Quaternary glacial history of Mount Olympus, Greece

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ABSTRACT

Erosional and depositional evidence on Mount Olympus, Greece, and across the adjacent piedmont provides clear indication that the mountain was more extensively glaciated over a longer period of time than has been previously reported. The stratigraphic record of Pleistocene–Holocene events on Mount Olympus is most clearly documented on the eastern piedmont, where three discrete sedimentary packages (units 1–3), each capped by a distinctive soil, reflect glacial and nonglacial activity in the Mount Olympus region. A working stratigraphic framework for sediments and soils is proposed and is tentatively correlated with a dated alluvial succession south of Mount Olympus. We suggest that the oldest sedimentary package (unit 1) predates 200 ka (isotope stage 8?). Lithologic and pedologic equivalents of the piedmont stratigraphy are found within major valleys draining Mount Olympus, as well as within cirque basins and on the summit plateau surface. These deposits can be clearly tied to three stages of cirque development on the upland and at valley heads. Taken together, upland and piedmont glacial features and deposits indicate the following general scenario: (1) earliest glaciation (isotope stage 8?) produced upland ice and valley glaciers that extended as piedmont lobes east, north, and west of Mount Olympus; (2) nonglacial (interglacial) conditions (isotope stage 7?) were accompanied by extensive erosion and subsequent pedogenesis; (3) a second glaciation (isotope stage 6?) involved production of upland ice and valley glaciers that did not reach the piedmont; (4) interglacial (interstadial) conditions (isotope stage 5?) provided time for stream erosion and substantial pedogenesis; (5) final(?) glaciation (isotope stages 4–2?) was restricted to valley heads (no upland ice) and glaciers that extended to mid-valley positions; (6) nonglacial conditions (isotope stage 1?) were associated with additional pedogenesis and stream incision. The largest cirque on the mountain (Megali Kazania) may contain depositional evidence for neoglaciation. Study of the neotectonic history of the Mount Olympus region indicates that uplift has persisted throughout the mid-Pleistocene and Holocene at a rate of about 1.6 m/k.y.; the total uplift since deposition of unit 2 is approximately 200 m.

INTRODUCTION

Mount Olympus, the highest mountain in Greece, takes the form of a massive limestone plateau that rises to a height of 2917 m asl (above sea level) and occupies an area of more than 300 km^2 at its base (Fig. 1). During the Pleistocene, this region of northeastern mainland Greece was a significant center of glaciation that, at lat 40°N, lay well to the south of the main alpine centers of Europe. Because of its southerly position, the mountain serves as an important reference point in regional studies of Pleistocene paleoclimate and post-Pleistocene climatic change. Despite its potential significance in this regard, the glacial geology of Mount Olympus has never been examined in detail, and existing knowledge of the region's glacial history has been confined to the results of pioneering reconnaissance studies that were undertaken more than 25 years ago (e.g., Wiche, 1956a, 1956b; Messerli, 1966a, 1966b, 1967; Faugères, 1969). These studies placed the snowline for the late Pleistocene on Mount Olympus at about 2400 m asl (a height exceeded by very few peaks in southern Europe), and concluded that glaciation in the Mount Olympus region was of limited extent, permanent ice being restricted to upland cirques, and small valley glaciers descending to elevations no lower than 1600 m asl. This early work did little to establish the sequence and timing of glacial events in the Mount Olympus region, although the implication (Messerli, 1967) was that glaciation was restricted to the latest Pleistocene (Würm; Messerli, 1967).

Field mapping of the Mount Olympus region over a four-year period indicates that, in failing to recognize widespread valley and piedmont glacial depositional features, previous studies have greatly underestimated the extent of the Pleistocene glacial record and, hence, the intensity of glaciation

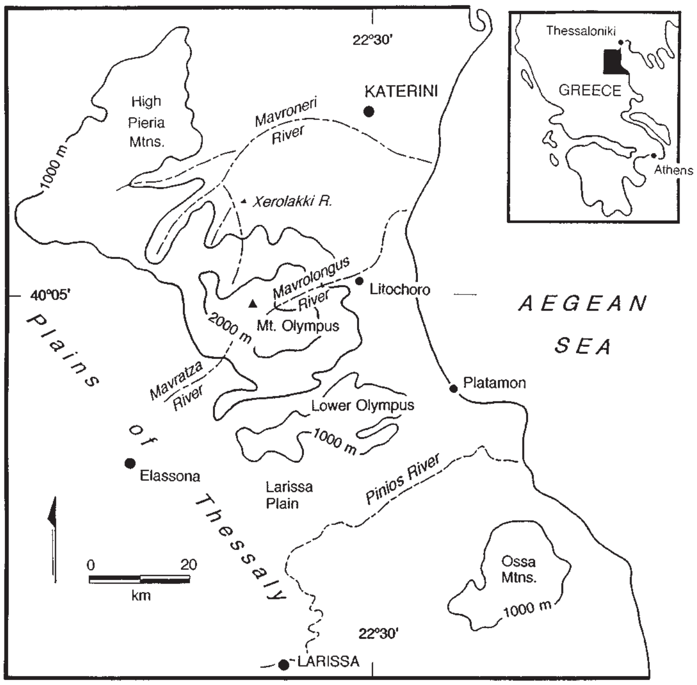

Figure 1. Geographic map of Mount Olympus and adjacent mountain ranges in northeastern mainland Greece, showing locations of major towns and rivers. Detail of Mount Olympus upland is shown in Figure 5.

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and the paleoclimatic significance of the Mount Olympus region. Preliminary results of the present study indicate that Mount Olympus was glaciated on at least three occasions, and that glaciation was extensive enough to produce piedmont glaciers and upland ice. In addition, there is evidence to suggest that the earliest glaciation occurred before 200 ka, and there was snowline depression to at least 1900 m asl—a height exceeded by numerous peaks in Greece (Genes et al., 1992, Smith et al., 1993). Furthermore, reconnaissance observations indicate the presence of glacial erosional and depositional features, suggesting that substantial glaciers existed in the mountains of the High Pieria to the north of Mount Olympus and in the Ossa Mountains south of Olympus. Similar features have also been observed in the vicinity of Mount Parnassos (2457 m), well to the south of Mount Olympus.

Proglacial and interglacial sediments on the piedmont east of Olympus extended beyond the present Aegean coastline, and may be correlative with units described on the north Aegean continental margin by Piper and Perissoratis (1991) and Lykousis (1991). Significant syndepositional and post-depositional normal faulting of piedmont deposits indicates that glaciation was contemporaneous with rapid tectonic uplift of the Olympus plateau that continues to the present day (Caputo and Pavlides, 1993).

The recognition of more extensive glacial erosional and depositional features, and the reinterpretation of features described by previous workers, suggests to us that there is serious need for a new evaluation of the glacial history of the Mount Olympus region. The following discussion outlines the results of the work of the authors and their students (Belfi and Smith, 1994, 1995; Calef and Smith, 1995; Clerkin and Smith, 1995; Fitzgerald and Smith, 1995; Hughes, 1994; Hughes et al., 1993; Jones and Smith, 1995; McIntyre et al., 1994a, 1994b) to date, and places our proposed sequence of Quaternary events into a provisional time framework.

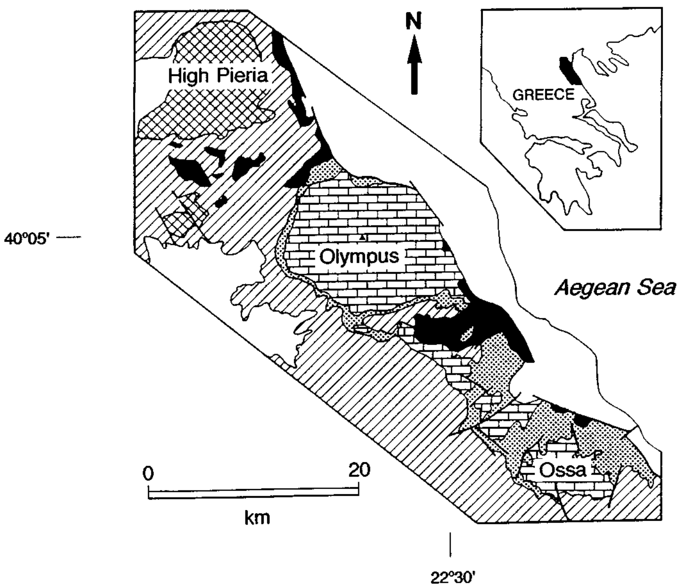

Figure 2. Generalized bedrock geologic map of the Mount Olympus region, simplified after Yarwood and Aftalion (1976), Nance (1981), Schmitt (1983), Katsikatsos and Migiros (1987), and Schermer et al. (1990). Brick pattern—Triassic and Cretaceous to early Tertiary shelf carbonates (Olympus-Ossa unit); stippling—Mesozoic continental margin sediments (Ambelakia unit); diagonal lines and cross-hachures—Paleozoic metamorphic rocks and granites, respectively (Pierian and Infrapierien units); black—ophiolitic rocks. Quaternary units are unshaded.

PHYSICAL SETTING

The Mount Olympus plateau comprises a metamorphosed and deformed sequence of Triassic and Cretaceous to early Tertiary continental shelf limestones (Godfriaux, 1968; Barton, 1975; Schmitt, 1983; Schermer, 1989, 1990) that were tectonically overridden during the Eocene by a series of thrust sheets comprising metamorphosed continental margin sediments (Ambelakia unit), basement gneisses, granites, and metamorphic rocks (Pierien and Infrapierien units), and ophiolitic rocks (Schermer et al., 1990). Uplift produced by late Tertiary to Holocene normal faulting subsequently exposed the Olympus carbonates in the form of a structural window through the overriding stack of thrust sheets, each of which now crop out in a more-or-less concentric arrangement on the flanks of the Mount Olympus and Mount Ossa massifs (Fig. 2). The Pieria Mountains (High Pieria), northeast of Mount Olympus, are underlain by late Paleozoic granites and metamorphic rocks (Yarwood and Aftalion, 1976; Nance, 1978, 1981).

The plateau summit is a broad, planar surface that is surmounted by several separate peaks and 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. The roughly circular plateau is tilted to the southwest so that the overall radial drainage has been modified by overdevelopment of valleys on the north and east slopes. The morphology of these valleys reflects a complex and repeated history of glaciation, tectonic uplift, and rapid fluvial erosion in such a way that classic U-shaped valley profiles are generally lacking, despite clear depositional evidence of glaciation within the valleys. Well-developed alluvial fans dominate the geomorphology of the piedmont and comprise a virtually unbroken alluvial apron along the eastern and western flanks of the mountain. Stream incision, related to tectonic uplift and eustatic changes of sea level, has produced a series of well-defined terraces within major valleys draining the piedmont.

The present climate of the region is generally Mediterranean (Humid Mesothermal–Dry Summer Subtropical), although the high elevation of Mount Olympus imposes a strong orographic influence on local conditions. Weather in the area is further influenced by the fact that Mount Olympus is situated within the confluence of cool, dry continental weather systems that move southward out of Europe, and warm, maritime weather systems arising from the Aegean. The present snowline (0° isotherm) has been placed (Messerli, 1967) at approximately 3500 m asl in the vicinity of Mount Olympus.

PREVIOUS INVESTIGATIONS

Previous studies of the Pleistocene and Holocene history of the Mount Olympus region, particularly as related to glaciation, are few. Summaries of the Quaternary history of the eastern Mediterranean region were provided by Emiliani (1955), Butzer (1958), Kaiser (1962), Messerli (1966a, 1966b, 1967), Farrand (1971), and Vita-Finzi (1975). Accounts of glaciation in northwestern and central Greece were documented by Pechoux (1970), and Lewin et al. (1991). Quaternary climatic cycles in the area around Mount Olympus were defined and discussed by Wijmstra (1969) and Tzedakis (1993). The geology and geomorphology of the piedmont region surrounding Mount Olympus have been considered by several workers, including Schneider (1968), Faugères (1969, 1977), Psilovikos (1981, 1984), and Demitrack (1986). Several studies have also been made of the neotectonic evolution and offshore Quaternary sedimentary history of the northern Aegean Sea (Cramp et al., 1984; Lyberis, 1984; Lykousis, 1991; Piper and Perissoratis, 1991; Dinter and Royden, 1993, 1994). Studies that treat specifically the glacial history of Mount Olympus are restricted to those of Wiche (1956a, 1956b), Messerli (1966a, 1966b, 1967), and Faugères (1977). We suggest that none of these latter studies adequately considers the diversity of erosional and depositional evidence of glaciation in the Mount Olympus region, and, as a result, that they significantly understate the complexity and the extent of glacial activity in the area.

GLACIAL GEOLOGY OF MOUNT OLYMPUS

The complexity of the Pleistocene and Holocene geology of Mount Olympus reflects the fact that regional surface processes have been superimposed upon tectonic activity that continues to the present day (Faugères, 1977; Pope and van Andel, 1984; Psilovikos, 1984; Demitrack, 1986; Caputo and Pavlides, 1993; Dinter and Royden, 1993, 1994). In addition, the record of Pleistocene glaciation includes erosional and depositional features that extend from the summit of Mount Olympus (Faugères, 1977; Hughes, 1994; Hughes et al., 1993; Clerkin, in press; Calef and Smith, 1995; Genes et al., 1992; Smith et al., 1993, 1994c, in press; Smith, in press) to the Aegean Sea (Faugères, 1977; Psilovikos, 1984; Belfi, 1995; Belfi and Smith, 1995; Smith et al., 1993, 1994a, 1994b, in press; Smith, in press) and westward and southward toward the Plains of Thessaly (Schneider, 1968; Demitrack, 1986). The focus of field investigations related to the present study has been within the northeastern quadrant of the Olympus plateau and the adjacent piedmont, where evidence of glaciation is most clearly documented and the influence of neotectonic activity is most readily discerned.

Mount Olympus Piedmont: Stratigraphic Framework

The materials of the Olympus piedmont (Fig. 3) comprise a complex assemblage of glacial and alluvial sediments that extend from the mountain front to the Aegean Sea (and beyond) on the east, and from the mountain to the Plains of Thessaly on the west and south. Faugères (1977) and Psilovikos (1981, 1984) recognized within the deposits of the eastern piedmont three distinct sedimentary packages. The definition of these sedimentary units is based largely on the degree of lithification of the sediments that compose them. (Note that because all sediments of the eastern piedmont are derived from Mount Olympus, and all consist of predominantly carbonate clasts, the degree of lithification is for the most part a function of secondary carbonate cementation.) The oldest sedimentary unit is completely indurated (Fig. 4A). It is rich in fine matrix, and where weathered, is characterized by a thick, deep-red, strongly clay-enriched soil. The intermediate unit is partially indurated; lithified beds are interlayered with nonlithified beds (Fig. 4B). This unit consists of moderately well-sorted, predominantly clast-supported, massive and stratified gravel. The soil profile developed on this unit is a relatively thick red-brown soil that is pedogenically distinct (less clay enriched, less rubified; Table 1) from the soil developed on the oldest sedimentary unit. The youngest unit is generally unlithified, well-stratified, predominantly clast-supported sand and gravel (Fig. 4C) on which a relatively thin brown soil has formed.

Results of the present study indicate that the three-part subdivision of piedmont sediments is valid, at least as a first approximation. Previous workers (Faugères, 1977; Psilovikos, 1981, 1984) suggested that the sediments, which they considered to be fanglomerates, record the following sequence of events: (1) deposition of the oldest unit under arid-semiarid conditions (with humid intervals) during early Villafranchian to early Pleistocene time; (2) deposition of the intermediate unit in a periglacial climatic regime during the early to middle Pleistocene; and (3) deposition of the youngest unit in a glacial climate during the middle to late Pleistocene. None of these units have been considered by previous workers to be of direct glacial origin. There is no indication in previous studies that ice played any role in the deposition of these sediments.

Smith et al. (1993, 1994a, 1994b, 1994c) and Smith (in press) suggested an alternative interpretation of the Olympus piedmont sediments, and proposed that the oldest (unit 1) sediments on the piedmont are predominantly glacial diamictons, with a minor proglacial component. The deep-red soil developed on these sediments is thought to record an extended interval, probably of interglacial duration, during which substantial pedogenesis occurred (Fitzgerald, 1996, in press; Jones, in press). Intermediate (unit 2) sediments on the piedmont are considered to have been deposited in a fluvial or glaciofluvial setting. These sediments can be traced into valleys that drain the Olympus upland, where they become progressively more diamictic (glacial?). Soils developed on these sediments are less pedogenically mature than those found on unit 1 sediments (Table 1). Soil colors are less strong, clay accumulation is less pronounced, and horizon formation is less distinct. The soils are, however, fully enough developed to record a weathering interval of interglacial or interstadial duration. The unit 2 sediments also contain buried partial (truncated) soil profiles that may likewise record interstadial weathering intervals (Fitzgerald, in press; Fitzgerald and Smith, 1995; Jones, in press; Jones and Smith, 1995). The youngest (unit 3) sediments are generally similar to unit 2 sediments, although they are not indurated. They are glaciofluvial and alluvial fan deposits, and can likewise be traced to probable glacial sources on Mount Olympus. Soils are thinner than those on either unit 1 or unit 2 sediments, and record present nonglacial conditions. This unit also contains buried partial (truncated) soil profiles. Unit 1 is considered to record deposition of glacial sediment (direct glacial deposition = till?) by ice in piedmont lobes east, north, and west of Mount Olympus. Units 2 and 3 record deposition of proglacial sediment from valley ice that never reached the piedmont slope of Olympus. Units 2

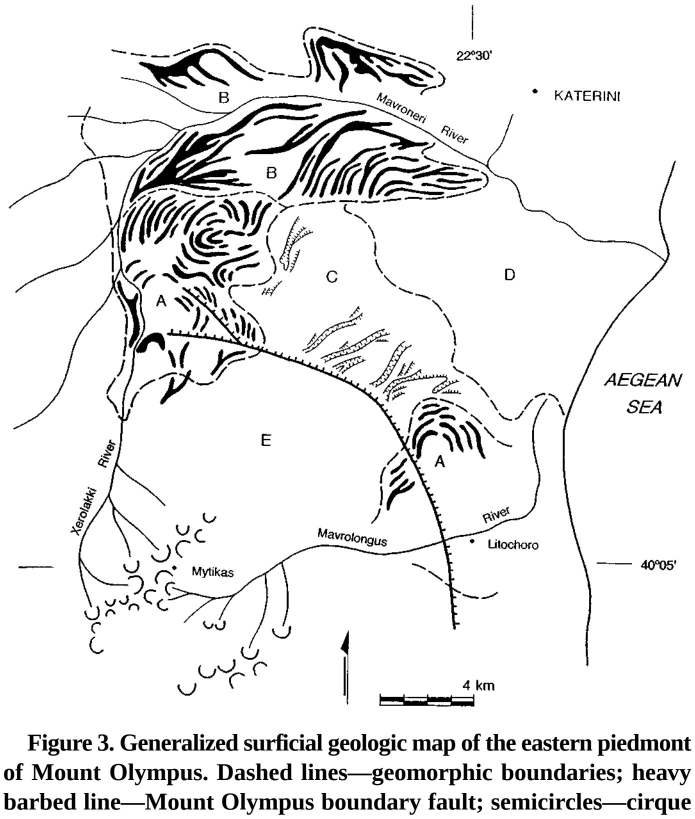

Figure 3. Generalized surficial geologic map of the eastern piedmont of Mount Olympus. Dashed lines—geomorphic boundaries; heavy barbed line—Mount Olympus boundary fault; semicircles—cirque basins; irregular heavy dark lines—end moraines; A—Piedmont glacial deposits of Olympus provenance; B—Piedmont glacial deposits of Pieria provenance; C—Modern alluvial deposits; D—Dissected (terraced) alluvial fan deposits; E—Valley and upland glacial deposits.

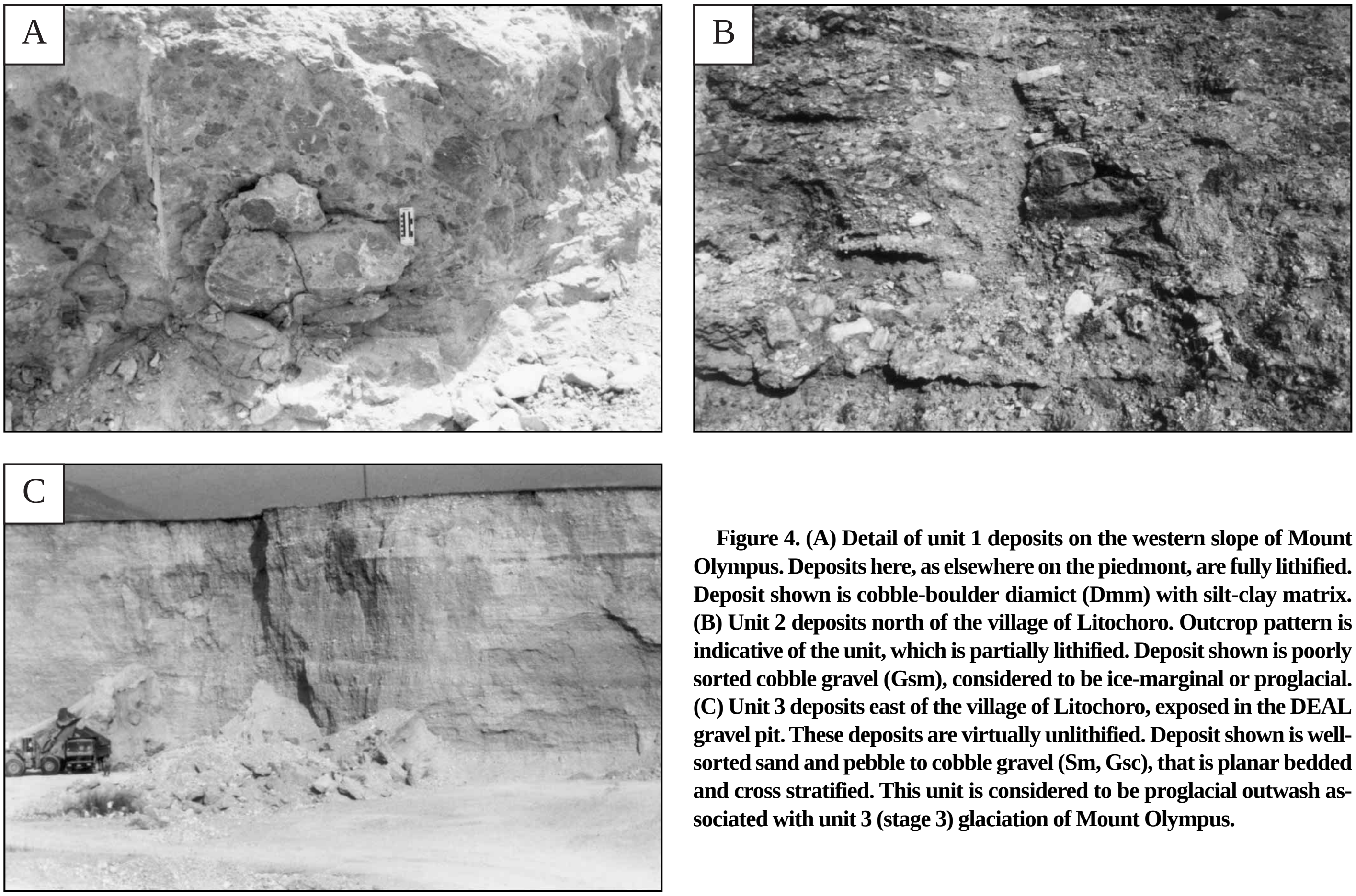

Figure 4. (A) Detail of unit 1 deposits on the western slope of Mount Olympus. Deposits here, as elsewhere on the piedmont, are fully lithified. Deposit shown is cobble-boulder diamict (Dmm) with silt-clay matrix. (B) Unit 2 deposits north of the village of Litochoro. Outcrop pattern is indicative of the unit, which is partially lithified. Deposit shown is poorly sorted cobble gravel (Gsm), considered to be ice-marginal or proglacial. (C) Unit 3 deposits east of the village of Litochoro, exposed in the DEAL gravel pit. These deposits are virtually unlithified. Deposit shown is well-sorted sand and pebble to cobble gravel (Sm, Gsc), that is planar bedded and cross stratified. This unit is considered to be proglacial outwash associated with unit 3 (stage 3) glaciation of Mount Olympus.

TABLE 1. SELECTED ATTRIBUTES OF SOILS ON THE EASTERN OLYMPUS PIEDMONT (INCLUDING PLAKA-GRITSA SOIL AND KATO MILIA-ROTINI SOIL) AND COMPARISON WITH RODIA NARROWS SOIL

Unit 3 Soils	Thickness†	Color§	% Clay	Clay Skins	Structure	PDI#
1. (DEAL)*	48 cm.	2.5YR	19	N.D.	mod md gran	10.6
2. (DRBS)	25 cm.	7.5YR	7	N.D.	mod fn gran	05.0
3. (PRRS)	38 cm.	2.5YR	7	N.D.	md sbang blk	11.3
4. (DRRBS)	46 cm.	5YR	9	N.D.	wk fn sbang blk	13.2
Unit 2 Soils						
5. (PRDR)	135 cm.	5YR	11	N.D.	str fn ang blk	38.0
Unit 1 Soils						
6. (PRB)	180 cm.	5YR	8	thk con	str fn sbang blk	72.9
7. (Prionia)	168 cm.	2.5YR	17	thk con	str md ang blk	77.5
8. (DRRC)**	N.D.	2.5YR	35	thk con	mod md sbang blk	N.D.
9. (P-G)††	213 cm	7.5YR	25	thk con	str fn sbang blk	81.7
10. (KM-R)	495 cm.	2.5YR	N.D.	thk con	str fn ang blk	50.8
11. Rodia Narrows	127 cm.	7.5YR	8	N.D.	mod md ang blk	26.9

Note: N.D. = not determined. Attributes for all soils are for optimum B horizon. All soils, except the Plaka-Gritsa soil (P-G) and the Dion Road Red Clay (DRRC) are surface soils. All soils, except the Kato Milia-Rotini soil and the Rodia Narrows soil, are Olympus provenance soils. The Kato Milia-Rotini soil (KM-R) is a surface soil of Pieria provenance.

*Letters in parentheses refer to informal soil names employed in this study (DEAL = DEAL gravel pit [surface brown] soil, DRBS = Dion Road Brown soil, PRRS = Plaka Road Red soil, DRRBS = Dion Road Red Brown soil, PRDR = Plaka Road Deep Red soil, PRB = Plaka Road Brown soil, Prionia = Prionia Road soil, DRRC = Dion Road Red Clay, P-G = Plaka-Gritsa soil, KM-R = Kato Milia-Rotini soil).

†Profile thickness, measured to top of C horizon (or top of lithified sediment).

§All colors are Munsell designations (moist). Only hue is noted.

#Profile development index (from Fitzgerald, 1996).

**Truncated buried soil (?); possible karren filling. No depth measured.

††Truncated buried profile. A and upper B horizons removed during deposition of unit 2.

TABLE 2. TENTATIVE CORRELATION OF OLYMPUS PIEDMONT SOILS WITH SOILS OF THE LARISSA PLAIN

Larissa Plain* Soil Name	Depositional interval	Olympus Piedmont† Soil name	Isotope stage
Pinios Group soils	<200 years	Unit 3 surface soils	1
Deleria soil	Historical		
Girtoni soil	6–7 ka		
Noncalcareous 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 at intervals		
		Unit 2 soil	5
Deep red soil	≤210 ka	Unit 1 soils	7

Note: Refer also to Figures 13 and 15 and Table 1.
*Soil names and depositional intervals from Demitrack (1986).
†This study (see Table 1 for details of Olympus piedmont soils).

and 3 also include nonglacial fluvial deposits—that is, these two sediment packages are thought to record both glacial–late glacial and postglacial deposition on the Mount Olympus piedmont.

The absolute timing of these events is difficult to establish. Because the sediments are rich in carbonate clasts (and matrix), conventional radiocarbon dating procedures are of little use. The application of cosmogenic ^{36}Cl procedures to date boulders that occur at the surface of piedmont moraines is the focus of current study. Nevertheless, a provisional chronology (Table 2) for depositional and pedogenic events on the piedmont can be achieved through correlation of the soil stratigraphy from the eastern Olympus piedmont (Fitzgerald, 1996, in press; Jones, in press) with a similar, but dated (^{14}C on shells, U/Th on pedogenic carbonates), stratigraphy from the southern Olympus piedmont (Demitrack, 1986).

Demitrack (1986, p. 42) described the oldest soils developed on alluvial deposits of the Larissa Plain as fragmentary and poorly exposed. The older of two soils were characterized “as a dark red, noncalcic clay with grussified clasts, which is exposed against the mountain front [Thessalian Hills] in a single large drainage north of Rodia.” The younger of the two soils is “yellowish red, clay-rich, and calcic, with multiple calcium carbonate crusts, the uppermost of which yielded a U/Th disequilibrium date of

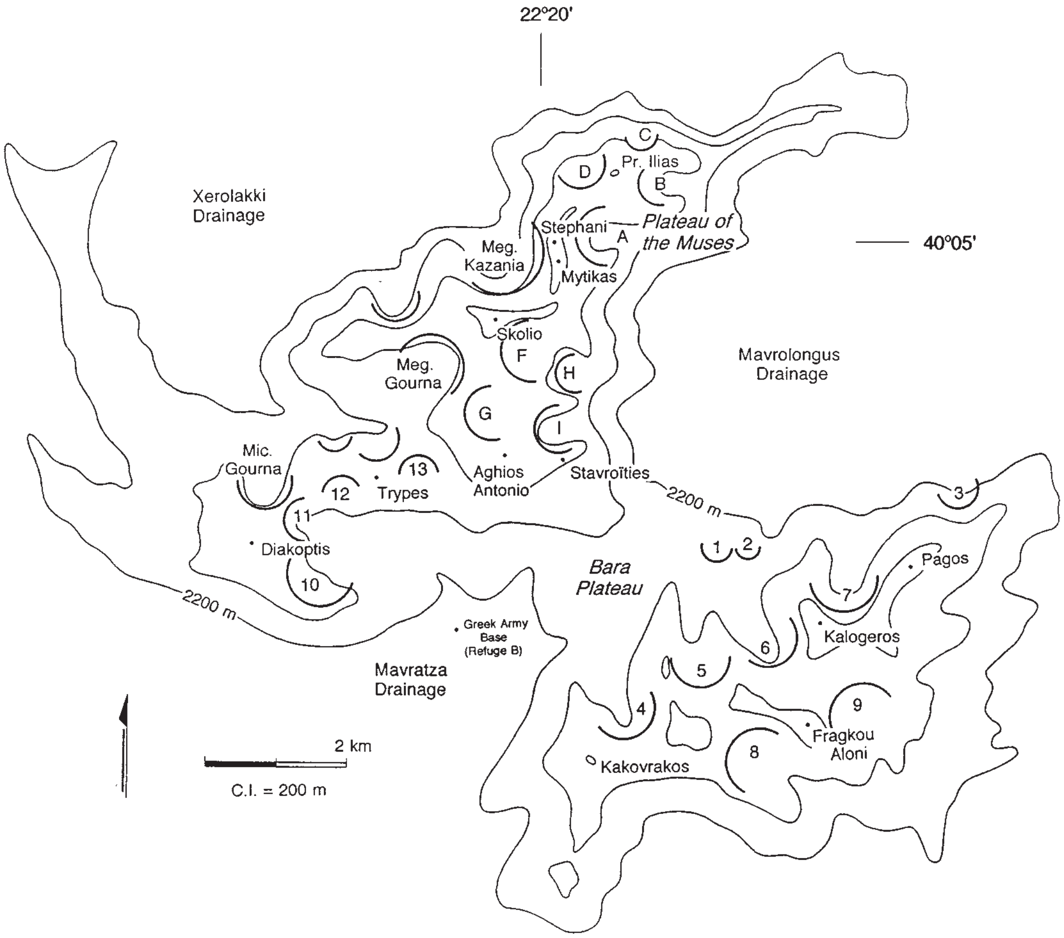

Figure 5. Geography of the Mount Olympus upland. Study has focused on the Plateau of the Muses (north of Aghios Antonio–Stavroïties) and the Bara upland (west to Diakoptis, east to Pagos). Letters and numbers designate cirques referred to in Table 3 and discussed in text.

≤210 000 years B.P." Demitrack further noted that the old soil (presumably the younger of the two soils—the dated soil) consists of a thick truncated B [Bt], with a Munsell color of 5YR, pervasive medium to thick clay films, and multiple carbonate crusts.

Tentative correlation of the soil developed on unit 1 sediments of the eastern piedmont with the oldest soils described by Demitrack from the Larissa Plain is based on the following considerations. (1) The stratigraphic positions of the parent materials of the two soil groups are similar. Both soil groups are developed on highly dissected deposits that are the oldest to postdate local bedrock. (2) The pedogenic attributes (Munsell color of optimal B, degree of clay enrichment (clay coatings and/or skins), and secondary carbonate accumulations) of the two soil groups match closely. If this correlation is valid, the unit 1 soil is considered to date back to oxygen isotope stage 7, although it may be as young as isotope stage 5.

The development of a detailed soil stratigraphy (Table 2) for the eastern Olympus piedmont, based, in part, on Harden profile development indices (Fitzgerald, 1996; Fitzgerald and Smith, 1995; Jones and Smith, 1995), supports the correlation of soils between the eastern and southern piedmont regions. Profile development indices (PDIs) for unit 3 soils (Table 1) are internally consistent and are distinct from PDIs of older soil groups. The unit 3 soils are considered to record modern nonglacial conditions (isotope stage 1). The PDI for the Rodia Narrows soil (Demitrack's soil AA of the Rodia Group soils), which was analyzed in this study, is intermediate between the PDIs for unit 3 soils and unit 2 soils, and may be the pedogenic equivalent of partial (truncated) soil profiles within the unit 3 sedimentary package of the eastern piedmont. It is the Rodia Narrows soil that has provided a U/Th disequilibrium date (on carbonate nodules) of ≥54 000 years. Formation of the Rodia Narrows soil is considered to have begun during the interstadial corresponding to isotope stage 3. PDIs for the unit 2 soils of the eastern piedmont are intermediate between, and distinct from, those of unit 3 soils and unit 1 soils. On the basis of these data, we assume that the unit 2 soil began developing under interglacial conditions between deposition of unit 2 deposits and unit 3 deposits, a time that most likely corresponds to isotope stage 5. The PDIs for the unit 1 soils are separate and distinct from those of the unit 2 and unit 3 soils. They are significantly greater than those for the unit 2 soils, and are considered to record pedogenic development that began under interglacial conditions during isotope stage 7. This placement of the unit 1 soils in isotope stage 7 is consistent with their placement in that stage based solely on the tentative correlation with Demitrack's dated oldest soils from the Larissa Plain.

Mount Olympus Upland

Study of the glacial geology of the Mount Olympus upland has focused on two areas: (1) the area north and east of the summit (the Plateau of the Muses: Hughes, 1994; Hughes et al., 1993), and (2) the area south and east of the summit (Bara: Clerkin, in press; Clerkin and Smith, 1995; Calef and Smith, 1995).

The general geography of the Plateau of the Muses and the Bara Plateau is illustrated in Figure 5. Principal peaks include Mytikas (summit 2917 m), Stephani (2909 m), Skolio (2911 m), Pr. Ilias (2813 m), Diakoptis (2592 m), Trypes (2607 m), Aghios Antonio (2817 m), Stavroïties (2626 m), Kakovrakos (2618 m), Fragkou Aloni (2684 m), Kalogeros (2701 m), and

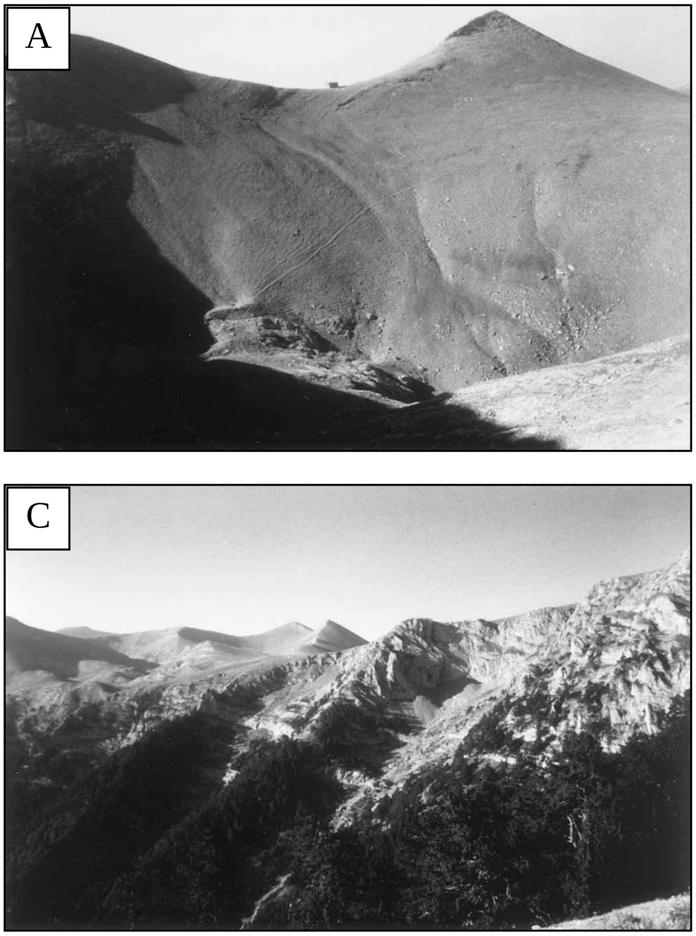

Figure 6. (A) The col at refuge SEO. View is to the northwest. This feature occurs on the divide extending from Mytikas to Pr. Ilias (Fig. 5), and separates upland cirques that drain east and north from the divide. Pr. Ilias, which defines the northern (right) slope of the col, is a horn on the arête that extends from Skolio to Pr. Ilias (Fig. 5). (B) Upland cirque basin north of refuge SEO. View is to the northwest. Typical of upland cirques, morphology is substantially degraded. This cirque heads at the col at refuge SEO, and feeds into the Xerolakki drainage. (Fig. 7 photos were taken at the mouth of this cirque basin.) (C) Valley head cirques at the head of the Mavrolongus drainage. View is to the southeast. These cirques, although lacking some elements of classic cirque morphology, have well-defined headwalls and sidewalls. The headwalls of these cirques cut unit 2 deposits of the Bara upland.

Pagos (2682 m). Upland basins occur between these peaks, and are sometimes separated from them by distinct topographic saddles (Fig. 6A). All of these features are considered to be relict glacial erosional landforms (horns, cirques, cols). Incised into the upland surface, often at the mouths of upland basins, and always at the heads of major drainage basins, are more clearly defined cirque basins and trough heads (Sugden and John, 1977; Genes, 1978). Study of the Plateau of the Muses has centered on those features considered to be cirques (Wiche, 1956a, 1956b; Messerli, 1967; Hughes, 1994; Hughes et al., 1993). Study of the Bara Plateau has focused on features previously described as nivation basins (Wiche, 1956a, 1956b; Messerli, 1966a, 1966b, 1967), as well as deposits considered by others to be of fluvial origin (Faugères, 1977).

On the basis of the evaluation of several morphologic attributes (height, length, width, k-value [defined in Table 3], and ratios), cirques on the Plateau of the Muses and the Bara Plateau have been divided into two general categories: upland cirques and valley head cirques (Hughes, 1994; Hughes et al., 1993; Calef and Smith, 1995). Table 3 summarizes major morphometric attributes of both upland and valley head cirques. Upland cirques are, for the most part, subdued features with poorly defined headwalls and sidewalls, but with distinct basinal form (Fig. 6B). Valley head cirques have well-defined cirque morphology (Fig. 6C). Both groups of cirques contain diamictic deposits (till?; Fig. 7A), and several of these deposits overlie striated bedrock surfaces (Fig. 7B).

Cirque floor elevations distinguish the two groups of cirques, and provide some basis for defining paleosnowline elevations (Table 3). Cirque floor elevations (for both the Plateau of the Muses and the Bara Plateau) range from 2200 m asl to 2660 m asl. On average, upland cirque floor elevations are close to 2470 m asl, and valley head cirque floors are roughly 70 m lower (approximately 2400 m asl).

Most cirques of the Mount Olympus upland fed ice that flowed toward the eastern piedmont. Four of the cirques (all upland cirques on the Bara Plateau) fed ice that flowed to the western piedmont. The cirques that rim the southeastern margin of Bara (between Kakovrakos and Pagos, Fig. 5) are particularly well-developed upland cirques (Fig. 8A) that display compound forms in which younger cirques are inset into older cirques. The older cirques comprise large, subdued basin forms associated with cols and horns that define the southern arête of the Bara upland (Fig. 8A). We propose that these basins represent the earliest stage (stage 1 = unit 1) of cirque development on the mountain, and that glaciers that developed in these cirques are responsible for the unit 1 deposits that are found within west-, north-, and east-draining valleys, and on the adjacent piedmont. Smaller subdued cirque forms are developed within several of the stage 1 upland cirques. These latter cirques (stage 2 = unit 2) are obviously younger than

TABLE 3. SUMMARY OF CIRQUE ATTRIBUTES

	Orientation	Floor elevation (m asl)	k-value*	Designation
Plateau of the Muses				
Cirque A	East	2560	1.10	Valley head
Cirque B	East	2600	0.27	Upland
Cirque C	North	2520	0.21	Upland
Cirque D	North	2660	0.36	Upland
Cirque F	East	2640	1.36	Valley head
Cirque G	East	2630	1.06	Valley head
Cirque H	East	2480	1.06	Valley head
Cirque I	East	2650	1.27	Valley head
Meg. Gourna	Southwest	2430	4.93†	Valley head
Mic. Gourna	North	2270	1.69	Valley head
Meg. Kazania	Northwest	2200	9.30†	Valley head
Bara Plateau				
Cirque 1	Northeast	2180masl	N.D.	Valley head
Cirque 2	Northeast	2230masl	N.D.	Valley head
Cirque 3	Northwest	2210masl	1.01	Valley head
Cirque 4	North	2370masl	1.56†	Upland
Cirque 5	North	2420masl	4.39†	Upland
Cirque 6	Northwest	2400masl	4.38†	Upland
Cirque 7	Northeast	2280masl	6.15†	Valley head
Cirque 8	Northeast	2460masl	0.73	Upland
Cirque 9	Northwest	2510masl	0.27	Upland
Cirque 10	Southeast	2410masl	0.13	Upland
Cirque 11	Southeast	2390masl	0.20	Upland
Cirque 12	South	2450masl	0.20	Upland
Cirque 13	South	2440masl	0.28	Upland

Note: Modified from Hughes (1994). Cirque designations (letters and numbers) are keyed to Figure 5.

*The k value (Haynes, 1968) describes the longitudinal profile of cirque basins in terms of logarithmic curves of the form $y = k(1 – x)e^{–x}$, where x = is cirque length (headwall to lip), y = cirque depth (headwall to basin), and k is a constant. Lower values of k (k < 1) indicate open cirques with gently inclined headwalls. Higher values of k (k >1) indicate deep cirque basins with steep headwalls.

†High k values for these cirques reflects the fact that the cirques are composite forms that were occupied by ice on two or three separate occasions.

Figure 7. (A) Diamicton at mouth of cirque illustrated in Figure 6B. View is to the southeast. Deposits here are poorly sorted, angular, boulder diamicts (Dmc). The location and distribution of these deposits precludes an origin as solifluction deposits. (B) Glacial striations on bedrock at mouth of cirque illustrated in Figure 6B, and directly beneath deposits illustrated in A. Direction of ice flow is north-northwest, parallel to the axis of the cirque basin.

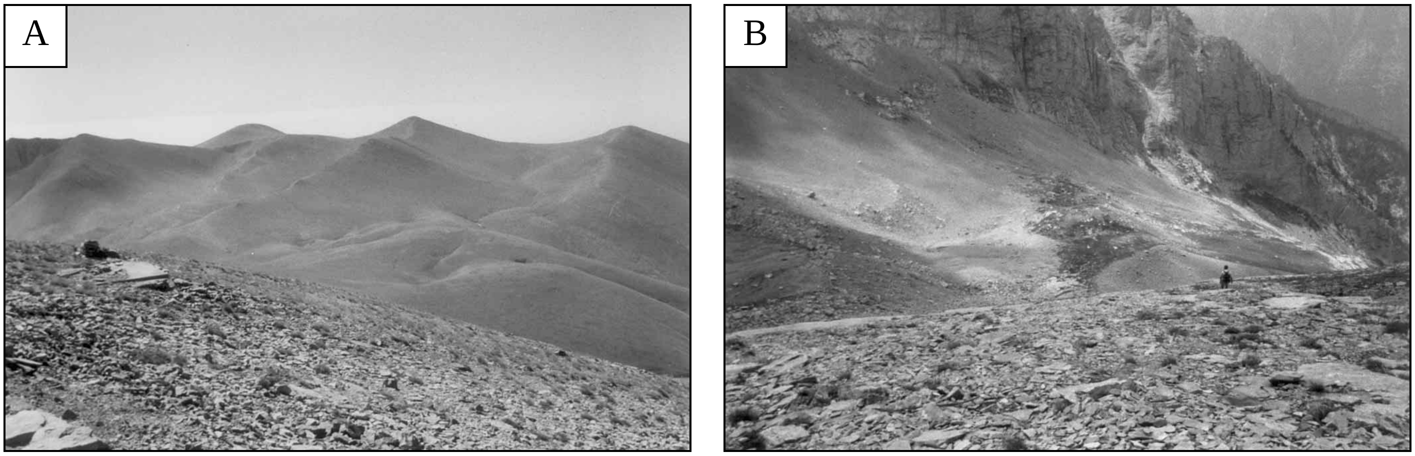

Figure 8. (A) Upland cirques on the Bara Plateau. View is to the east. The skyline is the complex arête between Kakovrakos and Kalogeros (Fig. 5). Two basins on right are compound cirques that record two stages of development (stage 1 and stage 2). Both cirques were reoccupied by small stage 3 glaciers. (B) Megali Kazania, the largest cirque on Mount Olympus. View to northwest. Deposits on floor of cirque basin include unit 3 (stage 3) recessional moraine (right). Interior to the unit 3 moraine is a large unvegetated moraine (center, left) that may be of Neoglacial age. Protalus ramparts occur between and beside these moraines. (C) Unit 2 deposits at the head of the Mavrolongus Valley. View is to the east. Kalogeros and Pagos are peaks in the background. Cliffs on left of photo are headwalls of cirques illustrated in Figure 6C. Unit 2 deposits here are massive to stratified diamictons similar to those illustrated in Figure 7A. It is these deposits, in part, that Faugères (1977) described as fluvial sediments related to preuplift drainage on Mount Olympus.

the stage 1 cirques, and they appear to be the youngest of the upland cirques. Glaciers that developed from these cirques are considered to be the source of deposits (unit 2) that cover much of the Bara Plateau, and that are also found within valleys that drain north and east from the mountain.

Valley head cirques (Fig. 6C), defined by more distinct cirque morphology and lower floor elevations, are incised into unit 2 deposits of the Bara Plateau and the Plateau of the Muses. These cirques (stage 3 = unit 3) clearly postdate stage 2 cirque development and upland deposition of unit 2 sediments.

The two cirque groups can also be distinguished on the basis of the materials that they contain. Upland cirques, and the upland surfaces surrounding them, contain sediments that are equivalent to lithified unit 1 and partially lithified unit 2 deposits of the piedmont sedimentary succession (Clerkin, in press; Clerkin and Smith, 1995; Calef and Smith, 1995). There is, however, only very limited evidence of unlithified unit 3 sediments on the upland, and these deposits occur within only a few of the upland cirque basins. Valley head cirques, in general, contain only unit 3 sediments. They are often incised into unit 1 or unit 2 deposits of the upland. The largest of the cirques on the mountain (Megali Kazania; Fig. 8B), which is a north-facing cirque immediately below the summit, records the most complete history of upland glaciation. Unit 1 and unit 2 deposits occur at the mouth of this cirque, and can be traced discontinuously, through the Xerolakki Valley, to the eastern piedmont (Fig. 9). Inset into these deposits are unit 3 deposits that originate in the cirque basin. Megali Kazania also contains deposits and constructional (morainal) topography that postdate unit 3 materials (Fig. 8B). These deposits are restricted to the cirque basin, and are tentatively considered to be of Neoglacial age.

The distribution of deposits considered to be of glacial origin on the Mount Olympus upland is depicted in Figure 10. Lithified unit 1 deposits, capped by a thick red, strongly clay enriched soil, are exposed beneath partially lithified unit 2 deposits at the Greek Army base (Refuge B) in the Mavratza Valley, west of the summit. The unit 2 deposits, which are the most extensive of the upland deposits, can be traced from a position west of the Greek Army base, across the Bara Plateau, to the head of the Mavrolongus Valley, where they are several tens of meters thick (Fig. 8C). These deposits, for the most part, lack any constructional morphology, and consist of massive matrix-supported diamictons and gravels that are composed of subangular to subrounded boulder and cobble clasts in a poorly sorted sand-silt-clay matrix (Figs. 7A and 8C) (Clerkin, in press; Clerkin and Smith, 1995). These deposits have few of the fluvial attributes ascribed to them by Faugères (1977), who considered the deposits to be related to stream development prior to uplift of Mount Olympus. They are considered, in this current study, to be of glacial origin for the following reasons. (1) The distribution of the sediments appears to be related to sources in basins that have been designated as cirques. The occurrence of these sediments is not restricted to the col at Bara, as described by Faugères (1977). Materials identical in texture and fabric have been mapped on the Plateau of the Muses and on the surface directly north of the summit of Mount Olympus (Mytikas). In all cases, the distribution of sediments can be traced to origins in upland cirque basins. (2) Sediment textures are predominantly coarse and poorly sorted—the sediments are typically bimodal or multimodal, with very large clasts in a finer matrix (Figs. 7A and 8C). This texture is consistent with that of glacial diamicton, and is generally inconsistent with fluvial deposits. (3) In several instances, it

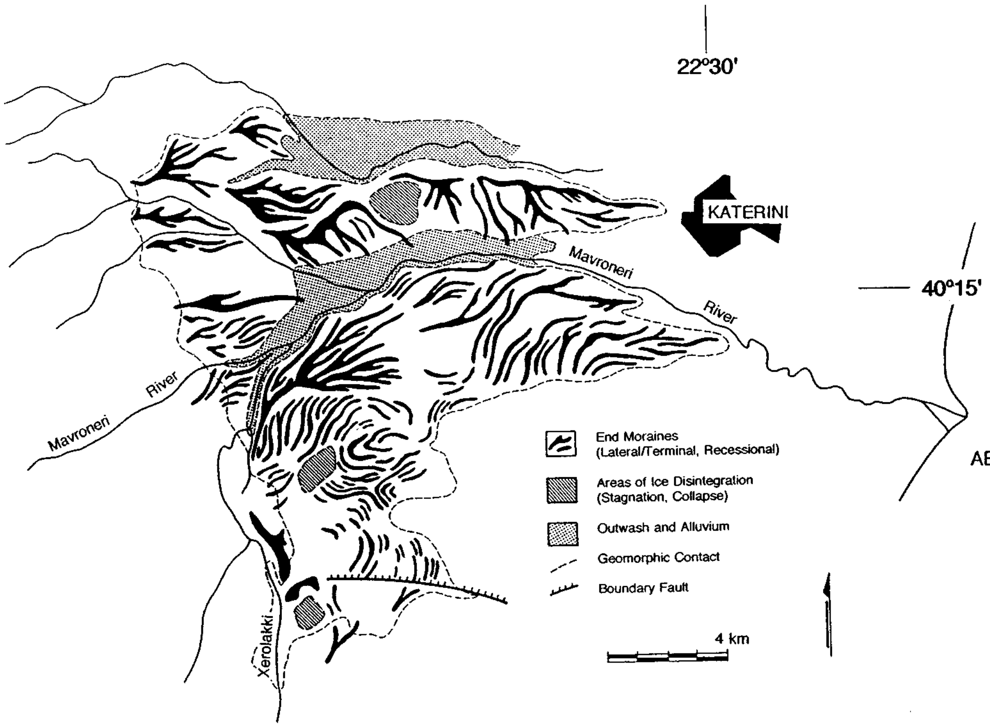

Figure 9. Detail of piedmont glacial deposits in the Xerolakki-Mavroneri drainage (see also Fig. 3). Deposits within the Mavroneri Valley record the convergence of valley ice from Mount Olympus and the High Pieria Mountains. These deposits have been mapped by others as Neogene fluvial and lacustrine sediments.

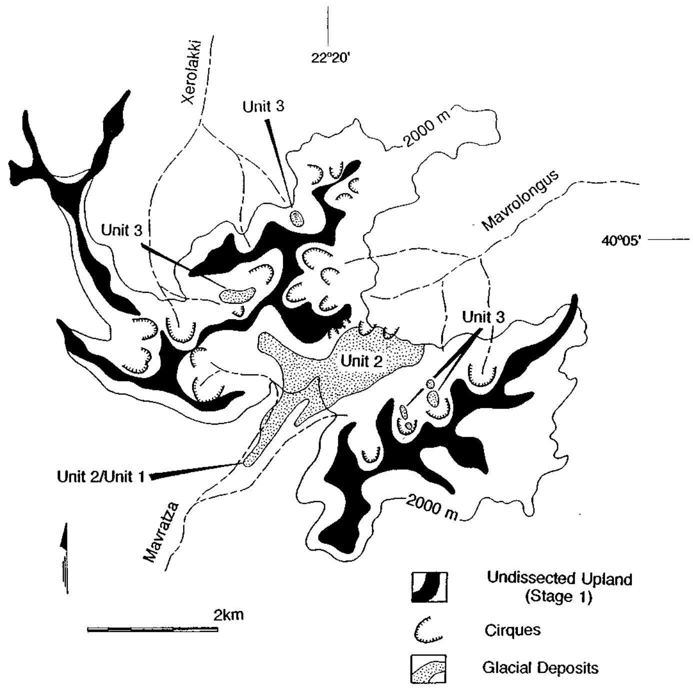

Figure 10. Glacial geology of the Bara Plateau. Undissected upland comprises arêtes related to stage 1 glaciation. Illustration of cirques is simplified. Glacial deposits of the Plateau of the Muses are not shown. The unit 2–unit 1 locations shown refer to the exposures at the Greek Army base (refuge B).

can be demonstrated that diamictic sediments directly overlie striated and polished bedrock (Fig. 7B).

Given a glacial origin for the upland sediments, their continuity and areal distribution require that they were deposited by a body of ice that was not restricted to cirques and valleys. Directional markings (striations, crescentic markings) on the Plateau of the Muses (Hughes, 1994; Hughes et al., 1993) indicate that ice flow on the upland surface was largely independent of cirque and valley constraints.

It could be argued that the Olympus upland provides insufficient surface area to support upland ice, outside of cirques. However, unit 1 and unit 2 sediments occur over large portions of the upland surface, and these sediments are, at least in part, of glacial origin. Whether the ice is called upland ice, or plateau ice, or a local ice cap can be debated, but the evidence suggests (Hughes, 1994; Hughes et al., 1993; Clerkin, in press; Clerkin and Smith, 1995) that during the glacial episodes that produced unit 1 and unit 2 sediments, cirque glaciers developed to a size that permitted them to spread from their basins and to cover substantial portions of the upland surface, thereby forming a continuous ice cover on the upland.

Valleys of Mount Olympus

Study of the valleys on Mount Olympus has concentrated on (1) the Mavrolongus (Enipius), which drains Olympus to the east, through the town of Litochoro, to the Aegean Sea, and (2) the Xerolakki, which drains Olympus to the north. These are the two most extensive drainage systems on the mountain. Preliminary study has been conducted on the west slope of Mount Olympus in valleys that drain to the west and south (to Elassona) and to the south and east (to Platamon). One of the problems in recognizing the influence of glaciation on Mount Olympus is the fact that the valleys that drain the mountain are typically youthful, in the Davisian sense, and display none of the classic U-shaped morphology of many alpine glacial valleys. This, we believe, is due largely to the fact that the mountain is composed predominantly of a relatively easily erodible carbonate lithology, and that it has undergone active tectonic uplift since late Tertiary time, so that original U-shaped valley forms have been deeply incised and substantially modified by fluvial erosion and mass wasting.

Despite the general lack of classic U-shaped cross-profiles, the valleys provide evidence that they have developed in several stages, and that early stages of valley development are most likely related to glaciation. The clearest evidence of this is to be found in the Mavrolongus Valley. Here, valley cross-profiles (Fig. 11) indicate a stepped morphology, the hip-roof profile of Goldthwait (1940), repeated at least three times.

Deposits that are considered to be of glacial origin can be found from valley head cirque basins, through major valleys such as the Mavrolongus and Xerolakki to the eastern Olympus piedmont. The deposits are typically scattered and discontinuous. Unit 1 and unit 2 deposits, within the valleys, seldom display any obvious constructional morphology. In general, these materials occur in topographically protected positions within the valleys. Unit 1 deposits are rare and have been recognized, at this point, only in valley floor positions near the mouths of major valleys. Unit 2 sediments are more widely distributed in valleys and are extensive enough that progressive changes in lithofacies types can be defined from valley head to valley mouth. Unit 3 deposits have been mapped only as constructional morainal deposits through upper and middle portions of major valleys. These latter deposits are seldom found in valley bottom positions and are generally absent from the lower reaches of valleys. Their occurrences are, for the most part, restricted to lateral and/or terminal moraines on valley sides.

The occurrence and distribution of glacial sediments in the eastern and northern valleys of Mount Olympus, coupled with the morphology of these valleys, suggest the following. (1) Ice originating in upland cirques filled major east- and north-draining valleys (and probably west-draining valleys) and spread as piedmont lobes onto the adjacent piedmont during unit 1 time. (2) Subsequent glaciation during unit 2 time eroded virtually all unit 1 deposits from the valleys, but left remnants of unit 1 sediments on uplands and extensive deposits of these sediments on the piedmont. Ice during unit 2 time extended to positions near the mouths of major north- and east-draining valleys, but did not reach the piedmont. Glaciers during this glacial episode originated in cirques that were inset into stage 1 upland cirques. (3) The last episode of Pleistocene glaciation produced valley glaciers that extended to mid-valley positions (halfway between head and mouth) in the Mavrolongus and Xerolakki valleys. This ice, which originated in valley head cirques, accomplished less erosion than did preceding ice. Unit 2 deposits are more extensively exposed within the valleys, and valley deepening was less significant than in preceding glacial stages.

Eastern and Northern Mount Olympus Piedmont

The most compelling evidence for the extent of Pleistocene glacial activity on Mount Olympus (and the High Pieria) is to be found in the sedimentary deposits of the eastern and northern Olympus piedmont. Direct glacial deposits (glacial diamicton or till) are well exposed on both the eastern piedmont and on the piedmont area between Mount Olympus and the southern High Pieria (Fig. 9). Similar deposits, tentatively considered to be of glacial origin, are also found west of Olympus, from the mountain front to the

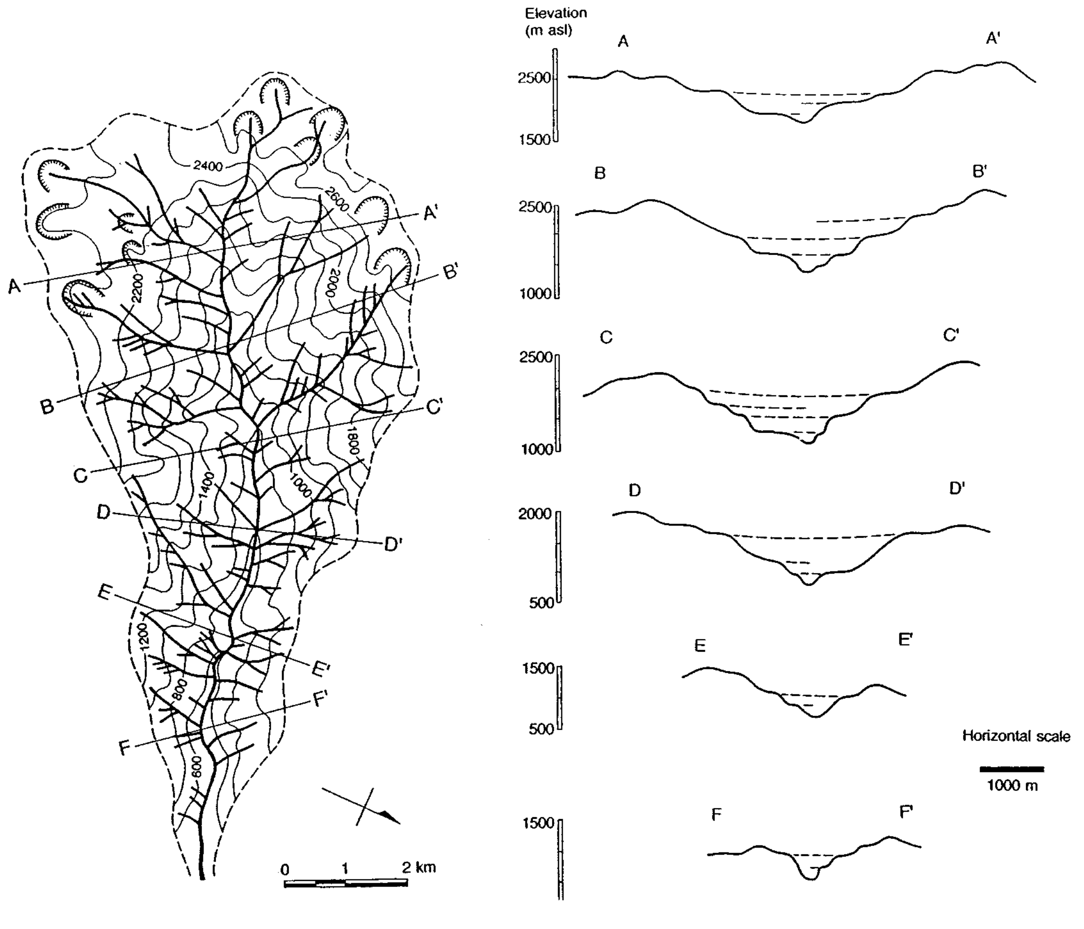

Figure 11. Cross-profiles of the Mavrolongus Valley. Profile locations are shown on accompanying map. Dashed lines represent projected valley cross-profiles.

Plains of Thessaly. In general, these deposits consist of poorly sorted (cobble to boulder clasts in a sand-silt matrix) diamictons and gravels that are highly indurated. Where these materials are directly associated with drainage from Mount Olympus, they are typical unit 1 sediments. Between Mount Olympus and the High Pieria, where clast composition is more cosmopolitan, having a high percentage of igneous and metamorphic clasts as well as carbonate clasts, the sediments are less well indurated. Soils developed on both materials are, however, generally similar (discussion following). In addition, the Olympus-provenance and the Olympus-Pieria–provenance sediments are interbedded in at least one locality near the confluence of the Xerolakki and the Mavroneri valleys. As a result, the Olympus- and Olympus-Pieria–provenance deposits, despite their compositional differences, are considered to be coeval.

The deposits that are considered to be of direct glacial origin display a distinctive constructional morphology (reflected both in surface contours and in subsequent, as opposed to consequent, drainage patterns) that is not a morphology associated with simple alluvial fan construction. The gross outline of the distribution of these materials is in the form of broad, elongate lobes that extend eastward from the valleys of the Mavrolongus and the Mavroneri (Figs. 3 and 9), and westward from the Mavratza Valley. These lobate accumulations are notable in that they are positive topographic elements on the piedmont. Elevations are as much as 100 m above the general piedmont surface. Furthermore, within the boundaries of the lobes, topography is commonly defined by the occurrence of distinct linear ridge forms. On the eastern piedmont, this morphology is complicated by the fact that these deposits are cut by a series of young faults that imposes a secondary linear morphology, essentially parallel to that of the deposits. The ridges are considered to be end moraines that record successive retreatal positions of piedmont ice.

The piedmont glacial sediments and the morainal ridges have been mapped in greatest detail within the lower reaches of the Mavroneri drainage (Fig. 9). Here, exposure and access are good, and topographic map and aerial photographic coverage facilitate mapping of geomorphic patterns. Both Olympus-provenance and Olympus-Pieria–provenance deposits are juxtaposed here, and comparisons between the two groups of deposits can be made readily. This area is of additional interest because previous workers have mapped and discussed these materials in terms of Neogene fluvial and lacustrine sediments (Psilovikos, 1981, 1984; Katsikatsos and Migiros, 1987; Latsoudas, 1985). Other workers (Faugères, 1992, personal commun.) have suggested that it is unlikely that glaciers could have extended this far onto the piedmont, because there is no adequate source for such extensive glaciers. Evidence discussed later herein refutes the fluvial-lacustrine origin of the sediments in question, at least in the Mavroneri drainage. The issue of whether there is an adequate source for extensive piedmont ice needs to be looked at in terms of sources other than the cirques of Olympus. We argue that uplands north of Olympus (the High Pieria), in combination with north-facing and northeast-facing cirques on Olympus, provided an adequate source of ice for piedmont glaciers in the Mavroneri drainage.

The sedimentary character of the deposits that compose the prominent lobate features of the Mavroneri drainage is complex. Extensive stream cuts along the course of the Mavroneri River, as it enters the piedmont, expose thick (40–50 m) successions of well-stratified, generally upward-fining sed-

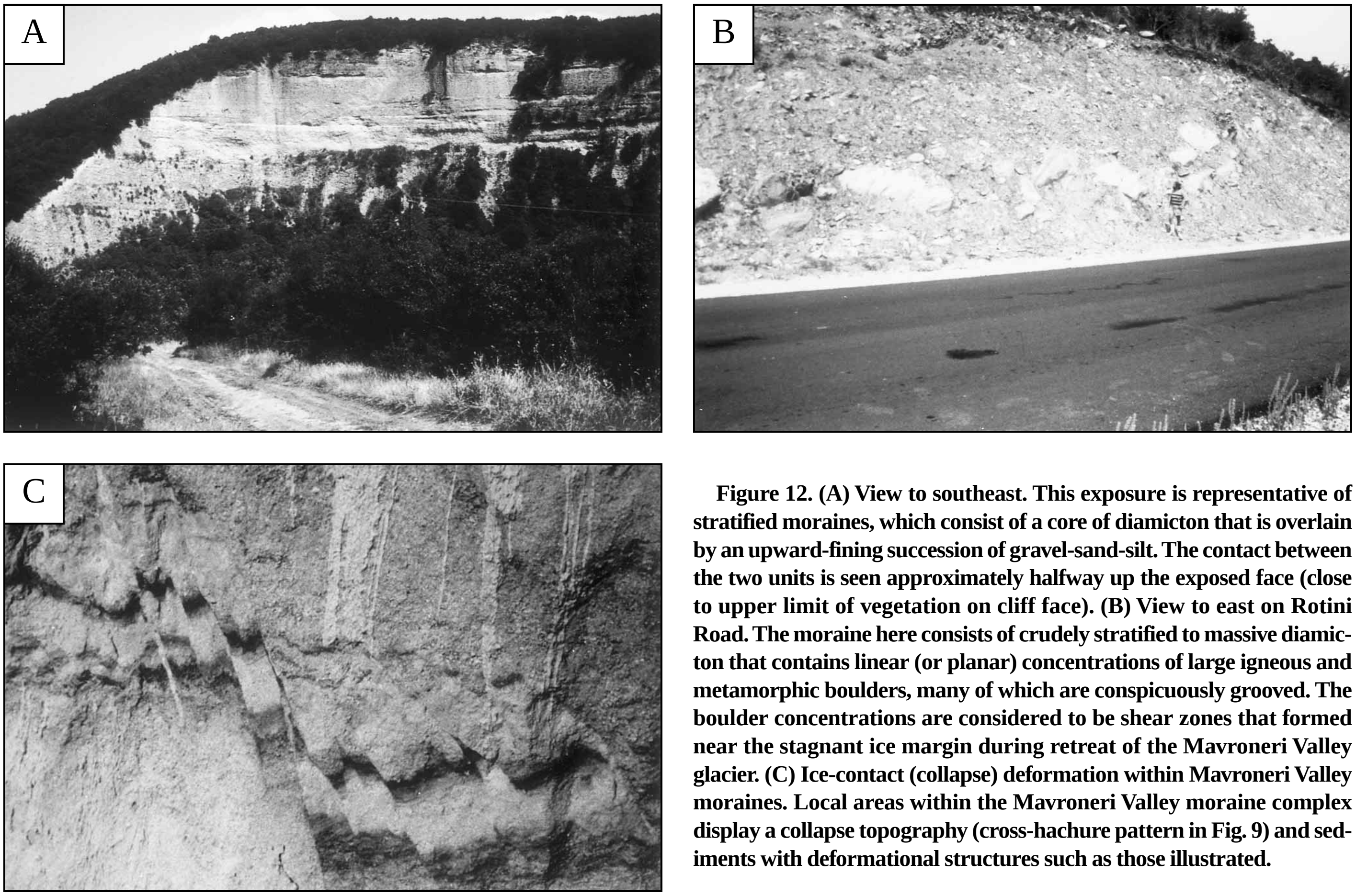

Figure 12. (A) View to southeast. This exposure is representative of stratified moraines, which consist of a core of diamicton that is overlain by an upward-fining succession of gravel-sand-silt. The contact between the two units is seen approximately halfway up the exposed face (close to upper limit of vegetation on cliff face). (B) View to east on Rotini Road. The moraine here consists of crudely stratified to massive diamicton that contains linear (or planar) concentrations of large igneous and metamorphic boulders, many of which are conspicuously grooved. The boulder concentrations are considered to be shear zones that formed near the stagnant ice margin during retreat of the Mavroneri Valley glacier. (C) Ice-contact (collapse) deformation within Mavroneri Valley moraines. Local areas within the Mavroneri Valley moraine complex display a collapse topography (cross-hachure pattern in Fig. 9) and sediments with deformational structures such as those illustrated.

iments (Fig. 12A). Commonly, these materials consist of a lower, massive, and matrix-supported diamicton that is abruptly, but conformably, overlain by a stratified and upward-fining sequence of gravel, sand, and silt. The materials are partially lithified, and maintain nearly vertical cliff faces. Soils developed on these materials (Table 1) are red, strongly clay enriched, and considered to be equivalent to unit 1 soils defined on the piedmont east of Mount Olympus (Fitzgerald, 1996, in press; Fitzgerald and Smith, 1995; Jones, in press; Jones and Smith, 1995). Elsewhere, the sediments composing the linear ridge forms consist of thick (several tens of meters) accumulations of very coarse, matrix-supported diamictons that display glaciotectonic deformation (Fig. 12B). In other places, massive, matrix-supported diamictons are interbedded with both coarse and fine, fluvially modified sediments, some of which display deformational features related to collapse of the sediment pile (ice-contact deformation; Fig. 12C). In these last-mentioned deposits, surface morphology typically mirrors internal sediment structure. Ridge forms degenerate to a chaotic arrangement of isolated hills and depressions (kame and kettle). Accumulations of fine, laminated sediments are common in these areas of chaotic (collapse) topography. Topographically (and stratigraphically) inset into the variety of deposits described above are distinctly fluvial sediments that form paired terraces on either side of the Mavroneri River.

The morphology and the sedimentary character of the deposits that occupy the lower reaches of the Mavroneri drainage together define a recessional glacial sequence for a rather large valley-piedmont glacial system. The distinct ridge forms are symmetrically arranged about the valley axis, and in places close across the valley (being breached only by the modern drainage). They are concentrically arranged, as would be expected in the case of a regularly retreating ice margin. They record disruption where they merge with similar ridges produced by ice lobes originating from Olympus valleys. Apart from their own distinctive morphology, the ridges produce a parallel (subparallel) pattern of drainage that is unique on the Olympus piedmont (where most drainage is a function of modern alluvial fan processes). Given these features, it is difficult to argue that the unusual morphology of deposits within the Mavroneri drainage can be attributed to fluvial and/or alluvial fan processes. The sediments cannot be readily explained in terms of simple fluvial and/or alluvial fan processes.

The deposits described above are, for the most part, composed of Pieria- or Olympus-Pieria–provenance sediments. These deposits can be shown to be coeval with Olympus-provenance deposits at the mouths of the Xerolakki and Mavrolongus Valleys. Stream cuts near the confluence of the Xerolakki and the Mavroneri rivers expose interbedded Olympus-provenance and Pieria-provenance deposits, and distinctive soils are developed through sediments of both provenances. The soils developed on Pieria-provenance, Olympus-provenance, and mixed Olympus-Pieria–provenance sediments are broadly similar (discussion following). If these soils are equivalent (Table 2), and if correlation can be made with soils described and dated on the Larissa Plain (Demitrack, 1986), all of these deposits are likely to be ascribed to unit 1 glaciation of the Mount Olympus region.

Olympus-provenance deposits considered to be coeval with the Mavroneri deposits described above occur at the confluence of the Xerolakki and Mavroneri valleys and at the mouth of the Mavrolongus Valley. These deposits form distinct lobate accumulations immediately adjacent to the mountain front (Figs. 3 and 9). They are composed of highly indurated diamicton, gravel, and sand (unit 1 deposits), and as a result, rise above the general level of adjacent piedmont deposits. As with the Mavroneri deposits, these materials display a surface morphology that consists of distinct ridge forms, arranged in a roughly concentric arcuate pattern at the mouths of major valleys draining, in this case, Mount Olympus exclusively. Ridge forms (moraines) are shorter, and less clearly defined than those of the Mavroneri. This is partly a function of the fact that modern drainage has developed largely independently of ridge morphology and is partly due to the fact that these deposits have been cut by a network of faults related to recent uplift of Mount Olympus. At the Xerolakki-Mavroneri confluence, the Olympus-provenance deposits merge with Olympus-Pieria–provenance deposits. Here the ridge forms of the Olympus-provenance deposits have been deformed against the margin of the more extensive Olympus-Pieria–provenance deposits (Fig. 9), further indicating that the two sets of deposits are coeval.

Deposits of Olympus-provenance glacial sediments exposed at the mouth of the Mavrolongus Valley (Enipius River), north and south of the town of Litochoro (Fig. 3), are similar in all regards to the Olympus-provenance deposits that occur at the Xerolakki-Mavroneri confluence. The Mavrolongus deposits are less extensive than the Xerolakki-Mavroneri deposits. The Mavrolongus deposits nonetheless define a distinct lobate accumulation that extends eastward from the mouth of the Mavrolongus toward the Aegean Sea. The gorge of the Enipius River is deeply entrenched into these materials and exposes sediments that define the three sedimentary units described earlier. It is within this valley, and in the coastal bluffs to the east, that the juxtaposition of the direct glacial–ice-contact–proglacial depositional continuum is most clearly documented. Here, massive, matrix-supported diamicton can be shown to grade eastward into progressively more sorted, clast-supported gravel and sand.

A glacial (as opposed to a fluvial and/or alluvial fan) origin for the deposits of the eastern and northern Olympus piedmont is indicated by the following: (1) the prevalence of diamictic sediments that consist of subangular to subrounded boulder and cobble clasts in a finer matrix; (2) the occurrence within these sediments of shear zones that contain (are defined by) grooved boulder clasts; (3) the superposition, without significant erosional break, of upward-fining gravel and sand over diamicton; (4) the lateral continuity and the internal uniformity of sedimentary units; and (5) a surface morphology of distinct ridges arranged concentrically about the mouths of major valleys draining Olympus and the High Pieria that show apparent fluid deformation at their confluence. The distinction between glaciofluvial (outwash fans, valley trains) and fluvial and/or alluvial (alluvial fans, flood plains) deposits is not always clear and distinct. However, the spatial distribution of these deposits, arranged close to the mountain and lobate about the mouths of major valleys (not all valleys, or even most valleys) and traceable through valleys to cirque origins, coupled with a distinct ridge morphology not found associated with adjacent alluvial fans, but characteristic of terminal-recessional moraine complexes in other glaciated localities, strongly supports the concept of an origin for these deposits as glacial piedmont lobes. If that is the case, ice spread from the Mavrolongus (Enipius) Valley, the Mavroneri (and Xerolakki) Valley, and probably from major valleys to the west of Olympus, for several kilometers onto the adjacent piedmont, to present elevations of less than 100 m asl. Acceptance of this conclusion carries with it acceptance of the idea that glacier ice extended much farther and much lower than suggested by previous workers (Messerli, 1967), who indicated the lowest ice to be at 1600 m asl (present). It also implies that the regional snowline was substantially lower than the elevation of 2200 m asl that has been previously suggested (Messerli, 1967).

Mount Olympus Piedmont: Soils and Paleosols

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 (Fitzgerald, 1996, in press; Jones, in press). The objectives of these studies have been to (1) establish a basis for correlation of deposits within the Mount Olympus area, and (2) provide a basis for correlation of Mount Olympus soils with a dated succession of soils south of Mount Olympus

(Demitrack, 1986). At the same time, efforts continue for the acquisition of dates on the Mount Olympus deposits.

Each of the sedimentary units (units 1–3) of the piedmont succession displays well-developed soil profiles (Figs. 13 and 14). Soils separate each of the sedimentary packages (are developed on lower units) and also occur within the sedimentary packages. Some profiles are complete, or virtually complete, and others are truncated as a result of erosion and subsequent sediment deposition. Some soils are laterally extensive and can be recognized throughout the piedmont area. These soils are considered to be representative of regional depositional hiatuses and extended subaerial exposure. Other soils appear to be more localized, and cannot be traced from exposure to exposure within the piedmont succession. These soils are thought to record localized depositional breaks related to shifting depositional centers in the construction of the Olympus compound alluvial fan on the eastern piedmont.

The most pedogenically developed soils occur on top of unit 1 deposits (Fig. 14—Prionia Road soil, Dion Road red clay, Plaka Road brown soil) or between unit 1 and unit 2 deposits (Fig. 14—Plaka-Gritsa soil). These soils are characterized by strong rubification; soil colors (for the optimal B horizon) range from 2.5YR 3/6 to 5YR 4/4. The soil is significantly clay enriched (Table 1) and displays distinct Bt horizon formation. Soil structure is strong, coarse, angular blocky to prismatic. The lower B and upper C horizons are marked by pronounced secondary carbonate accumulation (calcrete or Bk/Ck horizons). Profile development indices (PDIs) range from 73 to 82 (Fitzgerald, 1996).

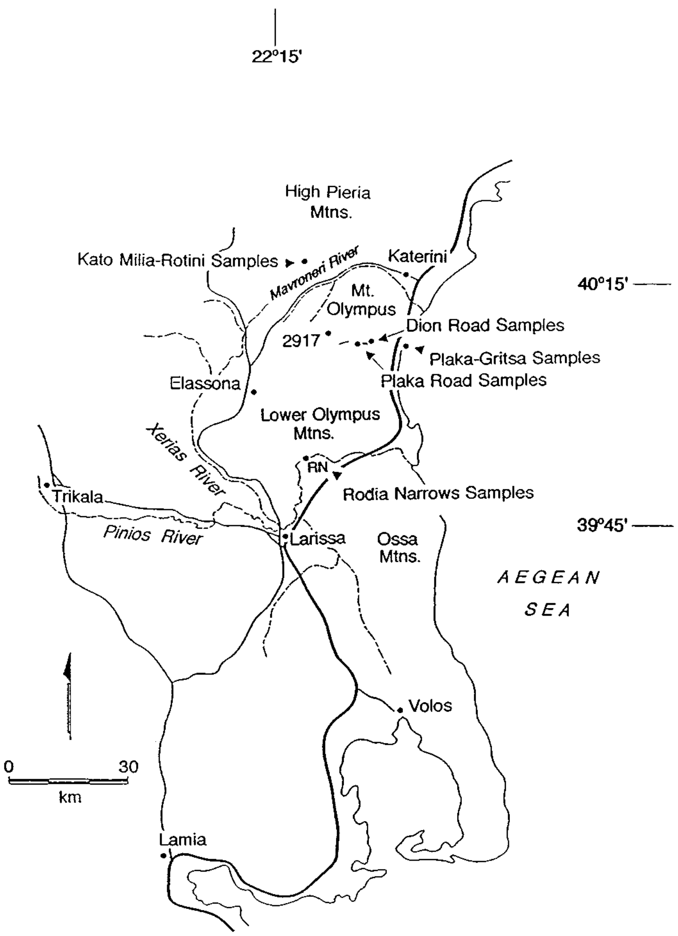

Figure 13. Locations of soil sites sampled for study in connection with this project.

A soil (Fig. 14—Kato Milia–Rotini soil) developed on Pieria provenance deposits in the Mavroneri Valley is pedogenically similar to unit 1 soils developed on Olympus provenance deposits (Table 1), and therefore is considered to be correlative (Fitzgerald, 1996, in press; Jones, in press). The

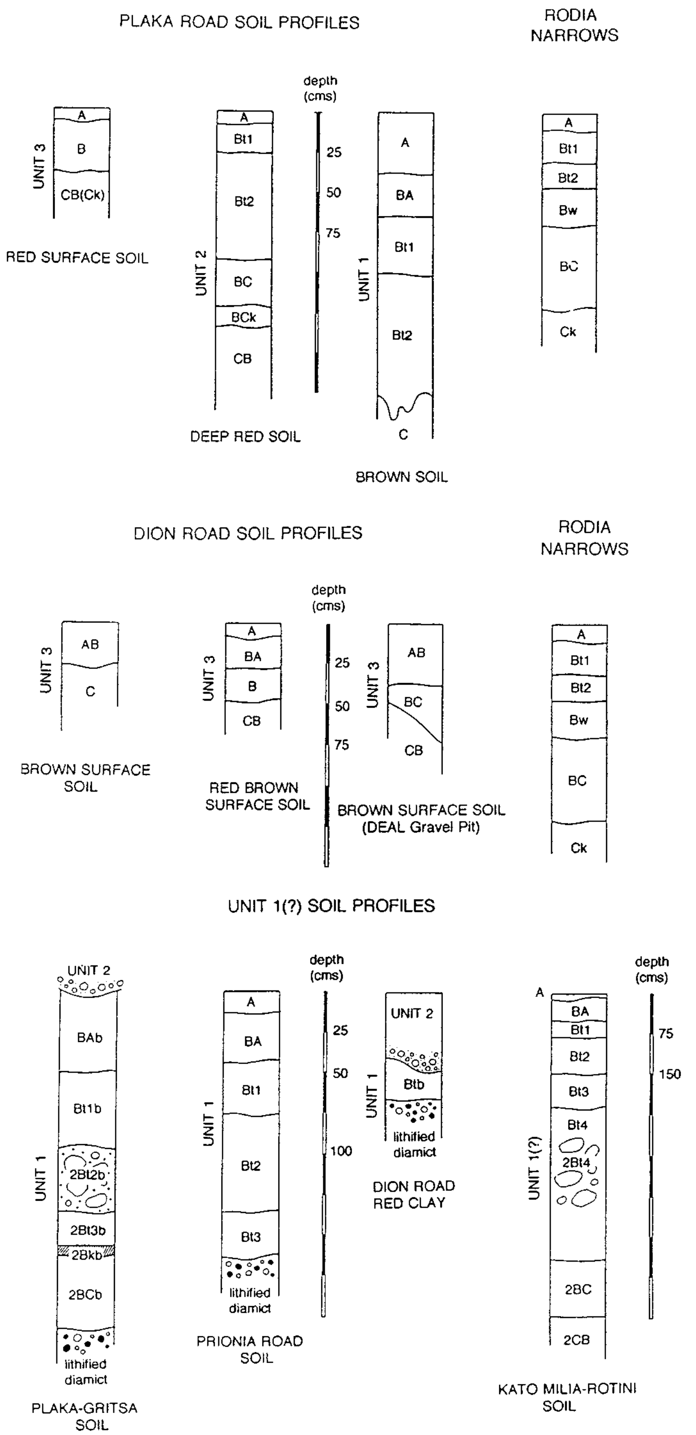

Figure 14. Simplified soil profiles for soils of the eastern piedmont of Mount Olympus (including Plaka-Gritsa and Kato Milia–Rotini) and Rodia Narrows (Larissa Plain). Top—Plaka Road profiles compared to Rodia Narrows profile. Center—Dion Road profiles compared to Rodia Narrows profile. Bottom—Other profiles from eastern piedmont.

Kato Milia–Rotini soil is significantly thicker than those soils (Prionia Road soil, Dion Road red clay), probably because the Pieria-provenance deposits are significantly less lithified than the Olympus-provenance deposits. Although details of the profiles differ, the surface soils in both provenances are represented by a complete (A/B/C/R) profile (Fig. 14, Table 1). As discussed previously, the unit 1 soil is tentatively correlated with a deep-red soil developed on fan remnants (Demitrack, 1986) of the southern Olympus piedmont. That soil has a U/Th date of ≤210 000 years old.

The unit 2 soils of the eastern piedmont are thick (2–3 m) and pedogenically well developed soils (distinct horizon formation, strong coloration [rubification], high clay content, moderate to strong blocky structure, PDI = 38) (Fig. 14—Plaka Road deep-red soil). Where these soils occur as surface soils, as is the case with the Plaka Road deep-red soil, they are strongly rubified, but less pedogenically developed than the surface unit 1 soil (PDI of 38 versus PDIs of 78 to 82). They are, however, thicker than the unit 1 soils, at least in part because they are developed in less indurated parent materials, as is the Mavroneri unit 1 soil.

Unit 3 soils are the surface soils over most of the piedmont deposits (Fig. 14—Plaka Road red surface soil; Dion Road brown surface soil, Dion Road red brown surface soil, DEAL gravel pit brown surface soil). These soils are relatively thin, and are the least pedogenically developed of the soils sampled on the piedmont. Profile development indices (Table 1) range from 5 to 13. Differences between soils are a function of subtle topographic details of the piedmont surface (soil catenas), and slightly different ages related to the development of soils on terraces that formed in response to both tectonic uplift and fluctuations of sea level.

A soil sampled at Rodia Narrows (Figs. 13 and 14) on the eastern margin of the Larissa Plain provides a reference to the soil succession dated by Demitrack (1986). This soil, which is a surface soil, is intermediate in development (PDI = 27) to that of unit 3 soils (PDI = 5 to 13) and unit 2 soils (PDI = 38) of the Olympus piedmont. It is considered to be a soil that is early unit 3 of the Olympus soil sequence (Table 2). It is likely that buried soils within the unit 3 deposits of the eastern Olympus piedmont began to develop at the same time as did the Rodia Narrows soil. However, the buried soils of the eastern piedmont formed in a more dynamic environment where erosion and deposition interrupted pedogenesis. These soils consist of only partial (truncated) profiles, and as a result were not sampled for analysis and determination of development indices.

Preliminary data from studies of the Olympus piedmont soils indicate the following: (1) a hierarchy of soil development can be established for the soils of the Olympus piedmont (Table 4); (2) on the basis of the degree of pedogenic development, soils can be correlated from one part of the Olympus piedmont to another; and (3) on the basis of the degree of pedogenic development, soils of the Olympus piedmont can be placed into a sequence of dated soils (Demitrack, 1986) of the Larissa Plain (Figs. 13 and 14—Rodia Narrows). The significance of a correlation between the Rodia Narrows soil and basal (or medial) unit 3 deposits of the eastern Olympus piedmont is that it is consistent with the suggestion that the unit 2 soil is contemporaneous with isotope stage 5, and that the unit 2 deposits represent isotope stage 6.

Mount Olympus Piedmont: Neotectonic History

The deposits of the Olympus piedmont are separated from the Olympus massif by a major normal fault that has been active since late Tertiary time (Schermer et al., 1990) and has resulted in uplift of Mount Olympus and subsidence of the Thermaikos basin to the east. This fault visibly offsets deposits of units 1 and 2. In addition, the sediments (including units 1, 2, and 3) that compose the eastern piedmont are offset by subsidiary normal faults and terraced as a result of continued displacement along these faults.

An important aspect of the present study involves the reconstruction of the recent tectonic history of the Mount Olympus area (McIntyre, 1994; McIntyre et al., 1994a, 1994b, in press; Nance and McIntyre, in press). In addition to its importance to the neotectonic history of the area, this work has significant bearing on the glacial history of Mount Olympus, because it is an essential factor in determining the magnitude, in absolute terms, of snowline depression during periods of glaciation of the mountain. Estimates of the rate of Quaternary uplift of Mount Olympus, based on the correlations proposed in Table 2, center on 1.6 m/k.y.; total uplift since deposition of unit 2 is about 200 m. These figures are based upon the following observations (Nance and McIntyre, in press): (1) a prominent north-northwest–trending frontal fault separates unit 2 deposits from rocks of the Olympus massif, with a minimum offset of approximately 150 m; (2) several subparallel northwest-trending faults, with a cumulative displacement of 130 m, offset the red soil developed on unit 1 deposits. Fault displacement (including offset on the frontal fault, as well as offset on subsidiary faults) exceeds about 280 m, yielding a minimum fault movement rate of roughly 1.25 m/k.y., if an isotope stage 7 age of 220 ka is assumed for the unit 1 soil. Cumulative displacement in excess of 200 m on the unit 2 soil produces the more reliable estimate of 1.6 m/k.y., if an isotope stage 5e age of 125 ka is assumed for the unit 2 soil.

SUMMARY AND CONCLUSIONS

Understanding that the existing data lack a firm chronologic base, and that the sequence of events can easily be shifted backward or forward in time, we propose the following general scenario for the glacial history of Mount Olympus. At some time prior to ca. 200 ka (oxygen isotope stage 8?), Mount Olympus was high enough and climate was cool and wet enough to produce glaciation. Upland cirques were developed by glaciers that filled then-existing valleys and spread as piedmont lobes onto the lowlands surrounding Mount Olympus. Ice was also extensive enough to pro-

TABLE 4. HIERARCHY OF SOILS OF THE MOUNT OLYMPUS PIEDMONT (EASTERN PIEDMONT AND MAVRONERI VALLEY) AND CORRELATION WITH SOILS OF THE LARISSA PLAIN (RODIA NARROWS)

Eastern Piedmont	Mavroneri Valley	Larissa Plain	PDI
Dion Road brown surface soil (DRBS)			5.0
DEAL Gravel Pit soil (DEAL)			10.6
Plaka Road red surface soil (PRRS)			11.3
Dion Road red brown surface soil (DRRBS)			13.2
		Rodia Narrows soil (50-55 ka)*	26.9
Plaka Road deep red soil (PRDR)			38.0
	Kato Milia-Rotini soil (KM-R)		50.8
Plaka Road brown soil (PRB)			72.9
Prionia Road soil (Prionia)			77.5
Dion Road red clay (DRRC)			N.D.
Plaka-Gritsa soil (P-G)			81.7

Notes: Hierarchy is based largely on profile development indices (PDI) from Fitzgerald (1996). Soils are arranged sequentially with oldest soils at the bottom. See also Table 1.

*Date from Demitrack (1986).

duce a small upland ice cap. Provisional estimates, based on reconstruction of glacier distribution and calculation of uplift rates, suggest that snowline depression during this glacial interval was approximately 3000 m. During the ensuing nonglacial (interglacial = isotope stage 7) interval, unit 1 sediments were extensively eroded and subsequently pedogenically altered (unit 1 soil). Uplift of Mount Olympus proceeded at a rate that produced between 100 and 200 m of increased summit elevation, on the basis of preliminary estimates of total uplift of post–unit 1 sediments (McIntyre, 1994; McIntyre et al., 1994a, 1994b). A second glacial episode (isotope stage 6) produced the inset upland cirques. Glaciers extended to positions near the mouths of present major valleys. Upland ice was extensive, covering the area of Bara as well as the Plateau of the Muses. Snowline was depressed to an elevation of 1000–1030 m asl (depression of approximately 2500 m). Proglacial sediments (unit 2) were deposited on the Olympus piedmont. A subsequent nonglacial period (isotope stage 5) was characterized by erosion, subsequent pedogenesis (unit 2 soil), and tectonic uplift. The final glacial stage (isotope stages 4–2) involved development of the valley head cirques and reoccupation of selected upland cirque basins. Glaciers extended to mid-valley positions, and there was no upland ice cap. Snowline was depressed by approximately 1300 m. Proglacial sediments were deposited on the adjacent piedmont (unit 3). Finally, the mountain was deglaciated, and present nonglacial conditions were established (including erosion and development of the unit 3 soils).

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