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A RE-EVALUATION OF THE EXTENT OF PLEISTOCENE GLACIATION IN THE MOUNT OLYMPUS REGION, GREECE

G. Smith[1], R. Nance[1] and A. Genes[2]

ABSTRACT

Mount Olympus, the highest mountain in Greece, was, according to most investigators, glaciated during the mid- to late- Pleistocene. Previous studies of the Mount Olympus region have suggested that glaciation was restricted to small valley glaciers in upland and valley head positions. These studies imply that the regional Pleistocene snowline was lowered to elevations of 2200 to 2400 m asl (present), and that glacial conditions (active glaciers) were restricted to the latest Pleistocene (= Würm).

The present study provides evidence that Mount Olympus was glaciated more extensively than has been previously indicated. In addition, this study shows that the Mount Olympus region was glaciated on several occasions, and that the original condition of glaciation significantly predated late Pleistocene (= Würm). Indeed, the Mount Olympus region may well provide the most complete record of Pleistocene glaciation yet documented in southern Europe.

Piedmont sediments, east and west of Olympus, record at least three stages of active deposition. Each of these sedimentary units can be related, directly or indirectly, to glacial activity on Mount Olympus. Soils that separate each of these units can be related to non-glacial intervals. These soils can also be tenta-tively correlated to a dated soil succession south of Olympus. If provisional correlations are correct, oldest soils on the Olympus piedmont record the Mindel/Riss interglacial event in the Olympus region. Oldest Pleistocene sediments, therefore, record Mindel-equivalent glaciation of the mountain.

Sedimentary units defined on the piedmont are also recognized on the Olympus upland and within valley head cirques. The distribution of these materials, as well as the occurrence of glacial erosional and depositional landforms, indicate that Mount Olympus supported upland ice during the first and second (of three) episodes of glaciation, and that the first episode of glaciation was extensive enough to produce piedmont ice lobes that covered parts of the eastern, northern, and western piedmont of the mountain. Furthermore, the evaluation of cirque floor elevations, coupled with the distribution of glacial sediments, indicates that (early-, mid-) Pleistocene snowline was as low as 1900 m asl (present), 1000 m below the present summit elevation.

1 Department of Geological Sciences, Ohio University, Athens, Ohio 45701
2 Department of Geography and Earth Science, University of Massachusetts, Boston, Massachusetts 02125

INTRODUCTION

Mt. Olympus, the highest mountain in Greece, takes the form of a massive limestone plateau that rises to a height of 2917 m asl and occupies an area of more than 300 km^2 at its base (Figure 1). During the Pleistocene, this region of northeastern mainland Greece was a significant center of glaciation that, at 40°N latitude, 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 Mt. 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 over twenty years ago (e.g. Wiche, 1956a, b; Messerli, 1966a, b, 1967; Faugères, 1969). These studies placed the snowline for the late Pleistocene on Mt. Olympus at about 2400 m asl (a height exceeded by very few peaks in southern Europe), and concluded that glaciation in the Mt. Olympus region was of limited extent and that permanent ice was restricted to upland cirques with small valley glaciers descending to elevations no lower than 1600 m asl. This early work also did little to establish the sequence and timing of glacial events in the Mt. Olympus region.

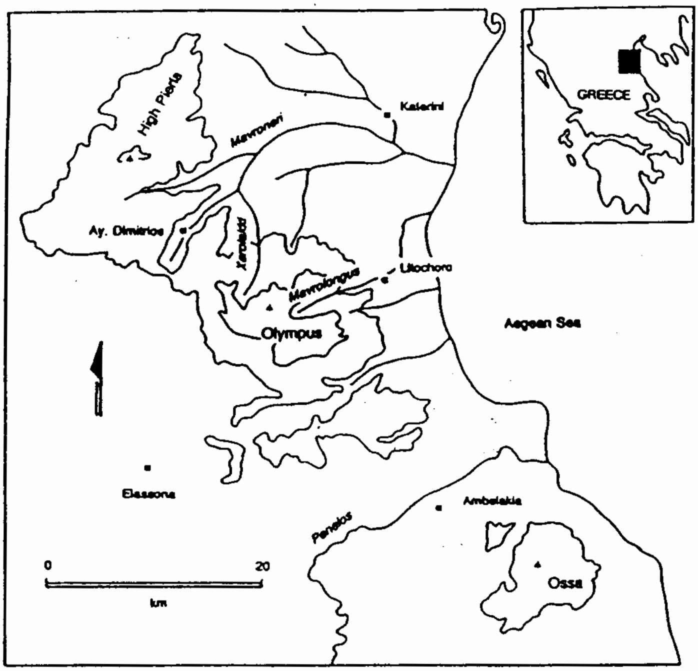

Fig. 1: Geographic map of Mt. Olympus and adjacent mountain ranges in northeastern mainland Greece (CI = 1000 m), showing locations of major towns and rivers.

Field mapping of the Mt. Olympus region over a three-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 and the paleoclimatic significance of the Mt. Olympus region. Preliminary results of the present study indicate that Mt. 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 earliest glaciation occurred more than 200 ka ago, with snowline depression to at least 1900 m asl - a height exceeded by several peaks in Greece (Genes et al., 1992, Smith et al., 1993, 1994). Furthermore, reconnaissance observations indicate that substantial glaciers existed in the mountains of the High Pieria to the north of Olympus and in the Ossa Mountains south of 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 syn- 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).

PHYSICAL SETTING

The Mt. 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) 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 Recent 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 outcrop in a more-or-less concentric arrangement on the flanks of the Mt. Olympus and Mt. Ossa massifs (Figure 2). The Pieria Mountains (High Pieria), northeast of Mt. Olympus, are underlain by late Paleozoic granites and metamorphic rocks (Yarwood and Aftalion, 1976; Nance, 1978, 1981).

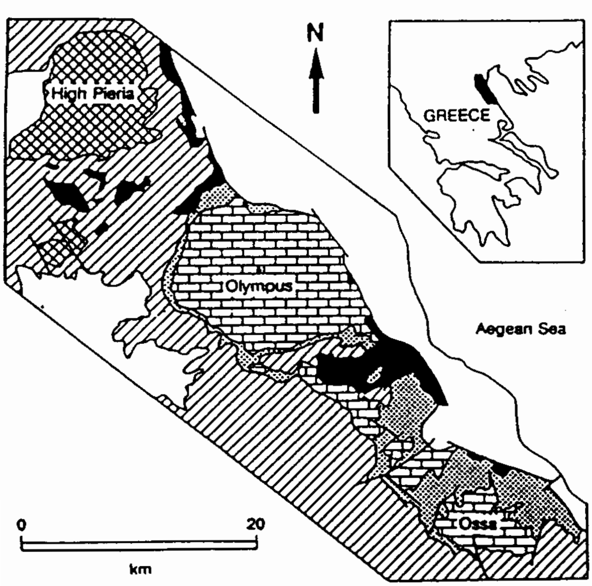

Fig. 2: Generalized bedrock geology map of the Mt. Olympus region, simplified after Yarwood and Aftalion (1976), Nance (1981), Schmitt (1983), Katsikatsos and Migiros (1987), and Schermer at al. (1990). Brick pattern = Triassic and Cretaceous to early Tertiary shelf carbonates (Olympus-Ossa unit). Stippling = Mesozoic and continental margin sediments (Ambelakia unit). Diagonal lines and cross-hatching = Paleozoic metamorphic rocks and granites, respectively (Pierien and Infrapierien units). Black = ophiolitic rocks. Quaternary units are unshaded.

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), the Cs (Csb) climate of Köppen, although the high elevation of Mt. Olympus imposes a strong orographic influence on local conditions. Weather in the area is further influenced by the fact that Mt. 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.

PREVIOUS INVESTIGATIONS

Previous studies of the Pleistocene and Recent history of the Mt. Olympus region, particularly as related to glaciation, are few. Summaries of the Quaternary history of the eastern Mediterranean region have been 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 have been documented by Mistardis (1969), Pechoux (1970), and Lewin et al. (1991). Quaternary climatic cycles in the area around Mt. Olympus have been defined and discussed by Wijmstra (1969, 1976) and Tzedakis (1993). The geology and geomorphology of the piedmont region surrounding Mt. 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; LePichon, et al., 1984; Lyberis, 1984; Lykousis, 1991; Piper and Perissoratis, 1991). Studies that treat specifically the glacial history of Mt. 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 consider the diversity of erosional and depositional evidence of glaciation in the Mt. Olympus region, and, as a result, that they significantly understate the complexity and the extent of glacial activity in the area.

GLACIAL GEOLOGY OF MT. OLYMPUS: INITIAL RESULTS

The complexity of the Pleistocene and Recent geology of Mt. Olympus reflects the fact that regional surface processes have been superimposed upon tectonic activity that continues to the present day. (Faugeres, 1977; Pope and van Andel, 1984; Psilovikos, 1984; Demitrack, 1986; Burton et al., 1991; Caputo and Pavlides, 1993). In addition, the record of Pleistocene glaciation includes a spectrum of erosional and depositional features that extend from the summit of Mt. Olympus (Faugeres, 1977; Hughes, et al., 1993; Smith, et al., 1993) to the Aegean Sea (Faugeres, 1977; Psilovikos, 1984; Smith et al., 1993) 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.

The Mt. Olympus Piedmont - Stratigraphic Framework

The materials of the Olympus piedmont (Figure 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) recognize 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 comprise them. [Note: Since

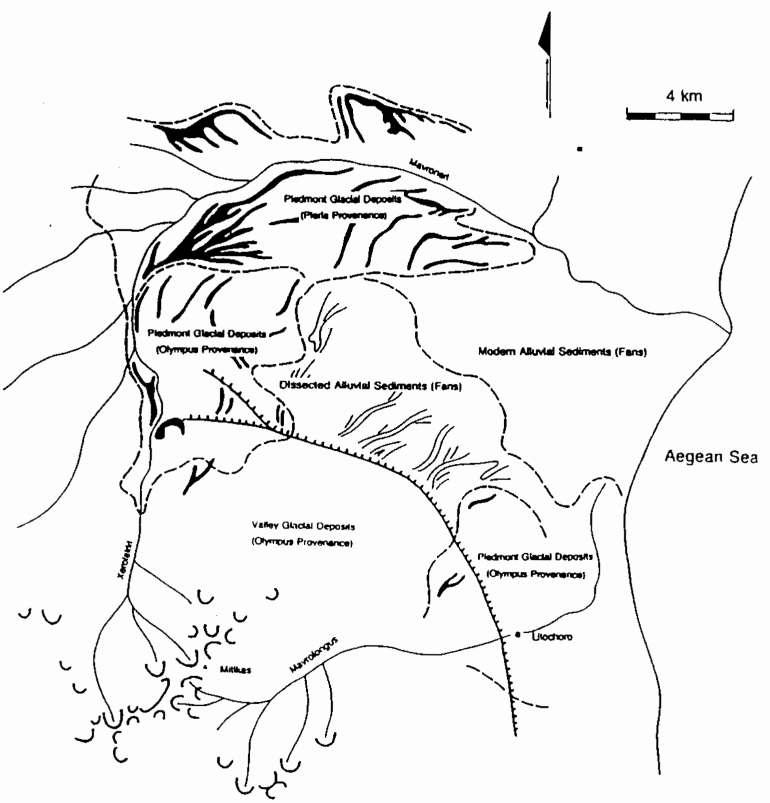

Fig. 3: Generalized geomorphology of the eastern and northern Olympus piedmont area, showing distribution of piedmont glacial deposits and alluvial sediments. Semi-circles = cirques. Heavy dark lines = end moraines. Barbed line = boundary fault. Dashed lines = geomorphic boundaries.

all sediments of the eastern piedmont are derived from Mt. Olympus, and all consist of predominantly carbonate clasts, degree of lithification is, for the most part, a function of secondary carbonate cementation.] The oldest sedimentary unit (unit 1) is completely indurated. It is rich in fine matrix, and, when weathered produces a thick, deep red, strongly clay-enriched soil. The intermediate unit (unit 2) is partially indurated; lithified beds are interlayered with non-lithified beds. This unit consists of moderately well-sorted, predominantly clast-supported, massive and stratified gravel. It produces a relatively thick red-brown soil that is pedogenically distinct from the soil developed on the oldest sedimentary unit. The youngest unit (unit 3) is generally unlithified, well-stratified, predominantly clast-supported sand and gravel that produces a relatively thin brown soil.

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) suggest that the sediments, all of which they consider to be fanglomerates, record the following sequence of events: (1) deposition of unit 1 under arid/semi-arid conditions (with humid intervals) during Lower Villifranchian to Lower Pleistocene time; (2) deposition of unit 2 in a periglacial climatic regime during the Lower to Middle Pleistocene (Günz and Mindel); and (3) deposition of unit 3 in a glacial climate during the Middle to Upper Pleistocene (Riss and Würm). None of these units have been considered by previous workers to be of direct glacial origin. Indeed, there is no clear indication in previous studies that ice played any role at all in the deposition of these sediments.

Smith and others (1993) suggest an alternative interpretation of the Olympus piedmont sediments. These authors propose that unit 1 sediments on the piedmont are predominantly glacial diamicts, with a minor proglacial component. The deep-red soil developed on these sediments records an extended interval, probably of interglacial duration, during which substantial pedogenesis and erosion occurred. Unit 2 sediments on the piedmont were 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. Soil colors are less strong, clay accumulation is less, and horizonation 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 soil profiles that may likewise record interstadial weathering intervals. Unit 3 sediments are generally similar to unit 2 sediments, although they are not indurated. They are fluvial and glaciofluvial 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 non-glacial conditions. This unit also contains buried partial soil profiles. Unit 1 is considered to record deposition of glacial sediment (till?) by ice in piedmont lobes east, north, and west of Mt. Olympus. Units 2 and 3 record deposition of proglacial sediment from valley ice that never reached the piedmont slope of Olympus. Units 2 and 3 also include non-glacial fluvial deposits. That is to say, these two sediment packages record both late- glacial and post-glacial deposition on the piedmont.

The absolute timing of these events is difficult to establish. Because sediments are rich in carbonate clasts (and matrix), conventional radiocarbon dating procedures are of no use. Indeed, efforts to date shells and charcoals within the piedmont sediments by ^{14}C methods have consistently provided anomalously young dates. It may, however, be possible to use U-series (U/Th) isochron procedures (Luo and Ku, 1991; Bischoff and Fitzpatrick, 1991) to date pedogenic carbonate accumulations (nodules, calcretes) within the soils developed on the piedmont sediments. This is a major objective of current research.

Until such time as absolute dates are available, a tentative chronology (Table 1) for depositional and pedogenic events on the piedmont can be achieved through correlation of the soil stratigraphy from the eastern Olympus piedmont (present study) with a similar stratigraphy from the southern Olympus piedmont (Demitrack, 1986). A provisional correlation of the soil developed on unit 1 sediments of the eastern piedmont with a soil developed on fan remnants south of Olympus suggests that the unit 1 soil is at least 200,000 years old (oxygen isotope stage 7). As a result, this soil is considered to represent the Mindel/Riss interglacial stage, although it may be as young as the Riss/Würm. The development of a detailed soil stratigraphy and soil profile development indices (Harden, 1982; Harden and Taylor, 1983) are currently underway in an effort to establish a reliable basis for correlation of soils between the eastern and southern piedmont regions.

The Olympus Piedmont - Neotectonic History

The deposits of the Olympus piedmont are separated from the Olympus massif

Table 1: Tentative chronology for depositional and pedogenic events on the eastern Olympus piedmont, with correlations to other localities. Depositional intervals (age) based on radiometic dating (^{14}C and U/Th) by Demitrack (1986).

Demitrack (1986)	age (ka)*	Pope & van Andel (1984)	Lewin et al. (1991)	Smith et al. (this paper)
Modern Pinios Alluvium		Kranidhi Alluvium		
Premodern Pinios Alluvium		Flambouro Alluvium (Upper Member)	Klithi Unit	Modern Alluvium
		Flambouro Alluvium (Lower Member)		
		Pikrodafni Alluvium		
Girtoni Alluvium	6-7			
Mikrolithos Alluvium	10-14			
New Red Fan Alluvium	14-30		Vikos Unit Aristi Unit	Unit 3 Deposits
Agia Sophia Alluvium	27-42	Loutro Alluvium (Upper Member)		
Old Red Fan Alluvium	54-125	Loutro Alluvium (Middle Member)		
		Loutro Alluvium (Lower Member)	Kipi Unit	Unit 2 Deposits
Terrace Fragments	210(?)			Unit 1 Deposits

by a major normal fault that has been active since late Tertiary time (Schermer et al., 1990), and which has resulted in uplift of Mt. 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 comprise the eastern piedmont are both offset by subsidiary normal faults and terraced as a result of continued displacement along these faults (Figure 4). An important aspect of the present study involves the reconstruction of the recent tectonic history of the Mt. Olympus area (McIntyre, 1994). Apart from its importance to the neotectonic history of the area, this work has significant bearing on the glacial history of Mt. Olympus, since it is an essential factor in determining the magnitude, in absolute terms, of snowline depression during periods of glaciation of the mountain.

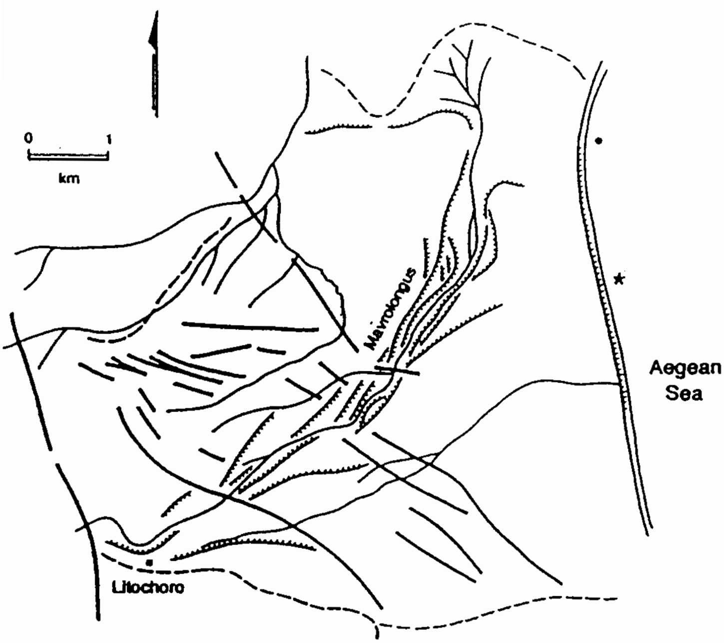

Fig. 4: Map of the eastern Olympus piedmont in the vicinity of the Enipius (Mavrolongus) River. Heavy lines = Pleistocene-Recent faults. Barbed lines = Pleistocene-Recent stream terraces.

The Olympus Upland

Study of the glacial geology of the Mt. Olympus upland has been focused on three areas (Figure 5): (1) the area north and east of the summit (the Plateau of the Muses), (2) the area south and east of the summit (Bara), and (3) the area west of the summit. Work on the Plateau of the Muses (Hughes, 1993, 1994) has been completed. Work on Bara (Clerkin, 1995) is currently underway.

The general geography of the **Plateau of the Muses** is illustrated in Figure 5. Principal peaks include Mytikas (summit = 2917 m), Stephani (2909 m), Skolio (2911 m) and Pr. Ilias (2813 m). Upland basins occur between these peaks, and are sometimes separated from them by distinct topographic saddles. 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). Study of the Plateau of the Muses has centered on those features considered to be cirques

(Wiche, 1956a, 1956b; Messerli, 1967; Hughes, 1994).

Based on the evaluation of several morphologic attributes (height, length, width, k-value, and ratios), as well as orientation and elevation (Hughes, 1994), cirques have been divided into two general categories: upland cirques, and valley head cirques (Smith and Hughes, 1994). Upland cirques are, for the most part, subdued features with poorly-defined headwalls and sidewalls, but with distinct basinal form. Valley head cirques have well-defined cirque morphology. Both groups of cirques contain deposits of diamict (till?;), and several of these deposits overlie striated bedrock surfaces). Of particular

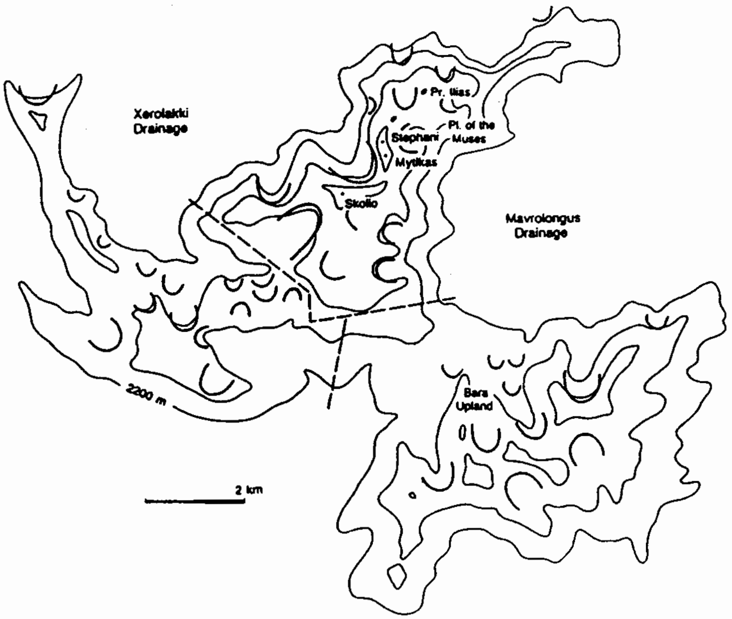

Fig. 5: Geomorphology of the Mt. Olympus upland (CI = 200 m). Semi-circles = cirques. Dashed lines divide upland into three study areas: (a) the Plateau of the Muses; (b) the Bara upland; and (c) the area west of the summit.

importance is the fact that 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 units 1 and 2 of the piedmont sedimentary succession. There is, however, no evidence of unit 3 sediments. Valley head cirques contain unit 2 and unit 3 sediments, but no unit 1 sediments. Soils equivalent to those that occur on piedmont sedimentary units are also found on cirque and upland sediments. The largest of the cirques on the mountain (Megali Kazania), which is a north-facing cirque immediately below the summit, contains deposits and constructional (morainal) topography that post-dates unit 3 materials. These deposits are restricted to the cirque basin, and are tentatively considered to be of Neoglacial age.

Cirque floor elevations further distinguish the two groups of cirques, and provide some basis for defining paleosnowline elevations. Cirque floor elevations (for both the Plateau of the Muses and Bara) range from 2200 m asl to 2670 m asl. On average, upland cirque floor elevations are close to 2500 m asl, while valley head cirque floors are roughly 200 m lower (ca. 2300 m asl).

The **Bara** upland has been studied only in reconnaissance. Nonetheless, a few general observations can be made. The cirques of Bara display the same distinction between upland and valley head groups. Most cirques fed ice that flowed toward the eastern piedmont. Four of the cirques (all upland cirques) fed ice that flowed to the western piedmont. Of particular importance is the evidence on Bara of deposition of unit 1 and unit 2 sediments. Unit 2 sediments are several tens of meters thick and overlie possible unit 1 soils.

Summary

Understanding that the existing data lacks 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 Mt. Olympus. At some time prior to ca. 200 kyr BP (oxygen isotope stage 8? = Mindel?), Olympus was high enough and climate was cool/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 Olympus. Ice was also extensive enough to produce a small upland ice cap. During the ensuing non-glacial (interglacial = Mindel/Riss?) interval, unit 1 sediments were extensively eroded and pedogenically altered (unit 1 soil). Uplift of Mt. Olympus proceeded at a rate that produced between 100 and 200 m of increased summit elevation, based on preliminary estimates of total uplift of post-unit 1 sediments (McIntyre, pers. comm.). A second glacial episode (Riss?) produced the valley head cirques. Glaciers extended to positions near the mouths of present major valleys. Upland ice was extensive, and covered the area of Bara as well as the Plateau of the Muses. Proglacial sediments (unit 2) were deposited on the Olympus piedmont. A subsequent non-glacial period (Riss/Würm?) was, again, characterized by erosion, pedogenesis (unit 2 soil), and uplift (to slightly more than 200 m above the unit 1 surface). The final glacial stage (Würm?) involved re-occupation of the valley head cirques. Glaciers extended to mid-valley positions, and there was no upland ice. Proglacial sediments were deposited on the adjacent piedmont (unit 3) Finally, the mountain was deglaciated, and present non-glacial conditions were established (including erosion and development of the unit 3 soils).

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