| Πρακτικά | 4ου Συνέδριου | Μάϊος 1988 |
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| Δελτ. Ελλ. Γεωλ. Εταιρ. | Τομ. XXIII/1 σελ. 13-27 | Αθήνα 1989 |
| Bull. Geol. Soc. Greece | Vol. pag. | Athens |

# AGE AND TECTONIC SIGNIFICANCE OF METAMORPHIC EVENTS IN THE MT. OLYMPOS REGION, GREECE

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## ABSTRACT

We have used the $^{40}Ar/^{39}Ar$ method to date continental margin strata and basement rocks from the Olympos region that were subducted and metamorphosed during Alpine orogenesis. Five deformational and metamorphic events are recognized: 1) 295 Ma crystallization and cooling of granitic intrusions into the Pelagonian basement; 2) ~100 Ma greenschist to blueschist-greenschist facies metamorphism and imbrication of continental thrust sheets; 3) 53-55 Ma blueschist facies metamorphism of the Pierien and Ambelakia units; 4) 36-40 Ma thrusting of blueschists over the Olympos unit; 5) 16-23 Ma uplift and cooling to T< 100-150°C, associated with normal faulting that has continued to the present. The Ar data constrain the temperatures of metamorphism during continental subduction to T≤ 350°C, and indicate that extension and uplift in the Olympos region were synchronous with thrusting in the external Hellenides.

## ΣΥΝΟΨΗ

Με τη μέθοδο χρονολόγησης $^{40}Ar/^{39}Ar$ χρονολογήθηκαν στρώματα ηπειρωτικού περιθωρίου και πετρώματα κρυσταλλικού υποβάθρου από την περιοχή Ολύμπου τα οποία υποβυθίστηκαν και μεταμορφώθηκαν κατά την διάρκεια της αλπικής ορογένεσης. Προσδιορίστηκαν τα εξής πέντε γεγονότα παραμόρφωσης και μεταμόρφωσης:

1) 295 εκατ. χρόνια, κρυστάλλωση και ψύξη γρανιτικών διεισδύσεων μέσα στο υπόβαθρο της Πελαγονικής.
2) Περίπου 100 εκατ. χρόνια, πρασινοσχιστολιθική έως κυανοσχιστολιθική - πρασινοσχιστολιθική φάση μεταμόρφωσης και τεκτονική λεπίωση ηπειρωτικών τεμαχών.
3) 53-55 εκατ. χρόνια, κυανοσχιστολιθική φάση μεταμόρφωσης των ενοτήτων των Πιερίων και Αμπελακίων.
4) 36-40 εκατ. χρόνια, επώθηση των κυανοσχιστόλιθων πάνω στην ενότητα Ολύμπου.
5) 16-23 εκατ. χρόνια, ανύψωση και ψύξη σε θερμοκρασίες T< 100-150°C, που σχετίζονται με ρήγματα κανονικού τύπου. Το τελευταίο γεγονός συνεχίζεται έως σήμερα.

Τα στοιχεία από το Ar περιορίζουν τις θερμοκρασίες μεταμόρφωσης κατά τη διάρκεια της υποβύθισης ηπειρωτικού φλοιού σε T≤ 350°C και υποδηλώνουν ότι η φάση του εφελκυσμού και της ανύψωσης στον Όλυμπο ήταν σύγχρονη με τις επωθήσεις στις εξωτερικές Ελληνίδες.

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E.R. SHERMER, D.LUX, B.C.BURCHFIEL. Ηλικία και τεκτονική σημασία των μεταμορφικών γεγονότων στην περιοχή του Ολύμπου.

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## INTRODUCTION

During the Alpine orogeny in Greece, the African plate collided with the European plate to form the Hellenic Alps. Deformation began in the internal (eastern) Hellenides with intrusion o middle Jurassic granites and obduction of middle Jurassic ophiolites in latest Jurassic time, and continued episodically through Cretaceous and Tertiary time as deformation progressed from eas to west into the external Hellenides. Whereas in the external part of the orogen there is abundan stratigraphic evidence for the ages of deformation, in the internal part, several periods of superposed deformation and metamorphism have made deciphering the orogenic evolution difficul Although the metamorphism and its relation to deformation have been the subject of study for many years, considerable controversy still exists as to the number, age, and regional significanc of various deformational phases, and there is little agreement on the paleogeographic reconstruction of the region (see Robertson and Dixon, 1984 for an introduction to the problems).

An understanding of the timing of various events and the detailed relationships between metamorphism and deformation is a key element in interpreting the orogenic evolution of the Hellenides. Geochronological studies in combination with geologic mapping provide significant constraints on two of the most important controversies regarding Alpine deformation: the timing of closure of oceanic basins originally present between Europe and Africa, and the timing of subduction both between the two major plates and within the continental fragments during continent-continent collision. By combining $^{40}Ar/^{39}Ar$ and Rb/Sr geochronology with detailed petrographic and structural analysis, we can constrain the pressure-temperature-time history of the various structural units, data that greatly assist in the paleogeographic reconstruction of the internal Hellenides.

In this paper we present $^{40}Ar/^{39}Ar$ data from metamorphic rocks of the Olympos region o the internal Hellenides. In this region, the Pelagonian zone of Aubouin (1959), continental margin strata and basement rocks were subducted and metamorphosed to blueschist and greenschist facies, and thrust over carbonate platform strata during the Alpine orogeny. Subsequent exposure of the subducted basement rocks by normal faulting has allowed an integrat study of the timing of metamorphism, its relationship to deformation, and the high-pressure, low-temperature thermal history of the subducted rocks. Due to space limitations, constraints o the orogenic evolution from metamorphic petrology, detailed field work and structural analysis are presented only briefly here, and will be addressed more completely in subsequent papers.

## GEOLOGIC SETTING OF THE OLYMPOS REGION

The location of Mt. Olympos within the Pelagonian zone and a simplified geologic map are shown in Figure 1. The term "Pelagonian zone" is used here in the same sense as Aubouin (195 and Mountrakis (1984) to include metamorphic rocks between the basal thrust of the Vardar zo to the east and the Subpelagonian zone to the west; this includes pre-Alpine rocks as well as the Mesozoic carbonate cover called "Pelagonian zone (s.s.)" by Celet and Ferrière (1978) and Papanikolaou (1981).

The structural succession in the Olympos region is composed of four principal units, including from top to bottom: 1) dismembered ophiolitic rocks and coherent late Jurassic ophiolite suites; 2) deformed greenschist and blueschist facies Paleozoic continental basement gneisses and granites overlain by Permo-Triassic metasedimentary and metavolcanic rocks, an Triassic and Jurassic platform limestone and dolomite (Flambouron and Almopia units of Papanikolaou, 1984; 3) blueschist facies continental margin carbonates, quartzo–feldspathic sediments, and basic to intermediate volcanic rocks (Ambelakia unit of Schmitt, 1983; Papanikolaou, 1984; 4) parautochthonous Triassic to Eocene neritic carbonate rocks and Eocene flysch, metamorphosed at very low-grade. The lowest unit is exposed in a tectonic window in th Mt. Olympos region. (Fig.1), the area of this study.

Blueschist facies metamorphic rocks of the Pelagonian zone extend from the flanks of Mt. Olympos in the north through the Cyclades islands and eastward into Turkey. In general these rocks comprise marble, calcschist, metapelite, metatuff, and metabasalt (Durr et al, 1978; Blake et al, 1981; Papanikolaou, 1978, 1984). Ophiolitic melange is locally associated with t blueschists, however, these rocks are generally unmetamorphosed, and thus must have been emplaced after metamorphism. K/Ar and Rb/Sr ages of white micas and glaucophane from the blueschists range from Late Cretaceous (~80Ma) to late Oligocene (25-29Ma); (Blake et al, 1981; Ferrière, 1982).

The terminology of the various Pelagonian units as defined in the Olympos-Ossa region by Schmitt, (1983) is used for this study. The continental basement unit (Flambouron unit of Godfriaux, 1968 and Papanikolaou, 1984) has been divided into an upper "Pierien" unit and a lower "Infrapierien" unit by Schmitt (1983), however there are several imbricate thrust faults within these basement units such that near the western and southern margins of the Olympos window, Infrapierien rocks to the north overlie Pierien rocks to the south. The blueschist facies metavolcanic and metasedimentary rocks of the Ambelakia unit underlie Pierien and Infrapierien rocks and overlie the Olympos-Ossa carbonate rocks and flysch.

Detailed mapping and sample collecting in the Olympos area have provided insight into the structural and metamorphic evolution of the continental margin during subduction and collision. As reported in Schermer and Burchfiel (1987), the following principal tectonic events have been recognized: At least two phases of thrusting within the Pierien and Infrapierien units occured prior to their emplacement above the Olympos carbonate platform. Emplacement of ophiolite nappes probably occurred during these phases. Thrusting was accompanied by isoclinal folding and greenschist-amphibolite facies and blueschist-greenschist transition facies metamorphism. Blueschist metamorphism of the Ambelakia and Pierien units coincided with two phases of folding and foliation formation, culminating in the southwest-vergent thrust emplacement of the Pierien unit over the Ambelakia unit and later emplacement of both units above the Olympos platform along the Olympos thrust (Godfriaux, 1968; Schermer and Burchfiel, 1987). Movement on the Olympos thrust must be younger than the Lutetian (middle Eocene) flysch that occurs in its footwall (Godfriaux,1968). Two subsequent phases of tight to open folds have deformed the thrust faults. The final phase of deformation includes several generations of normal faults that cut through the sequence of thrust faults and place the highest structural units down to the east and northeast against the lowest structural units. Younger normal faults cut Neogene and Quaternary alluvial deposits along the eastern side of Mt. Olympos and the Ossa mountains (Fig. 1)

Samples for geochronological analysis using the $^{40}Ar/^{39}Ar$ step heating method were collected from the different structural units in an effort to elucidate the complex history of metamorphism, thrusting, and normal faulting. As abundant structural evidence exists for the rapid uplift of these blueschist facies rocks, we hoped that dating of minerals with different closure temperatures (Dodson, 1973) would also provide a low-temperature thermal history of the units as they were exhumed from high-pressure, low-temperature conditions to the surface.

## PREVIOUS GEOCHRONOLOGICAL STUDIES

The age of first emplacement of ophiolitic rocks is known to be latest Jurassic to early Cretaceous (pre-Albian) in the Vardar zone because Tithonian sedimentary rocks contain ophiolitic debris and Albian limestone overlaps the thrust faults (Mercier, 1968; Mercier et al, 1975). However, subsequent shortening has reactivated many of these thrust faults so that the ophiolites rest on sedimentary rocks as young as Eocene in the Pindos zone. That post-Jurassic thrusting involved basement rocks of the Pelagonian zone is indicated by Rb-Sr mica-epidote-plag-whole-rock ages of 119 and 116 Ma (Yarwood and Dixon, 1977) and a mica-whole rock age of 124 Ma (Barton, 1976) on deformed granitic rocks of the Pierien unit. Yarwood and Dixon (1977) also obtained an isochron age on mica-epidote-plag-whole rock of 100 Ma on augen schists from the underlying Infrapierien unit. They correlated the greenschist facies metamorphism and foliation formation with this later event and suggested that two distinct Cretaceous events may be interpreted from the data. (All ages are recalculated using the decay constants of Steiger and Jaeger, 1977). Granitic intrusions into the Pierien basement have been dated at 302 Ma by U-Pb on zircons (Yarwood and Aftalion, 1976). The age of the blueschist metamorphism that affects both the Pierien and Ambelakia units is unknown; however, an Rb-Sr whole rock date of 39 Ma by Barton (1976) on phyllonites from the Olympos thrust zone has been interpreted as the age of metamorphism by several authors (Katsikatsos et al, 1982; Vergely, 1984). This age *may instead represent the age of* thrusting as the rocks are pervasively recrystallized and contain a mylonitic fabric that is parallel to the thrust fault. Dérycke and Godfriaux, (1978) reported that the lawsonite-bearing flysch of the Ambelakia unit in the Ossa mountains contains Paleocene fossils, however because of the structural complexity of this unit, it is uncertain whether all the lithologies containing blueschist facies assemblages in the study area are of similar protolith age.

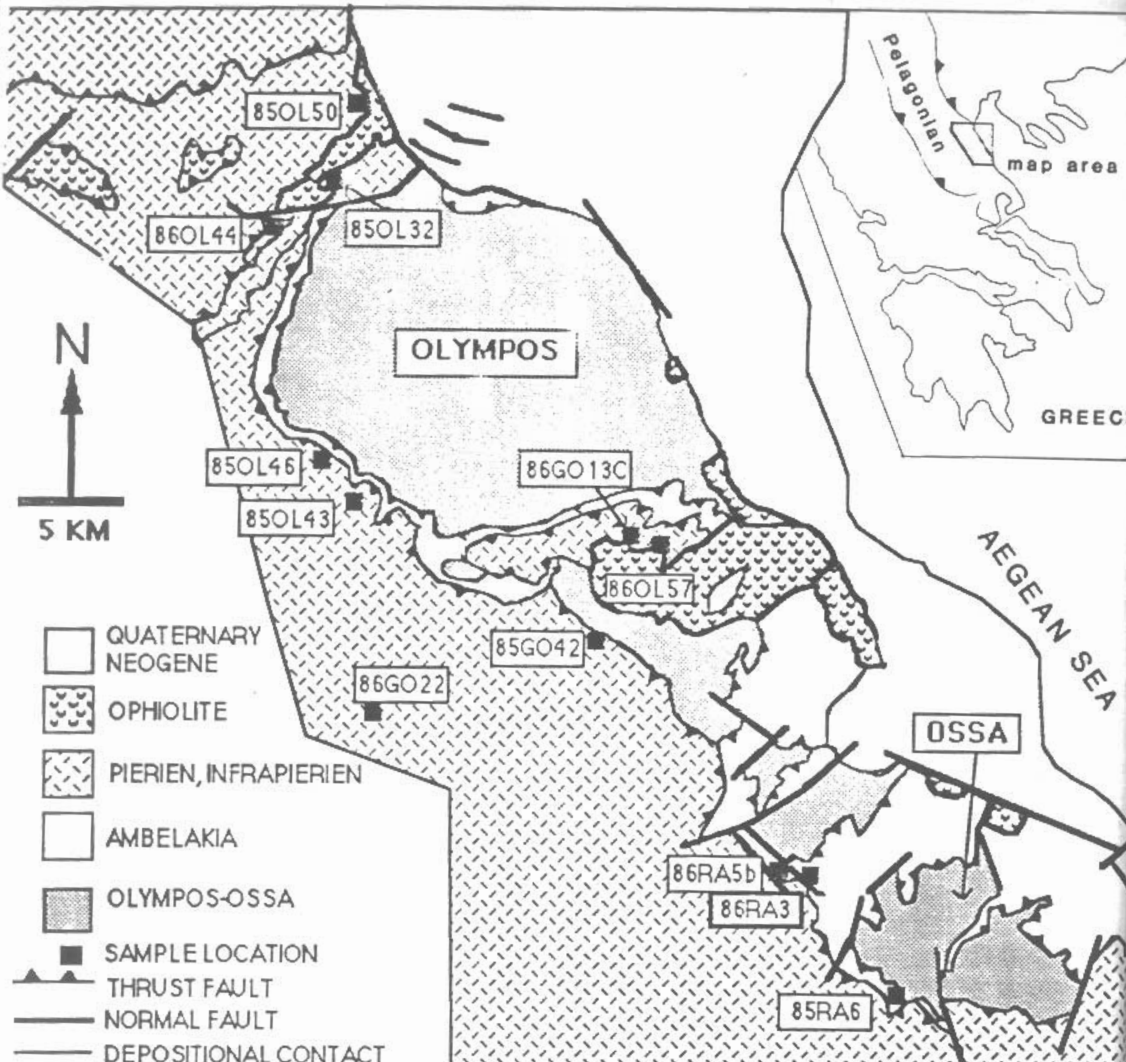



Figure 1: Simplified geologic map of the Olympos area, with locations of samples analy for Rb/Sr and $^{40}Ar/^{39}Ar$ dating. Mapping by the author on the flanks of Mt. Olympos, mod from Schmitt (1983), and Katsikatsos and Migiros (1987) in the Ossa mountains. Inset sh the location of the Olympos region within the Pelagonian zone.

## RESULTS

Incremental release age spectra for all the samples are shown in Figures 2,3,4. Data tables for all samples and information on analytical methods are available on request from the author. The $^{39}Ar/^{40}Ar$-$^{36}Ar/^{40}Ar$ isotope correlation plot (Roddick, et al, 1980) indicates whether the non-radiogenic component of Ar in the sample has an atmospheric composition ($^{36}Ar/^{40}Ar$= 0.0034 or $^{40}Ar/^{36}Ar$=295.5); if not, a corrected age is calculated from the intercept on the $^{39}Ar/^{40}Ar$ axis. Data are presented for each structural unit and discussed together in the following section. A brief summary of the metamorphic and structural characteristics of each unit is also described.

### Ambelakia Unit

Three samples collected from the Ambelakia unit (Fig. 1) show varying degrees of recrystallization and deformation, however, all rocks contain a dominant $S_2$ foliation fabric formed by phengitic micas that overprints a folded $S_1$ fabric; both fabrics appear to have formed during blueschist facies metamorphism. All samples were collected <300m away from the thrust fault that places Ambelakia schists above Ossa metasediments. The presence of the assemblage glaucophane-phengite-Na-pyroxene-albite-quartz± lawsonite ± chlorite constrains the P-T conditions of this unit to T ~250-350°C, P>4 kb (Godfriaux et al, in press; Schermer, 1987).

Step heating data from micas from the Ambelakia unit are shown in Figure 2. Sample 86RA5b shows a well-developed plateau at 39.6±0.9 Ma. The other two samples show complicated diffusive loss profiles from Oligocene at low-temperature release, to Cretaceous ages during the high-temperature increments. The $^{39}Ar/^{40}Ar$-$^{36}Ar/^{40}Ar$ isochron plot of sample 86RA3 indicates the increments of gas released at high-temperatures do not plot on a line corresponding to atmospheric extraneous Ar; these steps are regressed to give an age of 51±4 Ma, in agreement with the total gas age of 53.5±1.1 Ma. Sample 85RA6 also has an early Eocene total gas age at 52.8±0.7 Ma, and the spectrum appears to level off at ~44-55 Ma. However, during the high-temperature steps the K/Ca ratio drops sharply and the age increases, possibly indicating that an older mica of different composition is also present. There is no clear correlation of homogeneity of Ar composition with degree of recrystallization, as the apparently least-recrystallized sample, 85RA5b, shows the best-developed plateau, while the most thoroughly mylonitized rock, 85RA6, yields the most disturbed spectrum.

### Pierien Unit

Samples from the crystalline basement rocks of the Pierien unit have been divided into three groups based on structural level: 1) samples from 40-800 meters above the basal thrust; 2) granitic rocks higher in the sheet; and 3) mylonitic gneisses 10-50 meters below the normal faults that bound the upper part of the Pierien unit (Fig.1).

Samples from the lowest part of the sheet, including 85OL43, 85OL46, and 85GO42, consist of variably mylonitized granitic to granodioritic gneiss, containing the mineral assemblages quartz-microcline-plagioclase-phengite and quartz-plagioclase-phengite-riebeckite-acmite as the latest stable assemblages. All samples are strongly foliated and contain a mylonitic fabric and evidence of two metamorphic foliations; $S_1$ is isoclinally folded and transposed into $S_2$, however the same mineral assemblage is present in both foliations. The high phengite content of the micas indicates high-pressure conditions of metamorphism, P>6kb (Massonne and Schreyer, 1987), but temperature conditions are poorly constrained by the mineral assemblages. It will be argued below that temperatures probably did not exceed ~350°C.

Incremental release profiles from these samples are shown in Fig. 3a. Phengite sample 85GO42 has a well developed plateau at 53.9 ± 0.8 Ma. Regression of these data on an isochron plot gives a corrected age of 53.1±0.7 Ma. The other two phengites exhibit an age gradient from ~55 to ~36 Ma that resemble diffusive loss profiles. The final ~1% gas released is significantly older (middle Cretaceous) and could represent either excess argon incorporated into retentive sites, or another phase contaminating the sample.

Samples were collected from weakly foliated granodiorite and granite from a high structural level within the Pierien unit (Fig.1). Although the granodiorite is not strongly deformed at this locality, mylonitization is variably developed in rocks of similar lithology both above and below this level, and field relationships indicate it is part of the thrust sheet rather than a younger cross-cutting intrusive as interpreted by Katsikatsos et al (1982), and Davis and Migiros (1979).

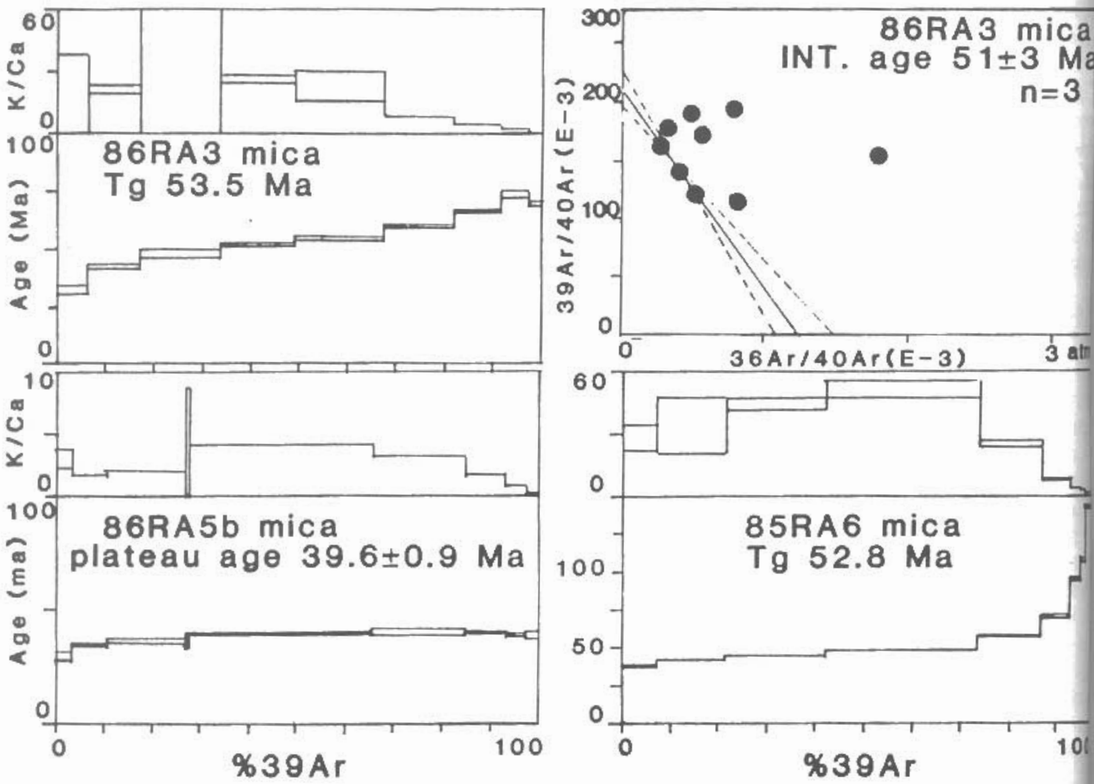
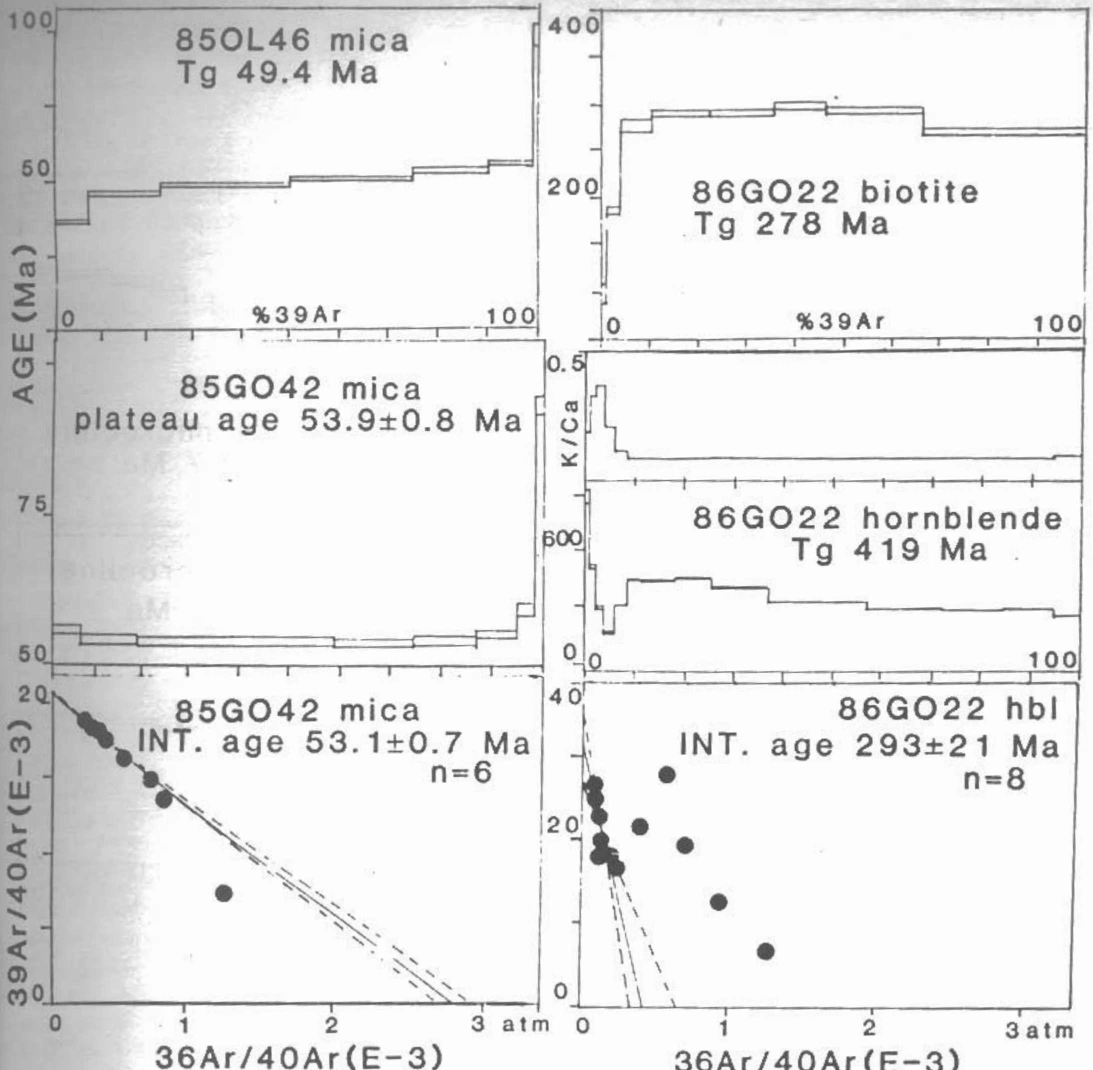
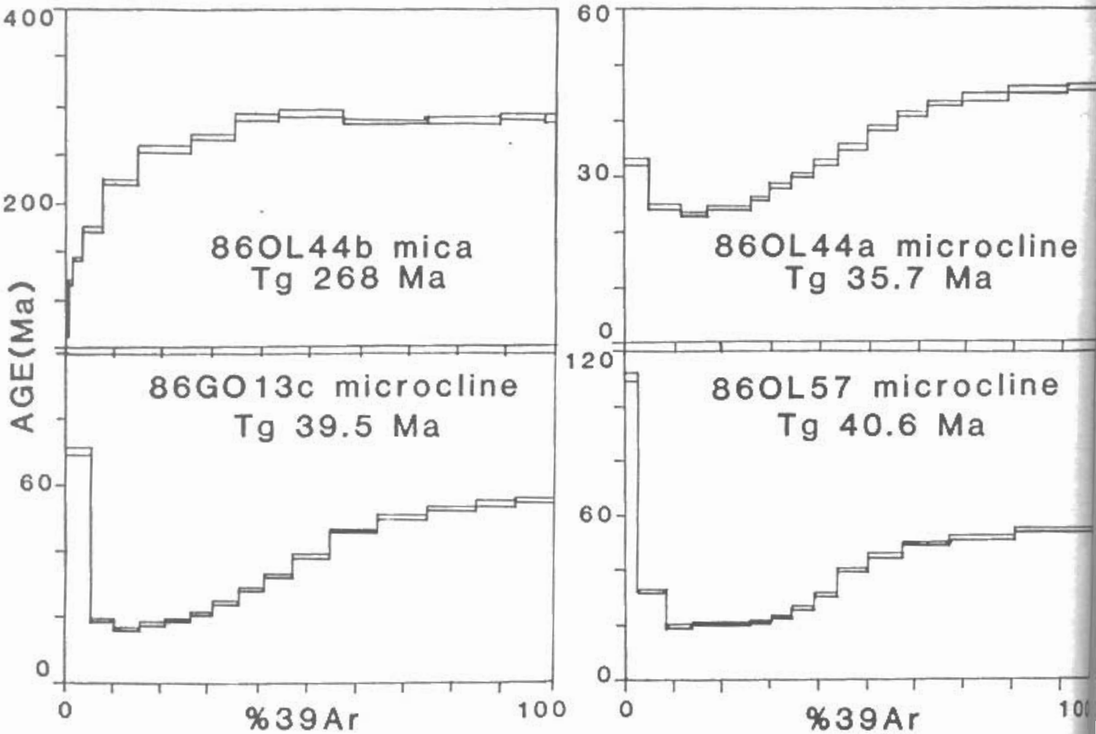



Figure 2: $^{40}Ar/^{39}Ar$ incremental release spectra and $^{39}Ar/^{40}Ar$-$^{36}Ar/^{40}Ar$ isotope correlation plots for samples from the Ambelakia unit. See Fig. 1 for sample locations. Abbreviations: Tg: total gas age; INT. age: $^{39}Ar/^{40}Ar$ intercept age; atm: indicates atmospheric argon composition at the lower right-hand corner of the isotope correlation plots, where $^{36}Ar/^{40}Ar=0.0034$.




a b

Figure 3: a) $^{40}Ar/^{39}Ar$ incremental release spectra and $^{39}Ar/^{40}Ar$-$^{36}Ar/^{40}Ar$ isotope correlation plots for samples from the lower part of the Pierien unit. b) $^{40}Ar/^{39}Ar$ incremental release spectra and $^{39}Ar/^{40}Ar$-$^{36}Ar/^{40}Ar$ isotope correlation plots for samples from granodioritic rocks in the upper part of the Pierien unit. c): $^{40}Ar/^{39}Ar$ incremental release spectra and $^{39}Ar/^{40}Ar$-$^{36}Ar/^{40}Ar$ isochron plots for samples from the uppermost part of the Pierien unit, below normal faults. See Fig. 1 for sample locations. Abbreviations as in Fig. 2.


400
200
60
30
0
120
60
0
AGE(Ma)
86OL44b mica
Tg 268 Ma
86OL44a microcline
Tg 35.7 Ma
86GO13c microcline
Tg 39.5 Ma
86OL57 microcline
Tg 40.6 Ma
0
100
%39Ar
0
%39Ar

C

The hornblende spectrum shown in Fig. 3b shows a saddle-shaped pattern characteristic of excess argon incorporation. The minimum age of 295 Ma could represent a maximum age for closure of the hornblende to Ar diffusion. This is supported by the $^{39}Ar/^{40}Ar$-$^{36}Ar/^{40}Ar$ isotope correlation intercept age of 293±21Ma. The biotite spectrum, while also disturbed, shows a similar age of 291±7 Ma, with indication of argon loss during or after late Cretaceous time.

The third group of Pierien samples have experienced the most complicated structural history of any of the samples analyzed in this study. In addition to containing mylonitic fabrics apparently related to thrusting, these samples also show a later cataclastic fabric related to their proximity to normal faults. Samples 86OL57 and 86GO13c come from granitic gneiss <25 meters below a low-angle normal fault that places ophiolitic rocks of the highest structural level against a thin sliver of Pierien basement thrust above the Ambelakia and Olympos units. Samples 86OL44a and 44b are from near the intersection of a thrust fault between the Pierien and Infrapierien units and a high-angle normal fault that places ophiolitic rocks against a variety of structurally lower units. Because these samples are too felsic, they do not show mineralogical evidence of blueschist facies metamorphism and consist of quartz-microcline-plagioclase-phengite ± epidote.

Muscovite sample 86OL44b preserves the original basement age at 290 Ma with a smooth diffusive loss profile down to a poorly defined late Cretaceous age. All three microcline samples show saddle-shaped spectra, having high-temperature increments that level off to early-middle Eocene ages, and minimum ages in the early Miocene.

In summary, samples from the Pierien unit show evidence for four distinct events of opening and closure to Ar diffusion: 1) late Paleozoic (~295-290 Ma) closure to diffusion in hornblende, biotite, and muscovite; 2) an event at 53-60 Ma, indicated by one plateau and several phengite samples that approach plateaus of this age; 3) another Eocene event at 36-40 Ma indicated by the low temperature increments of the phengite and 4) a Miocene event at 16-23 Ma representing final closure to Ar diffusion in potassium feldspar.

Infrapierien Unit.

Phengitic micas were separated from coarse mica schists from the Infrapierien unit (Schmitt, 1983) that were thrust over the Pierien gneisses (Fig. 1). This unit shows evidence of at least three periods of deformation and metamorphism. The first event produced isoclinal folds and $S_1$ foliation and was accompanied by amphibolite facies metamorphism. The second event formed tight folds with $S_2$ foliation, and was accompanied by metamorphism under blueschist-greenschist transition facies conditions. The third event developed an $S_3$ mylonitic fabric near thrust faults with the Pierien unit (Schermer and Burchfiel, 1987). $S_2$ and $S_3$ fabrics are overprinted by later cataclastic shears related to younger normal faults. Samples 85OL32 and 85OL50 are dominated by $S_2$ fabrics formed by coarse micas, blue-green amphibole, and epidote.

Release profiles for these samples are shown in Fig. 4. Sample 85OL32 shows a diffusive loss profile from ~98-99 Ma to ~56 Ma. The $^{39}Ar/^{40}Ar$-$^{36}Ar/^{40}Ar$ isochron plot indicates the high-temperature portion of the spectra has an intercept age of 98±2 Ma. The spectrum for sample 85OL50 is more complex, indicating a combination of Ar loss and excess argon incorporation. However, the isochron plot shows a good fit to the last five steps, resulting in an intercept age of 100±2 Ma, consistent with that of sample 85OL32.

## DISCUSSION

The complexity of the data presented above is in part a result of the long and complicated history of metamorphism and deformation in the Hellenic Alps. In the Mt. Olympos region, much of the deformation and metamorphism occurred at relatively high-presssure, low-temperature conditions. The low temperatures resulted in incomplete resetting of micas and K-feldspars from earlier higher temperature crystallization events. As a result of the low temperatures of metamorphism, we can "see through" many of the younger events to the older events in the incremental heating spectra.

Closure temperatures for hornblende, biotite, and microcline are estimated to be ~500-550°C, 300-325°C, and 100-150°C, respectively (Harrison, 1981; Harrison and McDougall, 1985; Harrison et al,1982) at a cooling rate of 30°C/Ma. Slower cooling rates would decrease the closure temperatures, but does not have a strong effect. The closure temperatures for Sr and Ar diffusion in muscovite have been estimated at ~500°C (Wagner et al, 1977) and ~350°C, respectively (Purdy and Jaeger 1976) for a cooling rate of 30°C/Ma. Although the closure

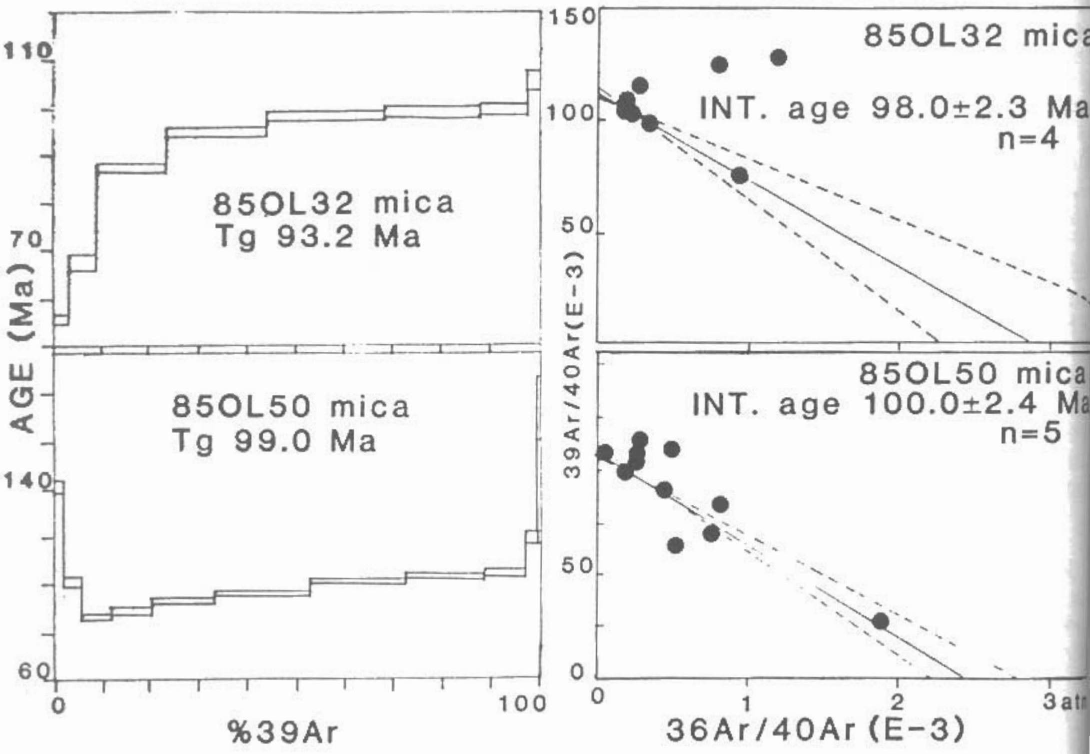



Figure 4: $^{40}Ar/^{39}Ar$ incremental release spectra and $^{39}Ar/^{40}Ar$-$^{36}Ar/^{40}Ar$ isotope correlation plots for samples from the Infrapierien unit. See Fig. 1 for sample locations. Abbreviations as in Fig. 2.

temperature of phengitic mica is unknown, it is probably not significantly different from that of muscovite. The effect of deformation on closure temperature also is unknown, although we would expect that a reduction in grain size during mylonitization or cataclasis would have the effect of opening diffusion in a mineral even at low temperatures. Thus, Sr and Ar diffusion in micas in deformed rocks may be controlled less by temperature than by chemical potential or fluid composition during recrystallization at low temperatures. The factors cited above may in part be the reason why the $^{40}Ar/^{39}Ar$ dates are older than Rb/Sr dates of samples from near the Olympos thrust (Schermer, 1987; Barton, 1976).

One of the most important results of this study is the observation that incomplete resetting of white mica and biotite ages in all structural units constrains the temperatures of metamorphism to be T~350°C or less even where mineralogical constraints on temperatures are poor, such as in the Pierien unit. Samples such as 86OL44b and 86GO22 are the best examples, as they preserve even the crystallization age of the basement rocks as well as a later resetting event. Mica samples from near the basal thrust of the Pierien unit and from the Ambelakia unit are nearly completely reset from a possible Cretaceous metamorphic event evidenced by the highest temperature gas fractions. However, the presence of two distinct Eocene ages in the micas, and Eocene and Miocene ages in the microcline samples indicate that this part of the metamorphic and cooling history occurred at relatively low temperatures.

We interpret the saddle-shaped spectra exhibited by the microcline samples to reflect a minor amount of excess argon superimposed on diffusive loss profiles. The upper ages on all the microcline profiles appear to have geological significance, by comparison with mica ages in the same samples and in nearby rocks from the same structural unit. In addition, the initial gas released from the microclines decreases from older ages to the minimum over the first ~10% of $^{39}Ar$ released and is not older than other Pierien rocks, indicating that any excess argon incorporated either was a small amount or had a $^{40}Ar/^{39}Ar$ composition similar to the radiogenic component and thus does not dominate the apparent ages over the whole spectrum. Thus we obtain a maximum age of the episodic loss event from the minimum ages in the spectra. These minima cluster in the early-mid Miocene, at 16-23 Ma.

The diffusive loss profiles in the blueschist facies rocks from the Mt. Olympos region are interpreted to be the result of thrusting and normal faulting superimposed on an early Eocene blueschist facies metamorphism rather than the result of slow cooling from Eocene time to the present (Schermer et al, in prep). The complete overlap of mica ages and "upper" potassium feldspar ages suggest that the temperature decreased from ~350°C to ~150°C in a very short period of time during the early to late Eocene, (a minimum cooling rate of ~10°C/Ma calculated from 55 Ma to 36 Ma); the average cooling rate from ~15 Ma to the present is also calculated to be ~10°C/Ma. Thus we do not consider that slow cooling (at rates <5°C/Ma; Harrison and McDougall, 1982) was responsible for the preservation of age gradients in the potassium feldspar spectra. The middle Eocene thrusting event is also constrained by the stratigraphic age of the footwall rocks. As a significant period of normal faulting and uplift has been documented in the field, and the microcline-bearing samples were collected from immediately beneath normal faults, we believe that the minimum ages of the feldspars indicate an Ar loss event resulting from extensional tectonism during early to middle Miocene time (Schermer and Burchfiel, 1987; in prep).

## TEMPERATURE-TIME HISTORY OF THE PELAGONIAN ZONE DURING ALPINE OROGENESIS

While the individual release spectra studied at first seem to be complicated, a pattern of similar ages within and among the groups of samples has emerged. The samples that have plateaus or well-constrained isochrons: 86GO22 hornblende at 295Ma, biotite at 290Ma; 85OL32 at 100 Ma, 85GO42 mica at 53 Ma, and 85RA5b mica at 40 Ma constrain the timing of four major deformational and metamorphic events in the history of the Pelagonian zone. The remaining samples show diffusive loss profiles, generally from one of these dates to a younger one, depending on the closure temperature of the mineral and in part on the proximity of the samples to major structures. The youngest ages recorded by potassium feldspar minima reflect a fifth, low-temperature, event that we interpret to be related to normal faulting and uplift of the metamorphic nappes.



The oldest event is recorded in the samples from the Pierien unit at ~295 Ma. As these ages come in part from relatively undeformed, unrecrystallized hornblende and biotite from the granitic basement terrane and correspond well to concordant zircon ages of 302 Ma reported by Yarwood and Aftalion (1976), they are interpreted to represent the crystallization and cooling of the intrusive rocks. The minor resetting of the biotite age during Cretaceous time, as shown by the inital 10% of gas released from this sample, indicates that temperatures in the upper part of the Pierien unit did not exceed ~325 °C for any long period of time since the late Paleozoic.

The granitic samples analyzed here were collected from an area mapped by Davis and Migiros (1979), and Katsikatsos et al (1982) as "recent" granites that intruded and metamorphosed a previously foliated gneiss complex. They considered the granites to be post-Late Cretaceous and pre-late Eocene. However, other workers (Godfriaux,1968; Schmitt, 1983; Vergely, 1984; Schermer, 1987) include the granites in the Paleozoic basement units. In addition to the field relations noted above, the $^{40}Ar/^{39}Ar$ data indicate that the latter interpretation is correct.

Regional stratigraphic relations suggest that ophiolite emplacement above the Pelagonian zone rocks occurred during latest Jurassic to early Cretaceous time (Mercier, 1968; Mercier et al, 1975; Vergely, 1984). Unfortunately, there is no direct evidence of the age of ophiolite emplacement in the Olympos region. Limestone mapped as Maestrichtian by Godfriaux (1968) is presumed to overlap the ophiolite and underlying rocks, however, most of the occurrences of ophiolitic rocks in the Olympos region have been disrupted by younger normal faults such that the original thrust faults are no longer present. The age of one phase of metamorphism and deformation in the Infrapierien unit, which does have a preserved ophiolitic thrust nappe on top of it in the Livadi area (Fig.1), is constrained by the mica ages of 98 and 100 Ma reported here; however the metamorphic fabric in these samples is not known to be directly related to the basal ophiolitic thrust. It is possible that the Rb-Sr ages of 119 and 116 Ma reported by Yarwood and Dixon (1977) from rocks of the Pierien unit in a higher thrust sheet are related to an earlier ophiolite emplacement. The limited geochronological data available from near the base of ophiolites and throughout the upper parts of the crystalline nappe stack prevents further constraints on the Cretaceous metamorphic history of this area, though Vergely (1984) has reported two major phases of ophiolite emplacement, one during latest Jurassic time further to the north in the Vardar zone, and one during early Cretaceous time in the Maliac and Othrys areas of east-central Greece.

The Eocene was apparently the time of major deformation and metamorphism in the Olympos region. Most of the blueschist-grade samples appear to record two events, one at 53-55Ma and the other at 36-40Ma. The earlier event is texturally associated with blueschist mineral formation, foliation formation, and isoclinal folding. The younger event apparently records the age of thrusting of the blueschists of the Ambelakia and Pierien units above the Olympos-Ossa unit. This thrusting event is constrained by the age of fossiliferous flysch in the footwall to be post-Lutetian (50-44 Ma). Textural and mineralogic evidence recorded in the mylonitic rocks associated with the thrust fault indicates that the pressure-temperature conditions of thrusting were not very different from those of metamorphism. We are uncertain whether these two events are in fact distinct in time and space, or whether they could represent a protracted deformational event that occurred during early to middle Eocene time.

The Olympos unit in the footwall does not show blueschist facies mineralogy: the rocks contain albite, pumpellyite, chlorite, and white mica. Lawsonite has been reported by Schmitt from a single pebble in one sample of the Lutetian flysch, however this could be a detrital phase. The Paleocene flysch of Ossa contains lawsonite, pumpellyite, albite, chlorite, and phengite. This assemblage does not unequivocally indicate that the Ossa carbonates and flysch were involved in subduction, as P-T conditions are only constrained to be <350°C, >2.5-3 kb (Winkler, 1979, p. 190).

It is clear from the $^{40}Ar/^{39}Ar$ and petrographic data that the Ambelakia and Pierien units were metamorphosed at approximately the same time and P-T conditions in the early Eocene, and thrust above the Olympos-Ossa carbonates during or after middle Eocene time. The lack of oceanic rocks in any of these three units implies that the subduction took place <u>within</u> the continental crust of the Pelagonian zone. Structural arguments developed elsewhere (in prep) and in Schermer and Burchfiel (1987), indicate that thrusting was SW-vergent. Thus we envision the early Tertiary events as the subduction, imbrication and obduction of the eastern margin of the Apulian plate (or a Pelagonian fragment) as deformation proceeded from NE to SW.



The present map pattern of the thrust nappes reflects severe disruption by younger normal faults such that on the eastern margin of the Olympos massif the contact between platform carbonates of the footwall and slivers of crystalline rocks and ophiolite in the hanging wall is not the original thrust fault (Schermer and Burchfiel, 1987). Several generations of normal faults are present that bring the highest structural units of ophiolitic rocks down onto the lowest units, cutting out as much as 5-6 km of structural thickness. Although cross-cutting relations prove that the normal faults are younger than the thrust faults, it is uncertain when extensional tectonism in this area may have begun. The $^{40}Ar/^{39}Ar$ data on microclines provide constraints on the age of extension and uplift of the metamorphic rocks. The minimum ages evident in the microcline release patterns cluster around 16-23 Ma. Several of the samples were collected from immediately beneath the normal faults, and cataclastic textures within them are clearly associated with the faulting. Thus, we interpret these minimum ages to be a result of a low-temperature extensional deformation that occurred during early to middle Miocene time. Temperatures appear to have been high enough to partially reopen Ar diffusion in K-feldspar, with a closure temperature of ~150°C, but were insufficient to reset the mica ages, and therefore were <350°C. These normal faults appear to be partly responsible for the uplift of the blueschist facies rocks at a rate fast enough enough to avoid reheating by thermal relaxation (e.g. England and Richardson,1977; Draper and Bone, 1980). During early to middle Miocene time, extension and subsidence occurred in the Mesohellenic trough to the west of the Pelagonian zone. To the east, the Aegean back-arc basin began to open at ~13 Ma (Angelier, 1978). Thus, during the time the Olympos platform and the overlying metamorphic rocks were being uplifted, cooled, and tectonically denuded, the areas on either side were also being extended and were subsiding.

## CONCLUSIONS

$^{40}Ar/^{39}Ar$ ages from metamorphic rocks of the Pelagonian zone in the Mount Olympos region provide constraints on the ages of several metamorphic and deformational episodes, and the time-temperature history of this part of the metamorphic belt. The low temperatures of metamorphism in these units has resulted in preservation of numerous age gradients in the Ar release spectra, as samples experienced partial Ar loss in later events but were not completely rehomogenized. The samples in this study show that a wealth of information can be derived from $^{40}Ar/^{39}Ar$ dating of micas recrystallized at low temperatures, as the diffusive loss profiles can constrain both initial crystallization and younger metamorphic or deformational events that may easily be obscured by Rb/Sr mica-whole rock dates.

Five deformational and metamorphic events have been recognized; 1) the crystallization and cooling of granitic intrusions into the continental basement from ~295-290 Ma; 2) a greenschist to blueschist-greenschist transition facies metamorphism of continental thrust sheets at ~100 Ma, possibly associated with imbrication of the basement rocks following ophiolite emplacement in Early Cretaceous time; 3) a blueschist facies metamorphism of basement rocks of the Pierien unit and metasedimentary and metavolcanic rocks of the Ambelakia unit at 53-55 Ma; 4) thrusting of the blueschists over the Olympos unit at 36-40 Ma ; 5) uplift and cooling below 100-150°C at 16-23 Ma, accompanied by normal faulting that has continued to the present.

Deformation in the Pelagonian zone occurred over a very long period of time (~90 Ma), and was episodic, involving subduction and imbrication of continental basement before, during, and after the collision of the Apulian and Eurasian plates and final closing of the Vardar ocean in latest Cretaceous time (Mercier et al, 1975; Burchfiel, 1980). During the early to middle Tertiary, a fairly rapid cooling rate of ≥10°C/Ma below metamorphic temperatures of ~350-400°C permitted preservation of the blueschist facies mineral assemblages as they were uplifted from depths of ~15-20 km. It is important to note that extensional deformation and tectonic unroofing of blueschist units followed soon after compressional deformation, possibly in response to thickening of the crust (Dalmayrac and Molnar, 1981) or through slab retreat processes similar to those in the Appenines described by Royden (1987). Thrusting progressed westward from the Olympos region throughout the Tertiary, and was synchronous with extension in a large part of the Hellenides that lay close to but east of the thrust front, and includes areas of the Mesohellenic trough, the Olympos region, and the Aegean back-arc basins.

## ACKNOWLEDGEMENTS

This material is based upon work supported under a National Science Foundation Graduate Fellowship, a Grant-in-Aid of Research from Sigma Xi, and Geological Society of America research grant awarded to Schermer, and support from the Schlumberger Corporation to Burchfiel. We thank D. Papanikolaou for logistical support in Greece and helpful discussions.

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