margin) and grooved boulders (Fig. 10) and are considered lateral-terminal moraines (ice margin deposits). Elsewhere, the moraines consist of a basal till unit that is overlain by an upward-fining sequence of (glaci)fluvial sediments.

The piedmont glacial deposits of the Mavrolongus (Enipius) River Valley extend beneath younger (unit 2 and unit 3) deposits and are exposed at the base of steep bluffs along the present Aegean coastline east of Litochoro (Fig. 11). The glacial sediments of the Xerolakki-Mavroneri River Valley can be traced continuously from cirques on the north face of Mount Olympus to the vicinity of Katerini on the Aegean coastal plain (see Fig. 9). These latter deposits merge with sediments that can be traced directly into the High Pieria Mountains, north of Mount Olympus.

The implications of extensive piedmont glacial deposits east and north (and west) of Mount Olympus are significant. At the very least, the distribution of these deposits, well beyond the Mount Olympus upland and the cirques that served as sources for the piedmont glaciers, implies that the regional equilibrium line during unit 1 time was significantly lower than any estimate indicated in previous studies.

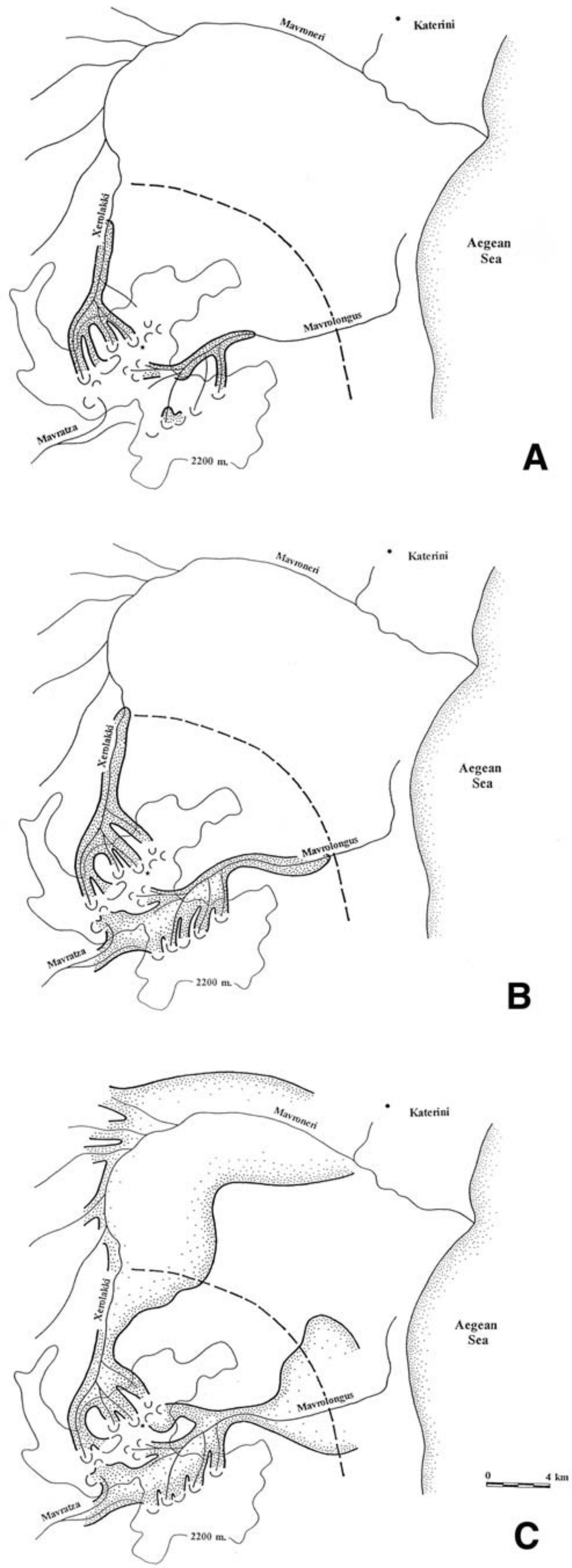


Figure 8. Schematic distribution of glacial ice in the Mount Olympus region based on the distribution of glacial deposits and glacial landforms described by Smith et al. (1997) for (A) unit 1 time (isotope stage 8), (B) unit 2 time (isotope stage 6), and (C) unit 1 time (isotope stages 4–2).

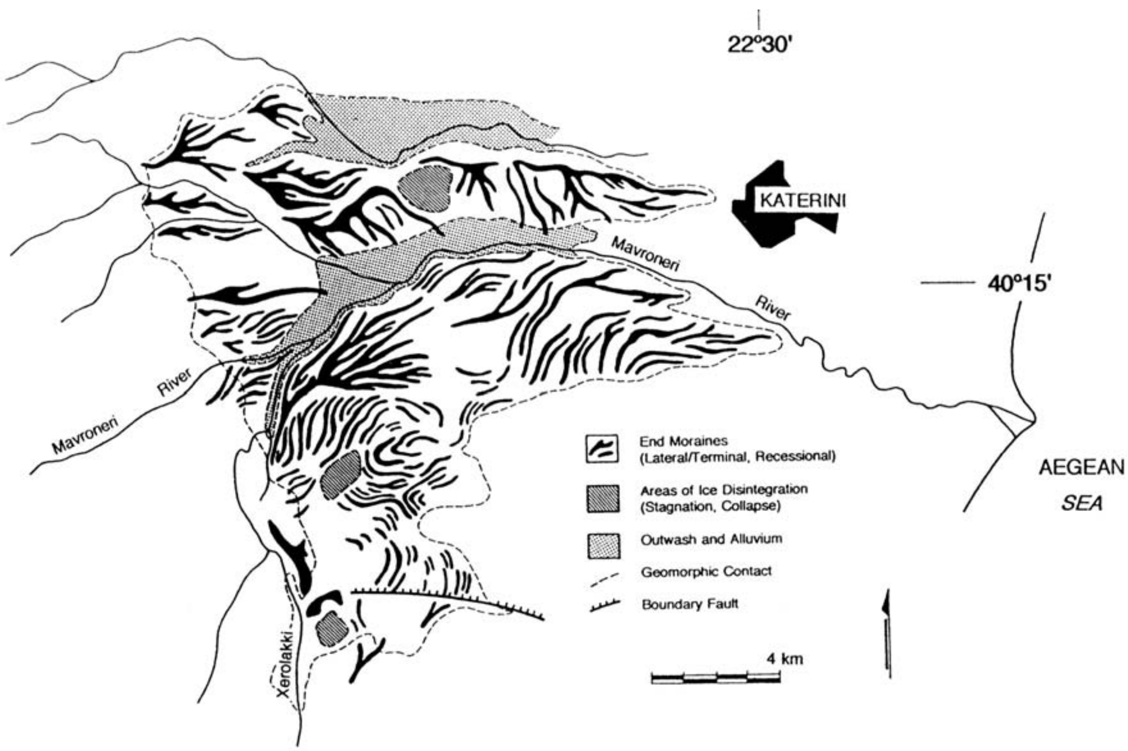


Figure 9. Detail of glacial deposits in the Xerolakki-Mavroneri Valley (from Smith et al., 1997). Complex end moraine systems (irregular dark linear features) provide compelling evidence for the presence of glacier lobes on the northeastern piedmont of Mount Olympus. See Figure 1 for location.

Figure 10. Shear plane within the end moraine of the Xerolakki-Mavroneri Valley. The light-colored boulders define a linear trend along the outcrop face. The boulders are predominantly granites from the High Pieria Mountains, and they are conspicuously grooved by glacial abrasion.

Figure 11. Coastal bluffs east of Litochoro, exposing unit 1, unit 2, and unit 3 sediments and the unit 1 soil (see Figure 1 for location). Unit 1 is exposed at the base of the section. The unit 1 soil is recorded in the red-colored sediments. Units 2 and 3 cut into the unit 1 soil and have removed its upper horizons.

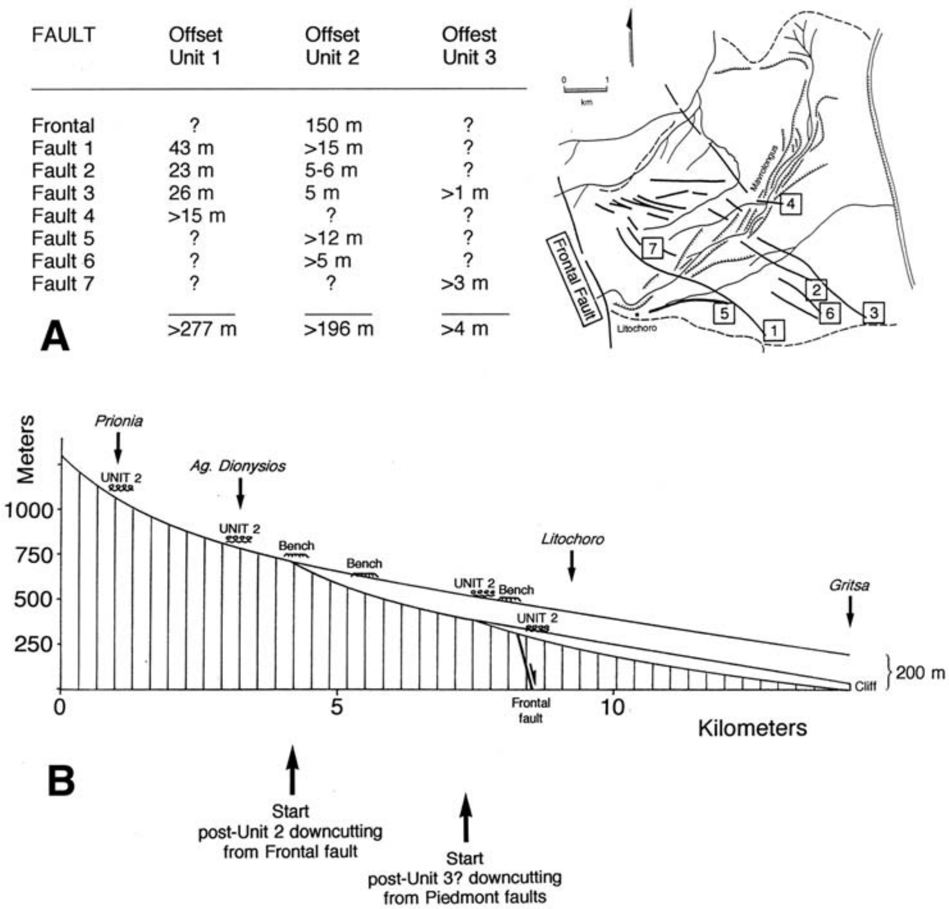
MAGNITUDE OF CLIMATE COOLING

The altitude of the equilibrium line during an episode of past glaciation can be estimated using a variety of techniques (e.g., Benn and Evans, 1998). However, in areas where the former extent of glaciation can only be approximated (Fig. 8), as is presently the case for Mount Olympus, use of the accumulation area ratio or balance ratio methods is precluded, because these require reconstruction of the past glacier's three-dimensional shape. Estimates of former equilibrium line altitudes in this study are therefore based on the elevations of cirque basins (for small glaciers) and the lengths (measured from head to terminus) of glaciers (for longer glaciers), supported, where possible (because they have been largely removed from valley sides as a result of tectonic uplift and rapid fluvial erosion) by estimates of the maximum elevation of lateral moraines. Although the position of the equilibrium line varies with both temperature and precipitation, it broadly corresponds to the elevation of the 0 °C isotherm, which can be calculated for any latitude using a standard formula for the rate of temperature decrease in the atmosphere with elevation above the ground surface (the adiabatic lapse rate).

Uplift Rate

In calculating the position of the regional equilibrium line in the case of Mount Olympus, it is necessary to consider not only the several stages of glaciation, but also the fact that the mountain has undergone continuous uplift throughout the period of glaciation. Neotectonic uplift of Mount Olympus is associated with the opening of the north Aegean basin (e.g., Papanikolaou et al., this volume) and has occurred in response to large-scale extensional detachment along its eastern flank that began in the Miocene (e.g., Kilias et al., 2002) and continues to the present day (e.g., Stiros et al., 1994). The calculation of former equilibrium line altitudes therefore requires knowledge of the rate of uplift of the mountain throughout the Quaternary.

Degradation of features of Pleistocene glacial erosion on Mount Olympus and the presence of deeply incised streams, erosional terraces, and fault scarps that offset the unconsolidated sediments of the youngest piedmont fan (unit 3) testify to the continuing uplift of the Olympus massif. Efforts directed at determining the rate of this uplift are based on the measured offset on faults that cut each of the three piedmont sedimentary units, as well as on the measured migration of breaks or knickpoints in the longitudinal profile of the Mavrolongus River Valley caused by renewed downcutting (Fig. 12). A prominent northwest- to NNW-trending frontal fault on the eastern piedmont, for example, separates the partially lithified Quaternary deposits of the second piedmont fan (unit 2) from those of the Olympus massif with a minimum offset of 150 m, and several subparallel northwest-trending faults with a cumulative displacement of ca. 130 m offset the paleosol developed on the oldest (unit 1) sediments (Fig. 12A). Kinematic indicators reveal normal dip-slip movement. Cumulative fault displacement for unit 1 exceeds 277 m, giving a minimum uplift rate of ca. 1.3 m/k.y. if an isotope stage 7 (Mindel/Riss) age of ca. 210 ka is assumed for the unit 1 paleosol and all displacement is considered to reflect uplift of the Olympus massif. On the other hand, a cumulative offset in excess of 196 m for the unit 2 paleosol yields



FAULT	Offset Unit 1	Offset Unit 2	Offest Unit 3
Frontal	?	150 m	?
Fault 1	43 m	>15 m	?
Fault 2	23 m	5-6 m	?
Fault 3	26 m	5 m	>1 m
Fault 4	>15 m	?	?
Fault 5	?	>12 m	?
Fault 6	?	>5 m	?
Fault 7	?	?	>3 m
	>277 m	>196 m	>4 m

Figure 12. Criteria used to determine the rate of uplift of the Olympus massif. (A) Cumulative fault offset of paleosols in the Enipeas piedmont northeast of Litochoro. (B) Measured migration of knickpoints in the longitudinal profile of the Mavrolongus River Valley. See Figure 1 for location.

an uplift rate of ca. 1.6 m/k.y. if an isotope stage 5e (Riss/Würm) age of 125 ka is assumed for the paleosol. Similar rates estimated from longitudinal profiles of the Mavrolongus Valley on the eastern side of the massif, which indicate 200 m of stream incision since unit 2 time (Fig. 12B), lend credence to the second estimate and further demonstrate that the fault offsets reflect the uplift of Mount Olympus rather than the subsidence of its piedmont. Other estimates, such as those based on the amount of downcutting since the start of isotope stage 1 (25 m in 11 k.y.), give values as high as ca. 2.3 m/k.y. However, all these estimates are based on the assumption that correlations of soils between the eastern piedmont and the dated succession of the southern piedmont are valid.

Estimates of the rate of uplift of Mount Olympus therefore range from 1.3 to 2.3 m/k.y. If an age of 1.8 Ma is used for the end of the Neogene (Gradstein et al., 2004), these values produce a range of total uplift for the Quaternary of 2.3–4.1 km. The most reliable estimate of the rate of uplift is considered to be that based on analysis of the amount of uplift of unit 2 because it is matched by the amount of downcutting of this unit known to have occurred since its deposition on the eastern piedmont. This estimated uplift rate is ca. 1.6 m/k.y., which is generally consistent with estimates determined by Faugères (1977) and Schermer et al. (1990).

Equilibrium Line Altitudes

The elevation of the equilibrum line is determined by values of temperature and precipitation for any site. The altitude of the present equilibrium line in the Mount Olympus region can only be estimated because it lies above the mountain's summit (2917 m). However, a maximum limit is provided by the 0 °C isotherm, which presently lies nearly 600 m above the summit at ~3500 m asl (Messerli, 1967). Thus, to produce glaciers on Mount Olympus today would require the equilibrium line altitude to be depressed by as much as 600 m in order to allow snow to accumulate and ice to form. Application of a standard adiabatic lapse rate (0.6 °C per 100 m at the latitude of Mount Olympus) to the figure of 600 m indicates that such a lowering of the equilibrium line would require a drop in average annual temperature of 3.6 °C. This, of course, is a very approximate figure because it disregards precipitation and assumes that depression of the equilibrium line altitude is solely a function of temperature. Nonetheless, given the location of

Mount Olympus in a midlatitude position and in a maritime setting, the figure is reasonable.

Employing the same general procedure, one can approximate the amount of equilibrium line altitude depression and the related temperature decrease associated with each of the glacial events on Mount Olympus during the Pleistocene. To these values of equilibrium line depression and temperature decrease it is necessary, however, to apply figures for the amount of uplift that Mount Olympus has undergone since each glacial event. For instance, the predominant cirque floor elevation (an approximation of equilibrium line altitude) for unit 3 cirques is 2200 m. However, the mountain has undergone some 120 m of uplift since the beginning of unit 3 time, based on the estimated uplift rate of 1.6 m/k.y. Thus, the equilibrium line altitude during unit 3 time was roughly 2080 m asl. The amount of equilibrium line depression during unit 3 time was therefore ~1420 m, which, assuming it was entirely the result of falling temperature, implies a temperature decrease of 8.5 °C. However, inasmuch as unit 3 glaciers extended for several kilometers beyond their cirque basins (Fig. 8A), it is likely that these figures are minimal and should be adjusted upward. On the other hand, the meteorological setting of Mount Olympus results in above-normal precipitation. The likelihood of abundant snowfall during unit 3 time, indeed at any time, would reduce the magnitude of the inferred temperature decrease. However, similar estimates of mean annual temperature decrease (8–9 °C) during the late Würmian have been proposed on the basis of rock glacier-climate relationships at Mount Tymphi (2497 m), less than 150 km west of Mount Olympus in northwestern Greece (Hughes et al., 2003).

Very general figures for equilibrium line altitude depression and temperature decrease during unit 2 time can be derived by approximating the position of the glacier equilibrium line as a function of the elevation range between the toe and the headwall of the unit 2 glacier systems. This method, for which a toe-to-headwall altitude ratio of 0.4 (e.g., Meierding, 1982) was used, is approximate at best, but does provide estimates of the proper order of magnitude.

During unit 2 time, glaciers extended distances of 12–13 km from upland cirque basins at elevations of ~2500 m to positions close to the mouths of major east- (Mavrolongus) and north- (Xerolakki) draining valleys at elevations close to 500 m (Fig. 8B). The elevation of the equilibrium line, based on a toe-to-headwall altitude ratio of 0.4, would consequently have been some 800 m above the toe, or at ~1300 m asl. This value is significantly higher than the maximum elevation (1000 m) of preserved unit 2 lateral moraines in the Mavrolongus Valley. However, the mountain, and features on the mountain, were some 288 m lower than at present, assuming a continuous rate of uplift for Mount Olympus of 1.6 m/k.y. since the beginning of unit 2 time. This would place the former equilibrium line a mere 1000 m asl and would indicate an equilibrium line altitude depression during unit 2 time of ~2500 m. If temperature alone were the controlling factor in determining snowline elevation, this figure would require a temperature decrease of 15 °C. This is well in excess of most estimates of temperature decrease during the Pleistocene, and suggests that equilibrium line altitude depression and glaciation of Mount Olympus were strongly influenced by locally high amounts of precipitation. Regardless of the reliability of the suggested values for temperature change during stage 2 time, however, the estimates for the magnitude of equilibrium line altitude depression are approximations of real values.

In stage 1 time, glaciers appear to have extended to the Aegean coastline (or beyond) in the Mavrolongus (Enipius) Valley and to an elevation of ~100 m in the vicinity of Katerini in the Xerolakki-Mavroneri Valley (Fig. 8C). In both valleys, ice originated from cirques on the Mount Olympus upland at average elevations of ~2500 m and extended as glaciers some 20–25 km beyond their upland sources. In addition, glaciers from the northern valleys of Mount Olympus merged with those from the High Pieria Mountains to form composite glacier lobes northeast of Mount Olympus. The complexity of glacier systems during this glacial episode makes it difficult to reconstruct the position of the equilibrium line. Based on a simple toe-to-headwall ratio of 0.4, however, the altitude of the equilibrium line was between 1000 and 1100 m asl. Uplift of Mount Olympus was on the order of 480 m between the beginning of unit 1 time and the present, assuming a continuous uplift rate of 1.6 m/k.y. This would place the unit 1 equilibrium line just 500–600 m asl and would imply a depression of equilibrium line elevation on the order of 3000 m. Equilibrium line depression of this magnitude is highly unlikely. Nonetheless, the extent of unit 1 glaciation is difficult to argue, and the calculated rates of uplift are consistent with estimates of other workers (e.g., Faugères, 1977; Schermer et al. 1990). Accepting that the basis for equilibrium line reconstruction is overly simplistic and that uplift rates may be minimally overstated, we are still left with the conclusion that during unit 1 time the magnitude of equilibrium line depression and concomitant temperature decrease was significantly greater than has been suggested by other work in southern Europe or the eastern Mediterranean region. As an absolute minimum, based on uplift-corrected cirque-floor elevations for the upland (unit 1 and 2) cirques (Table 2), equilibrium line depression was at least 1500 m (9 °C) during unit 1 and unit 2 time.

CONCLUSIONS

Evidence of glacial erosion and deposition on and around Mount Olympus, Greece, shows that the mountain was more extensively glaciated over a longer period of time than previous studies have indicated. The stratigraphic record of Quaternary events on the mountain's eastern piedmont comprises three discrete sedimentary packages (units 1–3), each capped by a distinctive soil, which together reflect glacial and nonglacial activity in the Mount Olympus region. These deposits can be tied to three stages of cirque development on the Olympus upland and at valley heads. Based on correlations with a dated alluvial sequence south of Mount Olympus, they suggest the following general history: (1) isotope stage 8 (Mindel) glaciation producing upland ice and valley glaciers that extended as piedmont lobes east, north, and west of the mountain (unit 1); (2) isotope stage 7 (Mindel/Riss) interglacial conditions accompanied by extensive erosion and subsequent pedogenesis; (3) isotope stage 6 (Riss) glaciation producing upland ice and valley glaciers that did not reach the piedmont (unit 2); (4) isotope stage 5 (Riss/Würm) interglacial conditions with stream erosion and substantial pedogenesis; (5) isotope stages 4–2 (Würm) glaciation restricted to valley heads (no upland ice) and glaciers that extended to midvalley positions (unit 3); and (6) isotope stage 1 nonglacial conditions associated with additional pedogenesis and stream incision. The largest cirque on the mountain (Megali Kazania) may contain depositional evidence for neoglaciation.

Evidence of neotectonics indicates that uplift of Mount Olympus has persisted since the mid-Pleistocene at a rate of ~1.6 m/k.y.; the total uplift since deposition of unit 2 has been ~200 m. Applied to cirque floor elevations, this rate produces estimates of equilibrium line altitude depression of 1420 m (8.5 °C) during unit 3 time and estimates for equilibrium line altitude depression during unit 1 and unit 2 time that range from a minimum of 1500 m (9 °C) to ~2500 m (15 °C).

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