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Exhumation of metamorphic rocks in N Aegean: the path from shortening to extension and extrusion

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Abstract

The Olympos-Ossa-Pelion (OOP) ranges, in NW Aegean, encompass Greece highest summit and are located near the extremity of the North Anatolian Fault (NAF). Structural and thermochronological data gathered in the OOP ranges show that the main exhumation of metamorphic nappes occurred in the Eocene, at ca. 43–39 Ma. This early exhumation, associated with ductile, then brittle-ductile normal faulting with northeastward transport, is nearly coeval with orogenic shortening in the close area. Cooling rates, and likely exhumation, have been low between ~40 Ma and ~20 Ma. $^{40}\text{Ar}/^{39}\text{Ar}$ crystallization ages (between 20 and 15 Ma) appears related to brittle-ductile normal faulting and likely associated with the onset of Aegean back-arc extension. The dating of a diabase dyke, and the geometry of associated brittle jointing, of onshore and offshore active normal faults imply a shift in extension direction after 4 Ma. Such a shift is probably related the propagation of the NAF in northern Aegean known to have occurred around 5 Ma.

1 Introduction

There is some consensus on the view that Aegean continental extension (Fig. 1) can be explained by some combination of gravitational forces in a thickened crust with pull forces associated with the retreat of the Hellenic Arc (e.g. McKenzie, 1978; Le Pichon and Angelier, 1981; Jolivet et al., 2003). It is also agreed that it postdates the compressional stacking of the Hellenic thrust-nappes, which is of upper Mesozoic to Lower-Cenozoic age in the internal part of the belt (Mercier et al., 1989; Vergely and Mercier, 1990; Schermer et al., 1990; Lips et al. 1998, 1999). However, the timing of inception of continental stretching, which is critical for constraining mechanical evolution models of the Aegean lithosphere, remains poorly constrained. Estimates range from 5 Ma (e.g. McKenzie, 1978) to more than 24 Ma (e.g., Gautier and Brun, 1994; Gautier et al., 1999).

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Evidence for extension in the Aegean comes from separate sets of observations. One set derives from seismology and earthquake geology. It focuses on the brittle, steeply-dipping normal faults that account for the present-day deformation of the upper crust. A second set, derives from observations of older (Tertiary) ductile structures.

5 It has been inferred from the latter that large amounts of extension of the lithosphere, associated with significant amounts of shear on shallow-dipping detachments at mid-crustal levels, induced rapid exhumation of metamorphic core complexes (e.g. Lister et al., 1984; Buick, 1991; Brun et al., 1994; Jolivet et al., 1994; Gautier et al., 1999). Finally a distinctive feature of the Aegean extension derives from recent tectonic and
10 geodetic (GPS) observations: the mechanical interaction between the Aegean extension and the westward-propagating North Anatolian Fault (NAF), which entered the Aegean at 5 Ma (e.g. Armijo et al., 1996, 1999) and induced transtension (Mc Neil et al., 2004). The relations between orogenic shortening, continental extension and NAF propagation, and their temporal evolution remain subject of debate. Is the exhumation
15 of metamorphic cores mainly due to extensional collapse or is it coeval with the stacking of the thrust-nappe edifice? To what extent is the Aegean extension controlled by motion on the NAF (or vice-versa)?

The Olympos, Ossa and Pelion (OOP) ranges (Figs. 1, 2a) are key to answer these questions because they are described as culminations affecting thrust-nappes, encompass Greece highest summit and are located along the SW edge of the North Aegean
20 trough at the extremity of the NAF. We report structural observations coupled with new $^{40}\text{Ar}/^{39}\text{Ar}$ dates in the time period covering the passage from compression to extension in the OOP ranges where some important structural information is well exposed. In particular, the OOP ranges are the footwall of active normal faults that splay from
25 the NAF and show exposures of low angle ductile normal faults. Our structural observations and dates provide constraints both on the timing and on the mechanics of stretching in the Aegean.

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2 Exhumation of Olympos-Pelion nappe edifices

2.1 Overview of structure of Olympos-Ossa-Pelion ranges

The OOP ranges constitute the uplifted and tilted footwall of NE-dipping normal faults (Figs. 2b, c). Offshore, in the W part of the North Aegean trough (Figs. 1, 2a), N 90° E to N 120° E striking normal faults cut the top sedimentary layers and the seafloor topography (Laigle et al., 2000; Papanikolaou et al., 2002). These normal faults are connected to strike-slip fault segments splaying from the Northern branch of the NAF (Fig. 2a). They strike more easterly than the overall trend of the Pelion-Ossa coast, of the Thermaikos Gulf and Chalkidiki Peninsulae (Fig. 2a). In the prolongation of the offshore normal faults, the Mount Olympos piedmont is cut by several tens of meters high scarps (Figs. 2a, b). These scarps that correspond to recent normal faults, strike N 110 to N 130° E oblique to the main Olympos range-front fault, which strikes ~N 160° E (Figs. 2a, b). More to the S, near Volos, W of the Pelion, the young normal faults strike E-W to WNW-ESE and, together with earthquake fault-plane solutions (Hatzfeld et al., 1999; Goldsworthy et al., 2002), indicate N-S to NNE-SSW extension oblique to the trend of the Pelion range (Fig. 2a).

The OOP ranges are classically described as antiforms, affecting the SW-verging thrust edifice of the Hellenic belt internal zones (e.g. Celet and Ferrière, 1978), and bounded to the NE by the Vardar suture, which is buried under the sediments of the Thermaikos Gulf and the North Aegean trough (Figs. 1, 2a).

The Olympos range (Fig. 2b), forms a half-window with para-autochthonous sediments in the core (Vergely and Mercier, 1990) overlain by nappes of metamorphic rocks containing HP/LT assemblages (Schermer, 1993). The core series (Mesozoic carbonate rocks) are topped by nummulite-bearing limestones of Paleocene to lower Ypresian age (Fleury and Godfriaux, 1974) conformably capped by undated detritic sediments (turbidites). Final emplacement of the metamorphic nappes onto these rocks thus occurred after the lower to middle Eocene (~50 Ma). The normal range front fault that bounds the eastern Olympos flank strikes NNW-SSE (Schermer, 1993; Jo-

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livet and Patriat, 1999). It displays triangular facets, suggesting steep normal faulting, more or less parallel to the foliation in the hanging-wall units of marbles. Foliation dips 20–30° ENE, with N 55° E-directed stretching lineations and down-to-the ENE ductile shear (Fig. 2b). This suggests that steep normal faulting has exhumed earlier extensional ductile deformation that was occurring in a N 55° E direction, transverse to the strike of the range-front fault.

The thrust nappe edifice in the Ossa range, S of the Olympos, is less exhumed and dissected by erosion (Celet and Ferrière, 1978; Walcott, 1998). Offshore active normal faults bound the range to the NE and account for the steep sea-facing range-front. Further S, the Pelion range (Fig. 2c), made of gneisses and micaschists interlayered with marbles and locally serpentinite slices, is considered to be the equivalent of the Ossa-Olympos nappe-stack, with some *mélange* (Celet and Ferrière, 1978; Walcott, 1998). Metamorphism and deformation characters are typical of relatively low P-T conditions (greenschist facies) although remnants of HP/LT assemblages are locally found (Walcott, 1998). The presence of raised fossil marine beaches along the eastern Pelion coast attests to recent uplift probably driven by the offshore faults. E-dipping units, forming the E flank of the range (Fig. 2c), show greenschist facies foliation dipping 10–20° NE and ~N 45° E stretching lineations (Walcott, 1998) associated with dominantly northeastward normal shear (Figs. 3a, 3b). Macro- (Fig. 3b) and micro- (Figs. 3c, 3d) textures of mylonitic gneisses are typical of ductile deformation at medium temperature >300°C (e.g. Passchier and Trouw, 1998). Lower grade, NE-dipping brittle-ductile normal shear-zones affect these units and mark often the contacts between them. At the outcrop-scale, the flat-lying foliation is overprinted by steeper brittle-ductile shears and by nearly vertical joints (Fig. 3e), implying an evolution under decreasing PT conditions down below those of the brittle-ductile transition (~300°C).

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2.2 Geochronology, cooling history of the OOP ranges and evidence for Eocene exhumation

2.2.1 Summary of previous geochronological studies

Published results of $^{40}\text{Ar}/^{39}\text{Ar}$ dating on white micas (WM) and feldspars from the OOP ranges (Schermer et al., 1990; Lips et al., 1998, 1999) are summarized in Table 1.

In the Olympos, most phengites and one microcline show age gradients in their spectra, with low temperature (LT) steps between ~36 and 42 Ma, and high temperature (HT) steps between 53 and 100 Ma (Table 1). Other phengites yield plateau or isochron ages between ~40 and 60 Ma. This was interpreted as an evidence for several phases of nappe stacking and metamorphism starting at ~100 Ma and ending at ~40 Ma (Schermer et al., 1990). Alternatively, the LT steps could be interpreted as the result of cooling of all samples below phengite closure temperature (~350°C) at that time. Microclines generally show diffusive gradients with younger LT steps between ~17 and 28 Ma (Table 1), suggesting enhanced cooling at these ages (Schermer et al., 1990).

In the Ossa range, all but one (WM3) of Lips et al.'s (1998) recrystallized WM ages are older than 50 Ma (~55 Ma in greenschist mylonites, 78–85 Ma in blueschist mylonites) while porphyroclasts give 293–102 Ma cooling ages (Table 1). Lips et al. (1998) infer the following history: cooling below WM closure temperature (~350°C) before 102 Ma, thrusting events at 78–85 Ma during blueschist metamorphism, and at 54–55 Ma during cooling below 300°C. The last event could have lasted up to 45 Ma (WM3 age), time since which the whole Ossa thrust-stack is at temperatures too low for ductile deformation.

As in the Ossa range, the ages of WM porphyroclasts from the Pelion are Paleozoic or lower Cretaceous (95 Ma) suggesting that Tertiary deformation occurred below ~350°C (Lips et al., 1999). All but one (WM9 ~54 Ma) ages of fine-grained WM from mylonite fabrics are in the 40–15 Ma range (Table 1). Lips et al. (1999) relates these latter ages to crystallisation of WM below their closure temperature, during extensional

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foliation-parallel shear mostly towards the NE.

2.2.2 Thermochronology of the Pelion metamorphic rocks

New K-Feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology and mica dating from the eastern Pelion range provide further constraints on its cooling and exhumation history. In most cases pseudoplateaus were used to calculate the ages (see Appendix A). K-feldspars are known to record cooling histories and especially rapid cooling events, which are theoretically marked by flat portions of the age spectra (Lovera et al., 1991). These flat portions may be used to define pseudoplateaus or isochrons and to statistically calculate ages. Details on interpretation of feldspar age spectra are given in Appendix A together with analytical procedures. Appendix B lists analytical results, and Table 2 summarizes age results.

Two feldspars from mylonitic orthogneisses along a NE-SW section of the range (sample G5 from a quarry SE of Kalamaki at 350 m a.s.l.; G7 from the seashore 2 km NW of the quarry) give a climbing age spectrum with a well-defined low temperature (LT) pseudo-plateau (5 to 35% Argon release) and a progressive increase towards older ages at high temperature steps (Figs. 4a and b). The first 5% of each age spectrum is obscured by excess argon, correlated with strong chlorine content (see $^{38}\text{Ar}/^{39}\text{Ar}$ correlation) likely associated with fluid inclusions decrepitation at LT as is often the case in K-feldspars. Mean ages on the LT steps are confirmed by inverse isochron diagrams that include all young steps (thus more data than pseudo-plateaus) suggesting that excess argon can be corrected even in the first steps, and that pseudo-plateau ages are meaningful. Such pseudoplateaus followed by an age increase can be interpreted as resulting from rapid cooling events, which occurred in the present case around 40 Ma. Note that G5 plateau is slightly older (42.7 ± 2.4 Ma) than that of G7 (39.2 ± 0.8 Ma). An alternative interpretation is that feldspar growth happened during nappe-stacking metamorphism around old feldspar cores. In this case pseudoplateaus correspond to quenching of those neoformed feldspar mantles after deformation. In any case, and given the fairly low argon retentivity in feldspars, this suggests

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that the dated samples are at temperatures below 220–150°C since 43–39 Ma, and that no later reheating is needed to explain the age spectrum. Such temperatures are too low for quartz plasticity and for only ductile deformation in gneissic rocks, implying that the ductile northeastward shear affecting the gneisses of the E Pelion flank have occurred before ~40 Ma.

Mylonitic samples G9606 and G9607 (micaschists affected by northeastward shear) were sampled 2 km NW of Kalamaki quarry close to a ~10° E dipping fault contact in units directly overlying the orthogneisses. Finegrained plagioclase (G9606) gives a fairly good plateau at 17.9±0.5 Ma on two steps that correspond to more than 90% of the gaz release (Fig. 4d). Muscovite (G9607) shows a raising spectra with a low temperature average age of 17.8±0.6 Ma on the two first steps (42% of gaz release, Fig. 4c), prior to ages that rise up to 250 Ma. Such age spectra is interpreted as the result of mixing ~18 Ma muscovites with older metamorphic grains. Like those obtained by Lips et al. (1999) on fine-grained white-micas (40–15 Ma, Table 1), these ~18 Ma ages likely correspond to crystallization ages associated with continuing normal motion on foliation parallel shear zones. This implies that extensional shear towards the NE occurred during the 40–15 Ma period thus after the cooling event documented on K-feldspars. Altogether the data ages suggest that part of the penetrative shear occurred at relatively low temperature (less than 220°C) probably by brittle-ductile shear localized in micaschists and marbles.

3 Pliocene reorganization along the edge of the Aegean through

The ductile fabric associated with eastward normal shear along the E coast of Pelion is cut by numerous joints and tension gashes (Fig. 3e), which are generally filled with quartz and/or epidote-chlorite, or locally with diabase dykes (Fig. 3f). The joints are nearly vertical and strike N 140° E on the average. They are perpendicular to stretching lineations in the surrounding rocks and roughly parallel to the trend of the coast. An outcrop on the seashore near Milopotamos (~10 km N of section of Fig. 2c) displays a

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diabase dyke parallel to the N 140° E gash set (Fig. 3f). A younger set of vertical joints, striking N 80° E to N 100° E, cuts obliquely the N 140° E gashes and the dyke, as well as the surrounding rock fabric (Fig. 3f). The sample G9611 taken from the diabase dyke has a saddle-shape age spectra characteristic of excess argon. The two steps with minimum age give 5.4 ± 0.2 Ma age while the inverse isochron age is 4.0 ± 0.2 Ma with a clear indication of excess argon (Fig. 4e). We interpret the isochron age as dating the emplacement of the dyke.

The simplest interpretation of joint geometry and dyke age is that northeastward brittle-ductile shear was followed by the formation of the N 140° E gashes at ca. 5.4 Ma. The fact that the N 140° E gashes are perpendicular to the stretching lineation suggests that the gashes formed at a time when the extension direction (σ_3) was roughly the same than the stretching direction during ductile normal shearing. This could suggest that the extension direction remained roughly the same since 40 Ma until ~4 Ma. Alternatively, the gashes may have formed at the end of ductile shear just after 40 Ma, and the diabase dykes would have intruded at ~4 Ma within the resulting, still favorably oriented, anisotropy. In any case, the late, ~E-W joint set, clearly formed after ~4 Ma. It reveals a recent, early Pliocene–Quaternary shift towards a more N-S extension direction consistent with the strike of onshore and offshore active faults and the moment tensor solutions of regional earthquakes (Fig. 2a).

4 Timing of metamorphic rock exhumation and of North Anatolian Fault propagation

Our structural observation and Ar/Ar data yield us to conclude that final exhumation of the OOP range resulted from three successive tectonic stages, all involving normal faulting (Fig. 5). Structural observations and cooling histories imply that, in the Pelion range (Lips et al., 1999; this work), as well as in Ossa and Olympos (Schermer et al., 1990; Lips et al., 1998), a large part of the exhumation of metamorphic units occurred before or during the Eocene. In eastern Pelion, rapid cooling down to temperatures

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below 220°C occurred around 40 Ma. At that time, presently outcropping gneisses were brought to less than ca. 10 to 6 km depth (for thermal gradients between 20 and 40°/km), and the ductile, penetrative eastward normal shear started to be more localized and brittle. The stacking of thrust nappes occurred after the deposition of the post-Ypresian turbidites in the Olympos, thus after ~50 Ma. Same age constrain (Lutetian nummulites in the Almyropotamos unit) on thrusting exist in Euboea, SE of Pelion (e.g. Shaked et al., 2000). We thus infer that the main phase of normal ductile detachment and exhumation, before and around 40 Ma, was most probably coeval with the final stacking of thrust nappes, and older than the onset of Aegean extension (Fig. 5). It could be due to upward wedge extrusion above a crustal thrust ramp as in the Himalayas or Pamir (e.g. Hodges et al., 1992; Brunel et al., 1994). As the Pelion units remained at temperatures compatible with brittle-ductile extensional shear and white-micas crystallization until ~18 Ma, we infer a modest amount of cooling (few tenths of degrees) between ~40 Ma and ~18 Ma and thus a limited exhumation (Fig. 5). The low-temperature crystallization ages between 20 and 15 Ma (Lips et al., 1999; this work), as well as the 17–28 Ma cooling event(s) in the Olympos range (Schermer et al., 1990), are ascribed to a second episode of extension nearly coaxial with the first one. That second event is associated with NNE-SSW normal faults responsible for the overall relief and trend of the coast. The age of that event corresponds to the onset of Aegean back-arc extension (Fig. 5; Jolivet et al., 1994; Gautier and Brun, 1994).

A final phase of extension, and possibly of exhumation, was triggered by the propagation of the North Anatolian fault (NAF) that entered the N Aegean about 5 Ma ago (Armijo et al., 1999). Along the Olympos-Pelion range and in the North Aegean trough, the onset of NAF-related deformation is marked by the formation of new faults (Figs. 1, 2a) that cut obliquely older extensional structures. Our results suggest that the change in the extension direction and in the geometry of the faults occurred after 4 Ma (Figs. 4e, 5), thus immediately after the NAF propagated across the Dardanelles, W of the Marmara sea (Fig. 1), at ~5 Ma (Armijo et al., 1999).

Although our conclusions require more data (e.g. low T° thermochronology) to be

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confirmed, we infer that multiphased exhumation histories, associated to changes in fault geometry and kinematics, like those we document in the OOP ranges, are probably common in the Aegean. In particular, a large part of the exhumation of metamorphic units may have been synorogenic, as suggested by Avigad and Garfunkel (1991) Jolivet and Patriat (1999) and Jolivet et al. (2003), for instance. In addition, the inception of the most recent active fault system is not the straightforward continuation of the Aegean back-arc extension. Our age constrains, as well as the documented large-scale changes in fault geometry and kinematics (e.g. Armijo et al., 1996, 2004), suggest that it has been largely affected by the propagation of the NAF since ~5 Ma.

Appendix A

A1 $^{40}\text{Ar}/^{39}\text{Ar}$ techniques

The minerals were separated using heavy liquids, a Frantz magnetic separator and finally by hand picking under a binocular microscope. The samples were irradiated at the Phoenix Memorial Laboratory reactor of the University of Michigan, in the L67 position for 20 h under a 10^{18} neutrons $\text{cm}^{-2} \text{s}^{-1}$ flux. Irradiation interference on K, Ca and Cl were corrected by irradiation of KCl and CaF_2 pure salts. J factors were estimated by the use of duplicates of the Fish Canyon sanidine standard with an age of 28.48 Ma (Schmitz et Bowring, 2001; Schmitz et al., 2003).

The samples were analyzed in Clermont-Ferrand. Samples were loaded in aluminum packets into a double vacuum Staudacher type furnace, which temperature is calibrated by means of a thermocouple, and step heated. The gas was purified by the means of cold traps with liquid air and Al-Zr getters. Once cleaned, the gas was introduced into a VG3600 mass spectrometer, and 2 min were allowed for equilibration before analysis was done statically. Signals were measured by the mean of a Faraday cup with a resistor of 10^{11} ohm for ^{40}Ar and ^{39}Ar while ^{39}Ar , ^{38}Ar , ^{37}Ar and ^{36}Ar were analyzed with a photomultiplier after interaction on a Daly plate. Gain between both

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collectors was estimated by duplicate analysis of ^{39}Ar on both during each analysis, and also by statistical analysis on a period of several years. This gain is in average of 95 and is known at better than 1.5%. This error is included in the age calculation, along with analytical errors on each signal and errors on the blank values. Age plateau given are weighted mean plateaus which error takes the error on the J factor into account. The isochron ages are obtained in an inverse isochron diagram of $^{36}\text{Ar}/^{40}\text{Ar}$ versus $^{39}\text{Ar}/^{40}\text{Ar}$ (Roddick, 1978; Roddick et al., 1980), which allows homogeneous excess components to be individualized in many occasions. Errors on age and intercept age include individual errors on each point and linear regression by York's method (1969). The goodness of it relative to individual errors is measured by Mean Square Weighted Deviation (MSWD).

For Micas, classical furnace step heating was conducted to extract age spectra and inverse isochrons. A more peculiar step heating schedule was conducted on K-feldspar in order to retrieve diffusion characteristics (Harrison et al., 1991; Lovera et al., 1989, 1991). We also conducted duplicated isothermal step heating at low temperatures (450–800°C), often yielding a sawtooth-shaped age spectrum where the second of the two stages is systematically younger and probably less affected by excess argon.

A2 Interpretation of age spectra, notably on K-feldspars

With the historical decrease of analytical errors, strict plateau criteria (Dalrymple and Lanphere, 1974; Berger and York, 1981) are less and less easily reconciled with real data, and thus pseudoplateaus were defined, when a significant amount of continuous steps overlap globally at 2σ even if contiguous steps do not. The use of pseudoplateaus or isochrons on series of steps on K-feldspars is justified by their peculiar structure, allowing, in certain circumstances the extraction of cooling histories and especially rapid cooling events, which are theoretically marked by flat portions of the age spectra (Lovera et al., 1989, 1991).

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Table 1. Summary of published Ar-Ar ages from the Olympos – Ossa – Pelion ranges.

Unit	Mineral (sample No.)	Age	Remarks
Mount Olympos – Schermer et al. (1990)			
Unit: Ambelakia	Phengite (A1)	39.6±0.9	Plateau age
	Phengite (A2–3)	37–100 (A2) 32–69 (A3)	Gradient in age spectrum
Unit: Pierien	Phengite (P1)	57±1.8 (HT)	HT plateau age, LT gradient down to 45 Ma
	Microcline (P1)	28–49.6	Diffusive gradient – LT steps at ~28 Ma
	Phengite (P2–3)	40–56 (P2) 36–55 (P3)	Gradient in spectrum
	Phengite (P4)	53.9±0.8 (pla) 53.1±0.7 (iso)	Plateau and isochron ages
	Phengite (P5)	61.7±0.8 (pla) 60.7±1.3 (iso)	HT plateau/isochron age, LT gradient down to 41 Ma
	Phengite (P6)	57–66 (grad) 60.3±1.4 (iso)	Gradient spectrum – Isochron age
	Microcline (P7) [1]	36–84	Diffusive gradient – LT steps at ~36 Ma
	Microcline (P8)	23–45.5	Diffusive gradient – LT steps at ~24 Ma
	Phengite (P9–10–11)	38–58 (P9) 42–59 (P10) 40–72.6 (P11)	Gradient in spectrum
	Microcline (P10–11)	16.25–56 (P10) 19.5–53.5 (P11)	Diffusive gradient – LT steps ~17 (P10) and 20 (P11)
Unit: Infrapierien	Phengite (IP1)	56–98	Gradient in spectrum – 98±2.3 Ma isochron on HT steps
	Phengite (IP3)	51–65	Gradient in spectrum – 63.3±1.7 Ma on HT steps
Notes	[1] Weakly deformed granodiorite with ~295 Ma hornblende and biotite cooling ages.		

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Table 1. Continued.

Unit	Mineral (sample No.)	Age	Remarks
Ossa – Lips et al. (1998)			
Allochthonous units (W flank of Ossa)	WM 1 [2]	54.2±2.8	Plateau age – age of mylonitic fabric
	WM 3	45.5±1.4	id-
	WM 138	53.7±3.6	id-
	WM 146	55.4±1.7	id-
	WM 149	55.8±4.0	id-
Notes	[2] White micas (WM) often show two populations in each sample (porphyroclasts, fine-grained micas in mylonitic foliation). WM Porphyroclasts gave cooling ages between ca. 293 and 102 Ma. We only report in this table the ages of WM in greenschist mylonitic fabrics. WM from blueschist mylonites yielded ages between ca. 78 and 85 Ma (fabric age). One biotite gave a well defined plateau at 80.9±2.2 Ma (cooling age).		
Pelion – Lips et al. (1999)			
Pelion massif	WM 5 [3]	37.1±1.1	Plateau age – age of mylonitic fabric
	WM 5	21.5±1.8	id-
	WM 5	15.5±3.2	id-
	WM6	34.9±2.6	id-
	WM 6	15.5±2.0	id-
	WM 7	26.8±4.1	id-
	WM 9	53.9±5.9	id-
	WM 9	39.1±1.6	id-
	WM 9	39.4±1.5	id-
	WM 10	32.3±1.25	id-
Notes	[3] We report Lips et al's results on white micas (WM) in greenschist mylonitic fabrics from the Pelion massif. WM porphyroclasts from Pelion samples gave Paleozoic(293, 305 Ma) or Cretaceous ages (95 Ma). WM from Antihassia (SW of Olympos) and Mavrovouni (between Pelion and Ossa) metamorphic massifs yielded Mesozoic cooling ages (89 to 150 Ma).		

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Table 2. $^{40}\text{Ar}/^{39}\text{Ar}$ ages statistical analysis obtained on metamorphic minerals from the Pelion ranges. For each sample, the age spectra and inverse isochrons are analysed, with selected steps and resulting age, plus notes detailing the reasons for the choice of selected steps. Age spectra: the range of ages on the spectra is indicated, plus the calculated age on the selected steps below; inverse isochron: the calculated age is shown with selected steps below, the resulting $^{40}\text{Ar}/^{36}\text{Ar}$ intercept and the MSWD of the regression. Finally, when age spectra and inverse isochron analysis disagree on age results, a preferred age is proposed for the reason given in notes.

Pelion – This work	Age spectra			Inverse isochron				Preferred age	Note
Mineral/Sample Lat Long coord.	Range of age in steps	Plateau (P) or Pseudo-plateau (PP) age (1)	Note (2)	Age (3)	$^{40}\text{Ar}/^{36}\text{Ar}$	MSWD	Note		
K-feldspar G5 N 39°19'50" E 23°13'	40 to 136	42.7±2.4 (PP on 6–16, 26%)	LT steps	42.1±0.9 (6–16)	290±15	15,9		42.7±2.4	Age on LT steps, likely represent last cooling
K-feldspar G7 N 39°20'52" E 23°13'38"	34 to 80	39.2±0.8 (PP on 8–19, 23.9%)	LT steps	39.6±0.4 (2, 4, 6, 8–19)	288±21	6,0	Isochron larger than plateau on all LT points	39.2±0.8	id-
Plagioclase G9606 N 39°21'18" E 23°11'53"	17.0 to >58	17.9±0.5 (PP on 1–2, 94%)	Used steps are the maximum of K/Ca on the spectra	–	–	–		17.9±0.5	
Muscovite G9607 N 39°21' E 23°21'	18.8 to >65	17.8±0.6 (PP on 1–2, 42%)	Used steps are the maximum of K/Ca on the spectra	26.6±2.3 (3–9)	1322±55	2,2	Isochron on HT points with strong excess, probably undercorrected and leading to unrealistic age	17.8±0.6	
Basalt G9611 N 39°22'40" E 23°12'18"	5.4 to >68 saddle shape	5.4±0.2 (PP on 3–4, 47%)	Used steps are the maximum of K/Ca on the spectra	5.3±0.8 (1–4)	312±17	26,0	HT points with excess rapidly increase MSWD	4.0±0.2	Saddle shape suggests excess revealed by isochron with best MSWD. Age probably close to real emplacement age.
				4.0±0.2 (2–4)	356±8	0,6	Isochron restricted to first 3 steps		

(1) All ages are pseudoplateau ages (criteria are discussed in the text) given with numbers of steps used to calculate them and the amount of ^{39}Ar released comprised in the “plateau”.

(2) LT: low temperature, HT: high temperature

(3) Ages are given with numbers of steps used to calculate them

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Appendix B

Table of analytical results

Results $^{40}\text{Ar}/^{39}\text{Ar}$ dating by step heating analysis. For plagioclase (Table B1), micas (Table B2) and basalt (Table B3) the table gives isotopic data errors and age, with the experimental ^{39}Ar moles released and cumulative % ^{39}Ar . Ratios are corrected for blanks, analytical deviations and neutron interference reactions only. J factor is given for each analysis. For the K-feldspars (Tables B4, B6), an additional table (Tables B5, B7) is provided, which gives diffusion parameters calculated during heating, with the inverse of absolute temperature ($1000/T$), and diffusion data for each step. Also shown are activation energy E and frequency factor as $\log(D_0/r_0^2)$ obtained by linear regression on arrhenius plots with associated errors.

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Table B1.

Temp °C	$^{40}\text{Ar}/^{39}\text{Ar}$	$^{38}\text{Ar}/^{39}\text{Ar}$	$^{37}\text{Ar}/^{39}\text{Ar}$	$^{36}\text{Ar}/^{39}\text{Ar}$ (10^{-3})	^{39}Ar (10^{-14} moles)	F ^{39}Ar released	% $^{40}\text{Ar}^*$	$^{40}\text{Ar}^*/^{39}\text{Ar}$	Age Ma	$\pm 1\sigma$ Ma
G 96–6	Plagioclase	J=0.0174380								
700	8.188	0.025	0.024	26.340	7.68	25.15	6.66	0.55	17.07	0.56
900	0.821	0.018	0.013	0.830	20.97	93.81	70.06	0.57	18.00	0.38
1004	1.394	0.020	0.171	1.680	0.94	96.87	65.42	0.91	28.50	0.90
1203	3.423	0.020	0.735	5.471	0.75	99.32	54.87	1.89	58.48	1.38
1407	17.747	0.028	2.485	45.620	0.21	100.00	26.33	4.77	144.09	3.98

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Table B2.

Temp °C	$^{40}\text{Ar}/^{39}\text{Ar}$	$^{38}\text{Ar}/^{39}\text{Ar}$	$^{37}\text{Ar}/^{39}\text{Ar}$	$^{36}\text{Ar}/^{39}\text{Ar}$ (10^{-3})	^{39}Ar (10^{-14} moles)	F^{39}Ar released	% $^{40}\text{Ar}^*$	$^{40}\text{Ar}^*/^{39}\text{Ar}$	Age Ma	$\pm 1 \sigma$ Ma
G 96 7	Sericite			J=0.0174300						
700	5.402	0.022	0.135	16.561	16.56	19.75	11.14	0.60	18.85	0.45
804	0.677	0.018	0.089	0.435	18.72	42.09	81.34	0.55	17.24	0.35
914	1.236	0.018	0.452	0.410	41.09	90.96	92.27	1.14	35.62	0.71
956	1.923	0.019	1.710	1.172	5.11	96.98	87.79	1.71	53.04	1.05
1007	2.644	0.020	3.029	2.768	1.09	98.25	76.87	2.08	64.33	1.37
1054	6.474	0.019	12.122	6.796	0.42	98.70	81.64	5.86	175.33	3.46
1106	10.160	0.021	21.815	11.800	0.22	98.92	80.23	9.88	286.74	5.61
1202	9.866	0.020	16.047	11.134	0.28	99.21	77.79	8.81	257.72	5.12
1409	10.889	0.021	17.073	15.591	0.77	100.00	68.62	8.66	253.62	4.82

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Table B3.

Temp °C	$^{40}\text{Ar}/^{39}\text{Ar}$	$^{38}\text{Ar}/^{39}\text{Ar}$	$^{37}\text{Ar}/^{39}\text{Ar}$	$^{36}\text{Ar}/^{39}\text{Ar}$ (10^{-3})	^{39}Ar (10^{-14} moles)	F^{39}Ar released	% $^{40}\text{Ar}^*$	$^{40}\text{Ar}^*/^{39}\text{Ar}$	Age Ma	$\pm 1\sigma$ Ma
G 96 11		basalte	J=0.0175000							
700	5.521	0.022	1.500	18.241	25.67	39.88	5.85	0.33	10.29	1.87
800	0.382	0.018	0.580	0.843	17.89	67.89	44.24	0.17	5.35	0.14
900	0.440	0.018	0.569	1.018	11.98	86.64	39.94	0.18	5.56	0.17
1000	0.912	0.019	0.773	2.378	5.96	95.95	29.25	0.27	8.46	0.22
1100	2.842	0.021	3.835	6.624	1.14	97.68	40.98	1.20	37.55	0.79
1200	4.554	0.023	5.358	9.546	0.54	98.50	46.73	2.22	68.88	1.66
1400	6.013	0.023	4.979	12.016	1.00	100.00	47.34	2.97	91.27	1.81

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Table B4.

Temp °C	$^{40}\text{Ar}/^{39}\text{Ar}$	$^{38}\text{Ar}/^{39}\text{Ar}$	$^{37}\text{Ar}/^{39}\text{Ar}$	$^{36}\text{Ar}/^{39}\text{Ar}$ (10^{-3})	^{39}Ar (10^{-14} moles)	F^{39}Ar released	% $^{40}\text{Ar}^*$	$^{40}\text{Ar}^*/^{39}\text{Ar}$	Age Ma	$\pm 1 \sigma$ Ma
G5	K-feldspar	J=0.0071350		wt=7.1 mg						
394	23.068	0.038	0.002	35.499	0.02	0.49	0.51	12.77	157.36	4.16
400	12.487	0.036	0.010	27.842	0.01	0.67	0.22	4.41	55.94	12.16
452	11.028	0.030	0.000	10.788	0.06	2.06	0.53	7.90	98.92	6.22
558	21.156	0.040	0.000	13.533	0.09	4.19	0.79	17.23	209.19	4.05
558	5.624	0.024	0.001	4.556	0.05	5.39	0.60	4.30	54.55	2.67
608	5.142	0.022	0.001	6.372	0.07	7.19	0.64	3.29	41.91	0.83
608	3.935	0.022	0.000	2.798	0.07	8.86	0.62	3.12	39.77	1.98
657	3.939	0.023	0.001	2.538	0.10	11.27	0.72	3.20	40.77	1.18
657	3.719	0.023	0.001	1.194	0.08	13.20	0.72	3.37	42.90	1.82
704	3.748	0.021	0.000	1.877	0.10	15.60	0.75	3.20	40.77	1.20
704	3.789	0.021	0.000	0.783	0.08	17.69	0.75	3.56	45.28	1.77
800	11.444	0.026	0.000	27.603	0.25	23.83	0.29	3.44	43.74	0.94
785	3.886	0.021	0.001	1.675	0.17	27.98	0.73	3.40	43.24	1.48
800	3.564	0.022	0.001	0.685	0.13	31.17	0.69	3.37	42.80	2.27
700	5.329	0.039	0.010	0.000	0.02	31.67	0.22	5.33	67.34	11.43
794	4.138	0.021	0.002	3.388	0.05	32.82	0.53	3.16	40.17	3.03
896	3.928	0.021	0.000	0.895	0.17	36.98	0.86	3.67	46.61	1.08
999	4.483	0.021	0.000	0.926	0.48	48.68	0.91	4.21	53.45	1.07
1097	7.081	0.024	0.000	1.357	0.71	66.28	0.93	6.69	84.09	1.65
1199	10.484	0.028	0.000	1.788	1.20	95.91	0.94	9.97	123.92	2.44
1400	12.604	0.027	0.001	5.597	0.17	100.00	0.80	10.98	136.08	2.91

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Table B5.

Temp °C	Time min	f	D/r ²	1000/T (K ⁻¹)	-log(D/r ²)	log(r/r ₀)
E=28899 cal/mol +- 1540 log(Do/ro)=1.39/s +-0.43						
394	20	0.49	1.55 E-08	1.499	7.809	-0.137
400	30	0.67	9.43 E-09	1.486	8.026	0.014
452	99	2.06	5.02 E-08	1.379	7.299	-0.013
558	21	4.19	8.31 E-07	1.203	6.081	-0.067
558	30	5.39	5.01 E-07	1.203	6.300	0.043
608	20	7.19	1.48 E-06	1.135	5.829	0.023
608	30	8.86	1.17 E-06	1.135	5.933	0.075
657	20	11.27	3.18 E-06	1.075	5.498	0.046
657	30	13.20	2.06 E-06	1.075	5.685	0.140
704	20	15.60	4.52 E-06	1.024	5.345	0.133
704	30	17.69	3.03 E-06	1.024	5.519	0.220
800	20	23.83	1.67 E-05	0.932	4.778	0.139
785	45	27.98	6.26 E-06	0.945	5.204	0.310
800	60	31.17	4.12 E-06	0.932	5.385	0.442
700	140	31.67	2.93 E-07	1.028	6.533	0.714
794	30	32.82	3.23 E-06	0.937	5.491	0.479
896	20	36.98	1.90 E-05	0.855	4.721	0.352
999	20	48.68	6.56 E-05	0.786	4.183	0.302
1097	20	66.28	1.41 E-04	0.730	3.850	0.313
1199	20	95.91	7.12 E-04	0.679	3.147	0.121

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Table B6.

Temp °C	$^{40}\text{Ar}/^{39}\text{Ar}$	$^{38}\text{Ar}/^{39}\text{Ar}$	$^{37}\text{Ar}/^{39}\text{Ar}$	$^{36}\text{Ar}/^{39}\text{Ar}$ (10^{-3})	^{39}Ar (10^{-14} moles)	F^{39}Ar released	% $^{40}\text{Ar}^*$	$^{40}\text{Ar}^*/^{39}\text{Ar}$	Age Ma	$\pm 1\sigma$ Ma
G7	K-Feldspar	J=0.0071300	wt=18.7 mg							
400	29.163	0.051	0.011	45.795	0.04	0.28	53.33	15.85	193.20	3.78
400	7.836	0.025	0.004	11.070	0.07	0.79	55.37	4.60	58.17	1.40
460	10.750	0.036	0.001	6.488	0.11	1.69	80.84	8.84	110.25	2.16
460	4.810	0.023	0.003	7.027	0.05	2.12	50.86	2.74	34.94	1.25
500	7.926	0.031	0.002	5.346	0.08	2.77	77.53	6.35	79.84	1.63
500	4.468	0.021	0.002	6.192	0.07	3.29	55.16	2.64	33.67	0.88
550	7.202	0.032	0.000	3.706	0.16	4.52	83.09	6.10	76.77	1.52
550	3.594	0.022	0.000	2.194	0.12	5.48	75.96	2.93	37.26	0.88
609	3.748	0.022	0.000	2.019	0.26	7.55	81.83	3.13	39.85	0.80
655	3.442	0.021	0.000	1.208	0.26	9.59	86.90	3.06	38.96	0.79
700	4.649	0.021	0.000	5.403	0.46	13.17	64.86	3.05	38.85	0.78
750	3.359	0.020	0.000	0.845	0.38	16.13	90.32	3.08	39.23	0.78
800	3.349	0.020	0.000	0.651	0.53	20.28	92.39	3.13	39.82	0.79
800	3.198	0.020	0.000	0.416	0.39	23.37	92.27	3.05	38.78	0.80
800	3.201	0.020	0.000	0.253	0.49	27.25	90.84	3.10	39.41	0.89
700	3.397	0.020	0.000	0.000	0.03	27.47	59.18	3.37	42.80	1.66
750	3.505	0.018	0.000	1.017	0.03	27.73	71.35	3.18	40.44	2.09
800	3.260	0.020	0.001	0.874	0.11	28.56	83.81	2.98	37.89	0.97
900	3.344	0.021	0.000	0.590	0.68	33.89	92.94	3.14	39.98	0.80
1000	3.753	0.021	0.000	0.622	1.45	45.30	93.96	3.54	45.00	0.97
1100	5.045	0.024	0.000	0.839	2.73	66.78	94.26	4.77	60.36	1.28
1200	6.373	0.027	0.000	0.739	3.80	96.68	95.89	6.13	77.16	1.65
1400	7.276	0.027	0.001	3.161	0.42	100.00	83.93	6.33	79.63	1.72

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Table B7.

Temp °C	Time min	f	D/r ²	1000/T (K ⁻¹)	-log(D/r ²)	log(r/r _o)
E=31368 cal/mol +- 4546 log(Do/ro)=2.15/s +- 1.30						
400	20	0.28	5.15 E-09	1.486	8.288	0.126
400	30	0.79	2.39 E-08	1.486	7.622	-0.207
460	20	1.69	1.46 E-07	1.364	6.835	-0.184
460	30	2.12	7.04 E-08	1.364	7.153	-0.025
500	20	2.77	2.08 E-07	1.294	6.682	-0.019
500	20	3.29	2.07 E-07	1.294	6.684	-0.017
550	20	4.52	6.28 E-07	1.215	6.202	0.011
550	30	5.48	4.22 E-07	1.215	6.375	0.097
609	20	7.55	1.76 E-06	1.134	5.753	0.065
655	20	9.59	2.28 E-06	1.078	5.642	0.202
700	25	13.17	4.28 E-06	1.028	5.369	0.236
750	20	16.13	5.66 E-06	0.978	5.247	0.348
800	20	20.28	9.89 E-06	0.932	5.005	0.383
800	40	23.37	4.42 E-06	0.932	5.354	0.557
800	100	27.25	2.57 E-06	0.932	5.590	0.675
700	60	27.47	2.57 E-07	1.028	6.590	0.847
750	30	27.73	6.20 E-07	0.978	6.208	0.828
800	30	28.56	2.05 E-06	0.932	5.689	0.724
900	25	33.89	1.74 E-05	0.853	4.759	0.532
1000	25	45.30	4.73 E-05	0.786	4.325	0.544
1100	25	66.78	1.34 E-04	0.728	3.874	0.515
1200	25	96.68	6.22 E-04	0.679	3.206	0.351

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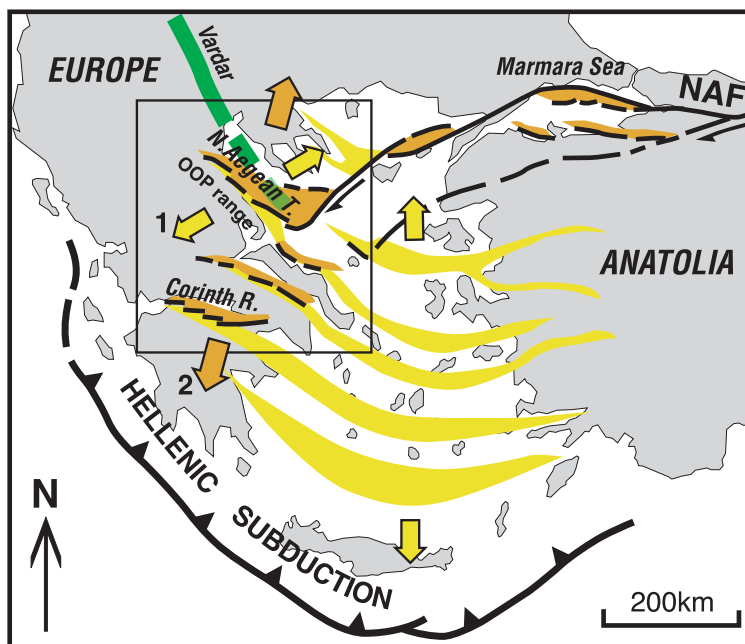


Fig. 1. Tectonic framework of Aegean extension (after Armijo et al., 1996). Active right-lateral motion occurs on two branches of North Anatolian Fault (NAF). Northern branch of NAF propagated west of Marmara Sea pull-apart basins around 5 Ma (Armijo et al., 1999). Late Cenozoic rifts (in orange) open to the SW of NAF extremity (North Aegean Trough, Corinth Rift) and reactivate, with some obliquity, Oligo-Miocene extensional structures (in yellow). Orange and yellow arrows respectively indicate directions of present-day, and Oligo-Miocene extension. OOP: Olympus, Ossa, Pelion. Green: approximate location of Vardar suture. Boxed area corresponds to Fig. 2.

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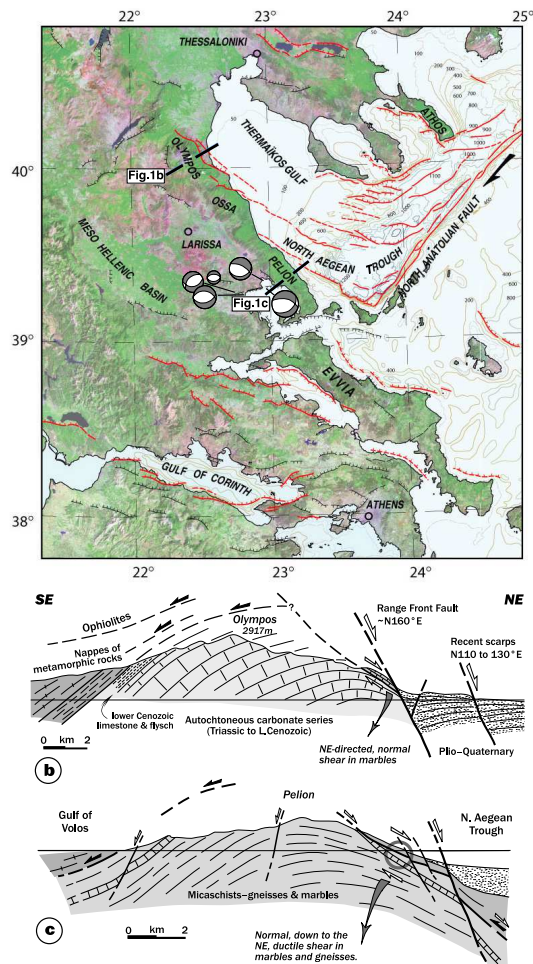


Fig. 2.

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Fig. 2. (a) Sketch map of recent faults in northern Aegean. Major active faults, in red, are NE-SW strike-slip segments belonging to the northern branch of the North Anatolian Fault (NAF), and NW-SE to E-W normal faults; secondary faults are in black. W of Pelion, fault plane solutions of normal faulting earthquakes (Hatzfeld et al., 1999; Goldworthy et al., 2002), indicates ~N-S extension (see also Fig. 8 in Hatzfeld et al., 1999). Background image: NASA Landsat TM Mosaic (<https://zulu.ssc.nasa.gov/mrsid/>). Bathymetry from Mascle and Martin (1990) excepted in North Aegean Trough and along NAF (Papanikolaou et al., 2002). **(b)** and **(c)** Synthetic sections of Olympos (b) and Pelion (c) ranges, from geological maps and field observations (no vertical exaggeration). Olympos range displays nappes of metamorphic rocks (gneisses, schists, metasediments, ophiolites) overlying a core of Mesozoic to lower Tertiary sediments. It is cut by steep, NE-dipping recent normal faults (Schermer, 1993). Pelion range is made of metamorphic rocks equivalent to those of Olympos nappe stack. Its flank facing North Aegean trough shows E-dipping units with evidence of NE-ward ductile to brittle-ductile shear. Dated samples (Fig. 4, Table 2) come from these units. Black arrows: motion on thrust nappe contacts; open arrows: motion on normal faults.

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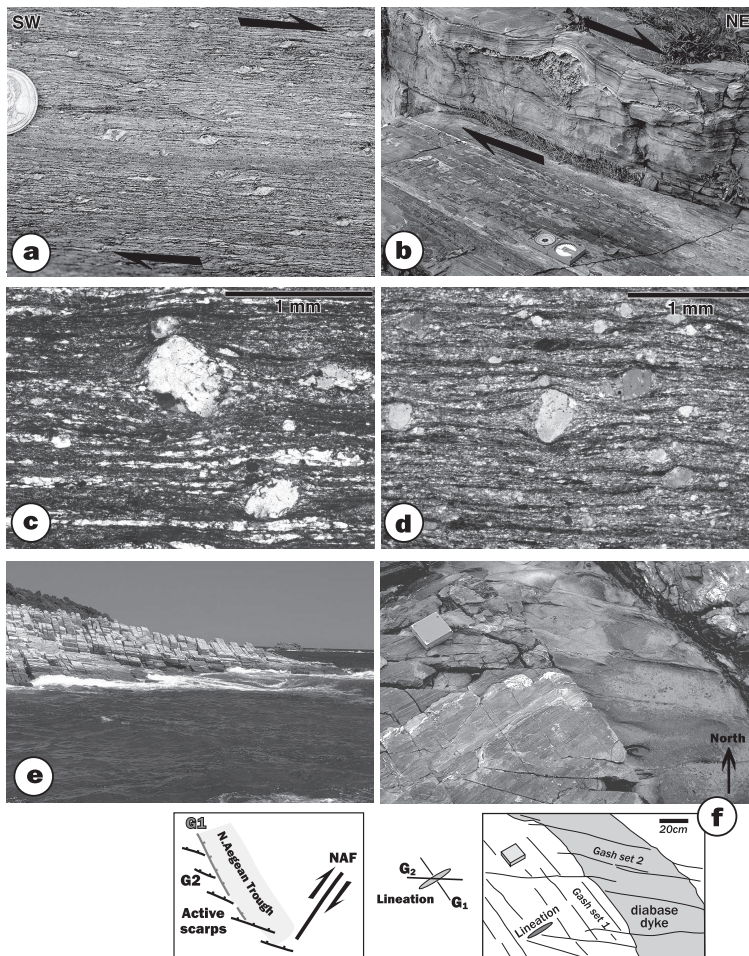


Fig. 3.

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Fig. 3. Deformation characters along eastern Pelion coast with macroscopic evidence of down to the NE (right) ductile shear in gneisses **(a)**, equivalent to dated sample G7 and in marbles **(b)**. Micro-textures of gneisses **(c)** and **(d)** show ribbons of recrystallized grains of quartz, recrystallized mantles and elongated asymmetric tails around feldspar porphyroclasts, both typical of deformation at temperature $>300^{\circ}\text{C}$. **(e)** along eastern Pelion flank, pervasive joints and gashes, equivalent to G1 in (f), are parallel to trend of the coast. **(f)** a diabase dyke (sample G9611, 5.4 Ma, Fig. 4e), parallel to N 140° E gashes (Gash set 1, G1), intrudes earlier ductile fabric of marbles outlined by stretching lineations on foliation planes. It is cut obliquely by a second gash set (Gash set 2, G2) striking N 90° E on the average. Bottom-left inset shows analogy with regional-scale structures: G2 parallel to recent normal faults (Figs. 1, 2a); G1 parallel to older faults and to the overall trend of the Pelion coast.

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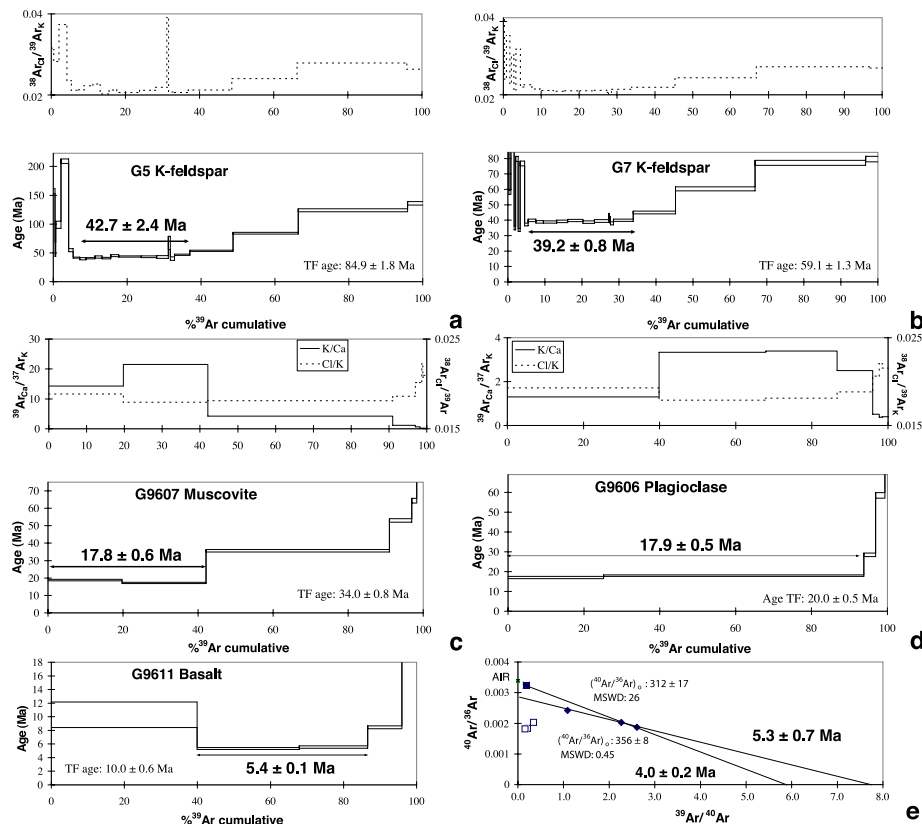


Fig. 4.

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Fig. 4. $^{40}\text{Ar}/^{39}\text{Ar}$ dating of mylonites and schists. **(a–b):** K-feldspar ages spectra (samples G5 and G7). LT steps define pseudo-plateaus whose ages are interpreted as dating a ca. 40 Ma cooling event (see discussion in text). The steps of highest ages, obtained above start of melting of feldspar, were not included in the models, but probably underline the existence of a relict core of old age, similar to that in the muscovites (Lips et al., 1999). **(c–d):** age spectra of muscovite (G9607) and plagioclase (G9606), excess argon or inherited core for the muscovite is likely but not resolvable with the inverse isochrone approach. **(e):** basalt whole rock spectra and inverse isochron using the first four steps (with an age of 5.4 Ma equal to the minimum age of the spectra) or the steps with lowest ages with an age 4 Ma which is preferred, suggesting that the minimum of the saddle is a maximum age as is usually the case when excess argon is present. Refer to Table 2 for precise Lat-Long location of samples.

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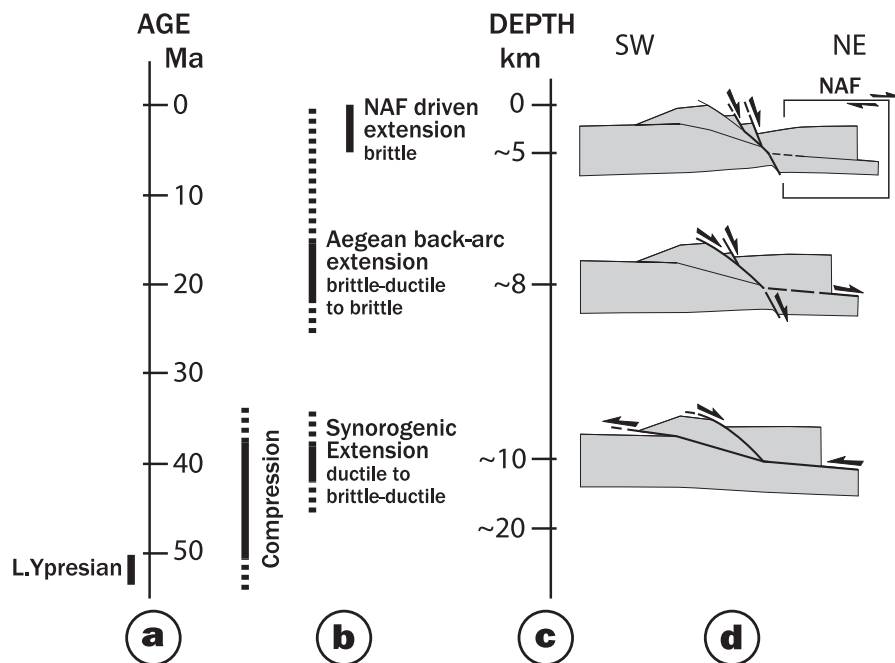


Fig. 5. Interpretative sketch showing evolution of deformation in the Olympos-Ossa-Pelion range. **(a):** linear time-scale. **(b):** main tectonic events. **(c):** qualitative estimate of depth of presently outcropping eastern Pelion rocks constrained by: 1 – cooling history of K-feldspars implying depth <10 km after ~40 Ma, 2 – low T^* crystallisation ages implying moderate exhumation between ~40 Ma and ~20 Ma, 3 – existence of a large structural relief (several km) due to recent motion on post 4 Ma active faults. **(d):** crustal-scale sketches showing probable geometry of major faults.

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