Int J Earth Sci (Geol Rundsch) (2009) 98:1935–1947
DOI 10.1007/s00531-008-0353-9

ORIGINAL PAPER

Rapid early-middle Miocene exhumation of the Kazdağ Massif (western Anatolia)

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Received: 2 May 2007 / Accepted: 6 July 2008 / Published online: 29 July 2008

Abstract Apatite fission-track analyses indicate that the Kazdağ Massif in northwestern Anatolia was exhumed above the apatite partial annealing zone between 20 and 10 Ma (i.e. early-middle Miocene), with a cluster of ages at 17–14 Ma. The structural analysis of low-angle shear zones, high-angle normal faults and strike-slip faults, as well as stratigraphic analysis of upper-plate sedimentary successions and previous radiometric ages, point to a two-stage structural evolution of the massif. The first stage - encompassing much of the rapid thermal evolution of the massif- comprised late Oligocene-early Miocene low-angle detachment faulting and the associated development of small supradetachment grabens filled with a mixture of epiclastic, volcaniclastic and volcanic rocks (Küçükkuyu Fm.). The second stage (Plio-Quaternary) has been dominated by (i) strike-slip faulting related to the westward propagation of the North Anatolian fault system and (ii) normal faulting associated with present-day extension. This later stage affected the distribution of fission-track ages but did not have a component of vertical (normal) movement large enough to exhume a new partial annealing zone. The thermochronological data presented here support the notion that Neogene extensional tectonism in the northern Aegean region has been episodic, with accelerated pulses in the early-middle Miocene and Plio-Quaternary.

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Keywords Fission-track analysis · Thermochronology · North Anatolian fault system · Aegean Sea · Detachment fault

Introduction

Much research has focused on the low-angle detachments associated with metamorphic core complexes in the Aegean and peri-Aegean region (Fig. 1). These include (1) southernmost Peloponnesus, northern Pelagonian Zone, and the Chalkidiki peninsula in Greece, (2) the Rhodope massif of southern Bulgaria and eastern Greece, (3) the Kazdağ and Menderes massifs of western Anatolia, (4) Crete, and (5) the Attic-Cycladic belt of the western-central Aegean (see Walcott and White 1998; Jolivet et al. 2004; for reviews). These basement complexes form an elliptic constellation with a N–S axis and centered on the Cycladic minimum in crustal thickness (<20 km). Such extension has followed a middle Eocene phase of crustal thickening (see Papanikolaou et al. 2004, for a review) and is considered to be driven either by orogenic collapse (e.g., Berckhemer 1977; Jolivet et al. 1994) or by roll-back of the Hellenic subduction zone (e.g., LePichon and Angelier 1981; Buick 1991). The beginning of extension in the Aegean region is poorly constrained, with age estimates ranging from the late Oligocene (e.g., Seytoğlu et al. 1992) to the late Miocene (e.g., Dewey and Şengor 1979).

The ductile to brittle fabrics in the metamorphic core complexes of the Aegean domain provide information on the finite strain field during extension. In terms of direction and rates, the (Oligo-Miocene?) strain field is similar to the present-day active strain pattern, which is known in considerable detail from Global Positioning System (GPS) data (Jolivet 2001). GPS velocities and the

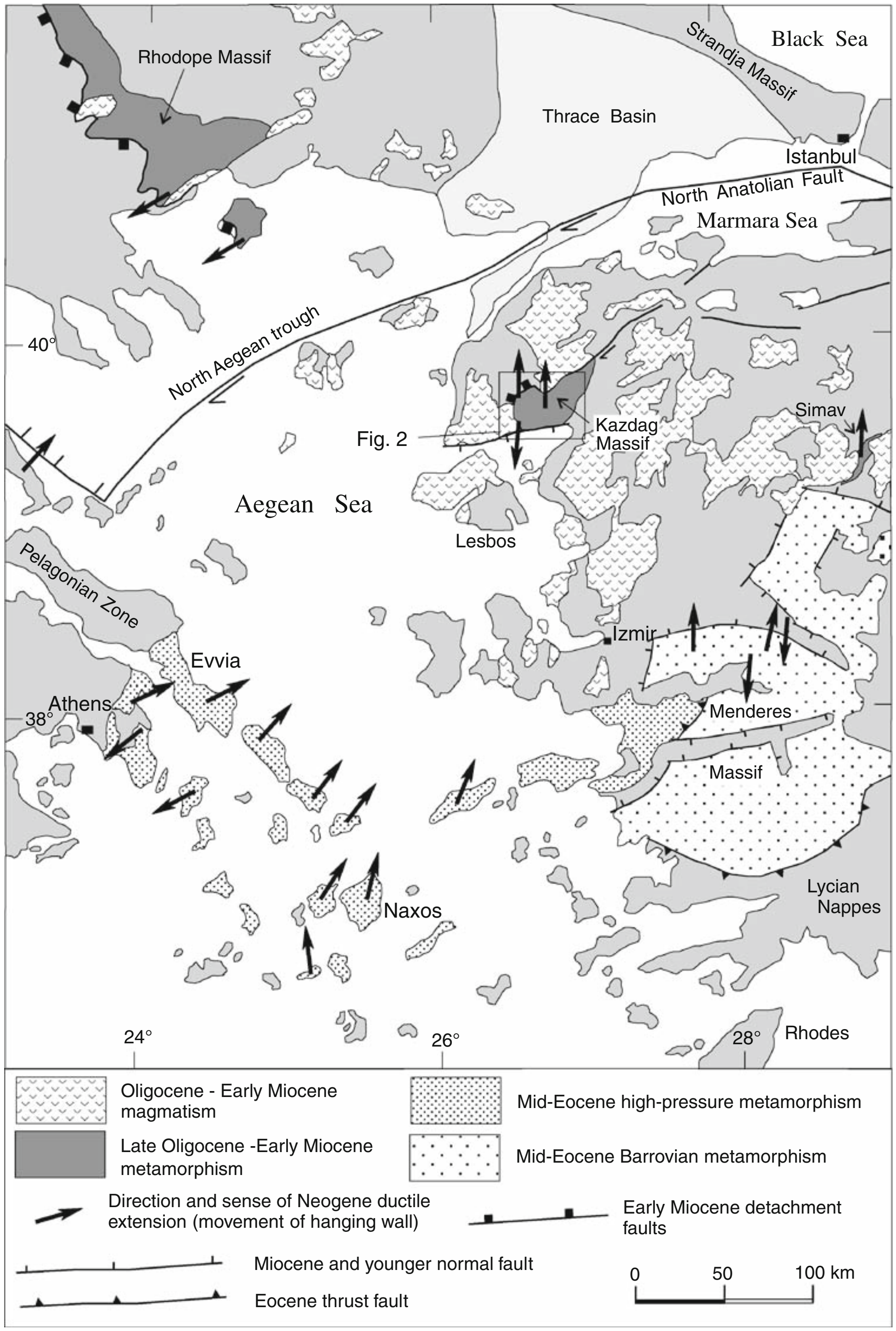

Fig. 1 Geotectonic map of the Aegean region (modified from Okay and Satır 2000) showing the outcrops of Eocene and Late Oligocene-Miocene metamorphism and magmatism and Neogene extension directions (data from Beccaletto 2004; Buick 1991; Dinter and Royden 1993; Gautier et al. 1993; Hetzel et al. 1995; Isık et al. 2004; Lee and Lister 1992; Sokoutis et al. 1993; Walcott and White 1998; Wawrzenitz and Krohe 1998)

presence of diffuse active normal faulting in the Aegean (e.g., Reilinger et al. 2006) suggest that the middle-to-lower crust is extending in a ductile manner. Has the extension been continuous from the late Oligocene (e.g., Seytoglu et al. 1992), or were there periods of quiescence or even periods of regional contraction (e.g., Koçyiğit et al. 1999; Bozkurt and Sözbilir 2004)? This problem can be addressed through detailed thermochronological and structural studies in the metamorphic core complexes. In this paper we present the first fission-track data on the Kazdağ Massif of western Anatolia. The integration of fission-track data and preexisting petrologic, isotopic, structural, and stratigraphic data provides a coherent picture of the thermochronological evolution of this basement complex and points to a wholesome, rapid exhumation in early-middle Miocene times.

A second problem addressed here is the relation between sedimentation and exhumation in the peri-Aegean realm. Neogene terrigenous sequences, often associated with volcanic rocks, cover large areas of northwestern Turkey. The tectonic setting during their deposition has been a matter of controversy, with both contractional (e.g., Yılmaz et al. 2000; Yilmaz and Karacik 2001) and extensional (e.g., Seytoglu et al. 1992) tectonic regimes favored during their formation. We show through structural and stratigraphic relations and fission-track dating that Neogene continental sedimentation and associated volcanism in NW Anatolia took place in supradetachment basins during mid-crustal extension.

Geologic setting

The Kazdağ Massif is located at the southern end of the Biga peninsula of Turkey (Fig. 1), a region where the combination of Aegean extensional tectonism and strike-slip faulting related to the North Anatolian fault system has induced significant crustal thinning and exhumation during the Neogene (Okay and Satır 2000). The massif is a NE-trending, 55 km long and 15 km wide structural and topographic dome of high-grade metamorphic rocks which represents both the highest peak (maximum elevation 1,766 m) and the deepest section of continental crust exposed in northwestern Anatolia (Schuling 1959; Bingöl 1969; Okay et al. 1991, 1996; Pickett and Robertson 1996; Duru et al. 2004). The topography of the Kazdağ Massif is explained as the result of transpression along a restraining step-over of the southern margin of the North Anatolian fault system (Okay and Satır 2000).

In order of decreasing abundance, the Kazdağ Massif is made of gneiss (and associated migmatite), amphibolite, marble, and meta-ultramafic rocks (metaserpentinite, metaperidotite) (Duru et al. 2004) (Fig. 2). The thickness of the entire succession exposed in the western part of the massif has been estimated >6 km (Okay and Satır 2000). The massif is metamorphosed in amphibolite facies without any noticeable change in metamorphic grade across the area. The predominant structure in the massif is a compositional banding and foliation that in the area studied by Okay and Satır (2000) dips consistently 35° to the northwest. The rocks also display a weak mineral stretching lineation plunging NNW.

Although the lack of dated fossils hampers the determination of the depositional age of the succession, the Kazdağ Massif is correlated with the Rhodope crystalline complex in northern Greece and Bulgaria (Papanikolaou and Demirtaşlı 1987). In fact, four zircon crystals from gneisses of the Kazdağ Massif analyzed by single-zircon stepwise Pb evaporation yielded a mean mid-Carboniferous age (308 ± 16 Ma, Okay et al. 1996). This was interpreted as the age of Hercynian high-grade metamorphism, thus pointing to a Laurasian (Rhodopian) affinity for this basement complex (Dinter et al. 1995; Wawrzenitz and Krohe 1998), a correlation that is also based on lithological and tectonic grounds. Bingöl (1969) reported K/Ar mica ages of 26 ± 3 and 27 ± 3 Ma from two Kazdağ gneiss samples. More recently, Okay and Satır (2000) investigated nine gneiss samples by the Rb/Sr method: muscovite ages cluster at 24–20 Ma, biotite ages at 20–18 Ma. They concluded that the massif is made of late Hercynian metamorphic rocks completely recrystallized during the latest Oligocene at peak conditions of 5 ± 1 kbar and 640 ± 50°C, with only the zircons retaining a memory of the older metamorphic event.

Permian-to-Neogene sedimentary, magmatic and metamorphic rocks tectonically overlie the basement rocks of the Kazdağ Massif. To the north and east of the massif, Triassic low-grade metamorphic and sedimentary rocks -including olistoliths of distinctive Permo-Carboniferous limestone- belong to the Karakaya Complex, an accretion-subduction complex marking the closure of the Paleotethyan oceanic domain. West of the Kazdağ Massif lies the Çetmi mélange (Okay et al. 1991; Beccaletto 2004; Beccaletto and Steiner 2005; Beccaletto et al. 2005), an unmetamorphosed Cretaceous tectonic mélange made of slices/blocks of altered basic and pyroclastic volcanic rocks, blocks of upper Triassic limestone, eclogite, serpentinite, listwaenite, and radiolarite within a matrix consisting of an alternation of greywacke and shale.

Low-angle normal faults with thick shear zones mark the contact between the Çetmi mélange in the hanging wall and the Kazdağ metamorphic rocks in the footwall. This is evident along the better exposed and well studied western margin of the massif. In this area, felsic gneisses generally show a well-defined mylonitic foliation -parallel to the compositional banding-, which increases in intensity toward the top of the metamorphic sequence. Shear sense indicators point to a top-to-the-north shear sense (Walcott and White 1998; Okay and Satır 2000), although top-to-the-southwest directions have been also measured (Beccaletto and Steiner 2005).

The Alakeçi shear zone is a 2 km thick zone of strongly mylonitized gneiss and serpentinite occurring between the Kazdağ massif and the accretionary mélange to the north (Fig. 2). The mylonites show a well-defined mineral lineation plunging N12°E at ca. 30°. The foliation is more scattered but shows a general dip to the northwest. The Alakeçi fault constitutes the upper contact of the shear zone and is interpreted as a low-angle detachment juxtaposing brittlely deformed upper crustal rocks (the mélange) over ductilely deformed middle crustal rocks (Okay and Satır 2000). The transition between

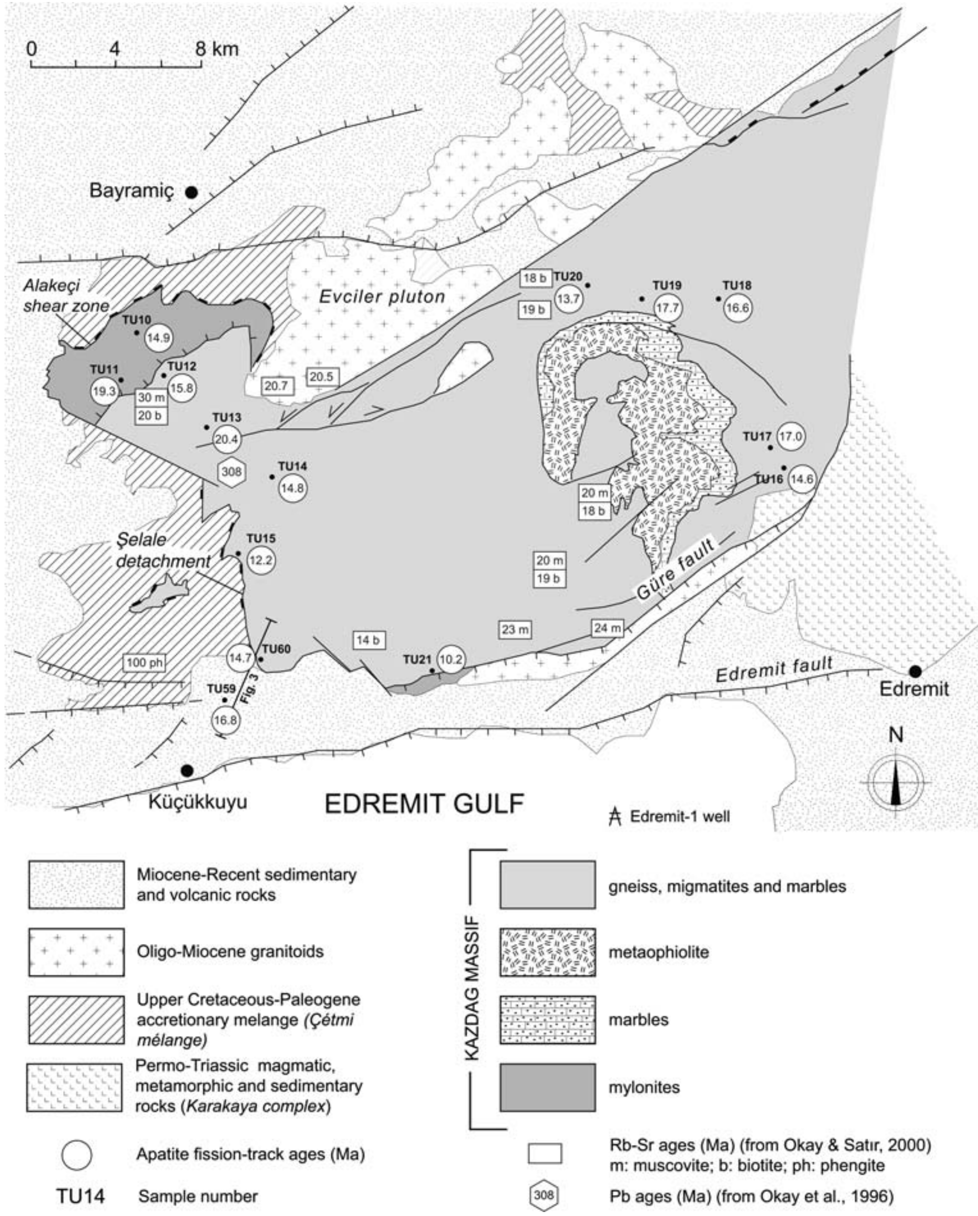

Fig. 2 Geologic map of the Kazdağ massif (modified from Duru et al. 2004) with fission-track ages (this study)

mylonites and the underlying Kazdağ gneisses is cut out by the younger, N-dipping Biçkidere normal fault. Minimum and maximum estimates of the pressure conditions for the mylonites in the shear zones are provided by the estimated depth of emplacement of the Evciler pluton (ca. 3 kbar) and by the Kazdağ regional metamorphism (ca. 5 kbar). Several lines of evidence suggest the existence of a variable dextral strike-slip component of the down-dip extension: (1) the lineation in the mylonites of the Alakeçi shear zone is slightly oblique to the boundaries of the shear zone, (2) serpentinite bodies within the shear zone are arranged *en echelon*, and (3) the azimuths of the lineations show a clockwise rotation going northward from Kazdağ to the Alakeçi shear zone.

Another low-angle shear zone separating the Kazdağ basement in the footwall and the Çetmi mélange (or the overlying Küçükkuyu Formation, see below) in the hanging wall was described by Beccaletto (2004) and Beccaletto and Steiner (2005). The Şelale detachment fault can be traced along the southwestern margin of the Kazdağ massif for about 10 km and dips to the south at 15–20° (Fig. 2). In spite of abundant S- or SW-trending slip lineations on the fault planes, shear sense indicators studied by Beccaletto and Steiner (2005) were inconclusive. Kazdağ marbles and gneisses are brecciated along the fault planes. The bulk of shear deformation along the Şelale detachment occurred in the greenschist facies, thus retrogressing the amphibolite facies rocks of Kazdağ. Several small elliptic granitoid bodies (150 m maximum length) are present in the mélange in the vicinity of the detachment. According to Beccaletto and Steiner (2005), cross-cutting stratigraphic relationships and other lines of evidence indicate that these granitoid bodies –dated at 29.94 ± 0.37 Ma by the U-Pb method- predate detachment activity.

The Kazdağ Massif, the Alakeçi shear zone and the Çetmi mélange are intruded by the granodioritic Evciler pluton dated at ca. 21 Ma (Aquitanian) by Rb/Sr analyses on biotites, analytically indistinguishable from the Rb/Sr biotite ages in the surrounding footwall gneiss (Okay and Satır 2000). To the north the pluton has intruded late Oligocene—early Miocene andesites, dacites and intercalated lacustrine sedimentary rocks. Such volcanic rocks are geochemically close to the Evciler pluton and considered as its extrusive equivalents (Genç 1998). The pluton is generally undeformed yet, near the southern margin of its outcrop, the granitoids are foliated and lineated subparallel to the regional fabric in the adjacent gneisses. Isotopic and geobarometric data (see Okay and Satır 2000, for a review) indicate that the Evciler pluton intruded the Kazdağ metamorphic rocks at about the Oligocene-Miocene boundary at a depth of ca. 7 km, shortly after the peak deformation and metamorphism.

The Kazdağ basement rocks are tectonically overlain in the south by the Miocene continental sedimentary rocks and volcanics of the Küçükkuyu Formation. At the base of the Küçükkuyu Formation there is a highly tectonized and altered layer, ca. 250 m thick, of volcanic rocks (Fig. 3). Beccaletto and Steiner (2005) regard this strongly sheared, fractured, hydrothermally altered layer as the lowest member of the Küçükkuyu Formation. Such volcanic layer is overlain through poorly exposed contacts by shale-dominated lake turbidites (intermediate member). Such a rhythmic infill, together with slump and normal fault structures, suggests the presence of syn-sedimentary tectonics. Accommodation came to an end with the deposition of the upper member, consisting of acidic to intermediate tuffites without any micro-fracturing and hydrothermal alteration. The age of the Küçükkuyu Formation is supposed to be early Miocene (Inci 1984), based on a palynomorph association from the bituminous shales in the intermediate member. Beccaletto and Steiner (2005) dated at 34.4 ± 1.2 Ma a biotite grain sampled in a detritic tuffite of the upper member. However, this age does not fit with the age of the flora of the intermediate member. Thus, Beccaletto and Steiner (2005) interpreted this age not as the age of the deposit, but as the age of the source of the detritic material for the upper member. Late Eocene—Early Oligocene tuffs crop out widely in the northern part of the Biga peninsula.

Apatite fission-track analysis

Thirteen samples were collected from the Kazdağ core complex along two transects trending NW–SE, i.e. perpendicular to the structural fabric. Samples were taken at different altitudes to detect possible relationships between age and elevation. An additional sample (TU59) was taken from a tuffite from the upper member of the Küçükkuyu Formation in order to compare exhumation of the Kazdağ gneisses with the age of overlying sediments. Procedures for sample preparation and analysis are outlined in Table 1 and described in more detail in Zattin et al. (2000).

Apatite fission-track ages from Kazdağ range from 20.4 ± 2.4 to 10.2 ± 2.5 Ma (Table 1, Figs. 2, 4 and 5) and are consistent with the older U/Pb and Rb/Sr dates previously described. The ages do not show a clear correlation with elevation or with structural position (Fig. 5, Table 1). Even samples collected along a nearly vertical profile (samples TU16-20) did not yield progressive ages. However, the five youngest ages (from 14.6 to 10.2 Ma) were yielded by samples taken near the borders of the massif at lower elevations. Track-length distributions are

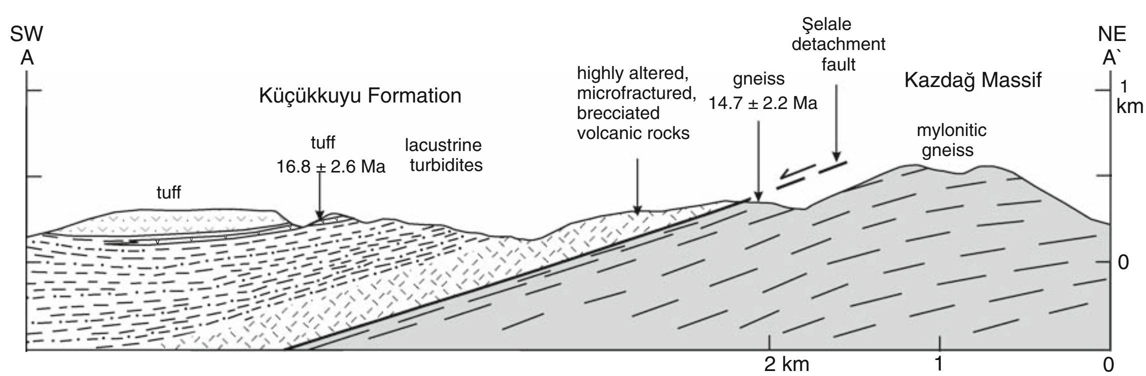

Fig. 3 Cross-section showing the relation between the Kazdağ metamorphic core complex and the Miocene Küçükkuyu Formation. For location see Fig. 2

Table 1 Apatite fission-track analyses (see Fig. 2 for location of samples)

Sample number	UTM	Elevation (m)	Rock type	No. of crystals	Spontaneous		Induced		$P(\chi)^2$	Dosimeter		Age (Ma) ± 1σ	Mean confined track length (μm) ± std. err.	Std. dev.	No. of tracks measured
					ρ_s	N_s	ρ_i	N_i		ρ_d	N_d				
TU10	35S 0463625 4398025	470	Ultramilonite	30	0.29	34	0.43	509	99.9	1.21	5,755	14.9 ± 2.7	13.87 ± 0.47	1.50	10
TU11	35S 0462932 4395823	500	Mylonite	20	0.22	39	0.26	449	88.7	1.20	5,717	19.3 ± 3.2	14.40 ± 0.37	1.39	14
TU12	35S 0464764 4396669	530	Amphibolite	20	1.47	143	2.05	1,997	81.9	1.19	5,678	15.8 ± 1.4	14.52 ± 0.13	1.05	67
TU13	35S 0466961 4393718	650	Gneiss	20	0.74	85	0.73	846	85.1	1.10	5,244	20.4 ± 2.4	13.47 ± 0.19	1.18	39
TU14	35S 0469919 4391454	675	Gneiss	20	1.21	149	1.65	2,038	99.3	1.10	5,215	14.8 ± 1.3	13.90 ± 0.21	1.39	43
TU15	35S 0467634 4388182	470	Gneiss	20	0.99	127	1.64	2,114	44.5	1.09	5,186	12.2 ± 1.2	13.99 ± 0.15	1.05	51
TU16	35S 0493728 4391651	1020	Gneiss	25	1.35	68	1.84	928	60.9	1.09	5,157	14.6 ± 1.9	14.27 ± 0.11	0.93	66
TU17	35S 0493050 4392441	1300	Gneiss	20	2.97	171	3.47	1,998	45.0	1.08	5,127	17.0 ± 1.4	14.51 ± 0.18	0.92	25
TU18	35S 0490557 4399315	1280	Gneiss	20	1.36	108	1.56	1,238	74.2	1.07	5,098	16.6 ± 2.0	14.16 ± 0.21	1.04	24
TU19	35S 0486982 4399562	510	Gneiss	20	6.84	717	8.43	8,834	56.3	1.19	5,640	17.7 ± 0.8	14.36 ± 0.12	1.17	100
TU20	35S 0484449 4400189	360	Granodiorite	20	7.52	576	10.81	8,284	20.9	1.07	5,069	13.7 ± 0.7	14.37 ± 0.10	1.01	100
TU21	35S 0477189 4381567	250	Gneiss	29	0.20	18	0.39	345	83.6	1.06	5,040	10.2 ± 2.5	–	–	–
TU59	35S 0467838 4381076	290	Tuffite	20	0.49	47	0.51	483	88.0	0.93	5,334	16.8 ± 2.6	–	–	–
TU60	35S 0469161 4383347	381	Gneiss	20	0.35	47	0.41	547	99.5	0.93	5,334	14.7 ± 2.2	–	–	–

Central ages calculated using dosimeter glass CN5 and ζ-CN5 = 369.01 ± 3.3. ρ_s: spontaneous track densities ($\times 10^5$ cm^{-2}) measured in internal mineral surfaces; N_s: total number of spontaneous tracks; ρ_i and ρ_d: induced and dosimeter track densities ($\times 10^6$ cm^{-2}) on external mica detectors (g = 0.5); N_i and N_d: total numbers of tracks; $P(\chi^2)$: probability of obtaining χ^2-value for v degrees of freedom (where v = number of crystals-1); a probability >5% is indicative of a homogenous population. Sample preparation: Apatite grains were separated using heavy liquids and magnetic separation techniques. Mounts of apatite in epoxy were polished and then etched with 5N HNO_3 at 20°C for 20 s to reveal spontaneous fission tracks. Samples were then irradiated with a CN5 dosimeter in the reactor at the Radiation Center of Oregon State Univ. with a nominal neutron fluence of 9×10^{15} n cm^{-2}. After irradiation induced fission tracks in the low-U muscovite detector were revealed by etching with 40% HF at 20°C for 45 min. FT ages were calculated using the external-detector and the zeta-calibration methods with IUGS age standards and a value of 0.5 for geometry correction factor. χ^2 test was used to detect whether the data sets contained any extra-Poissonian error

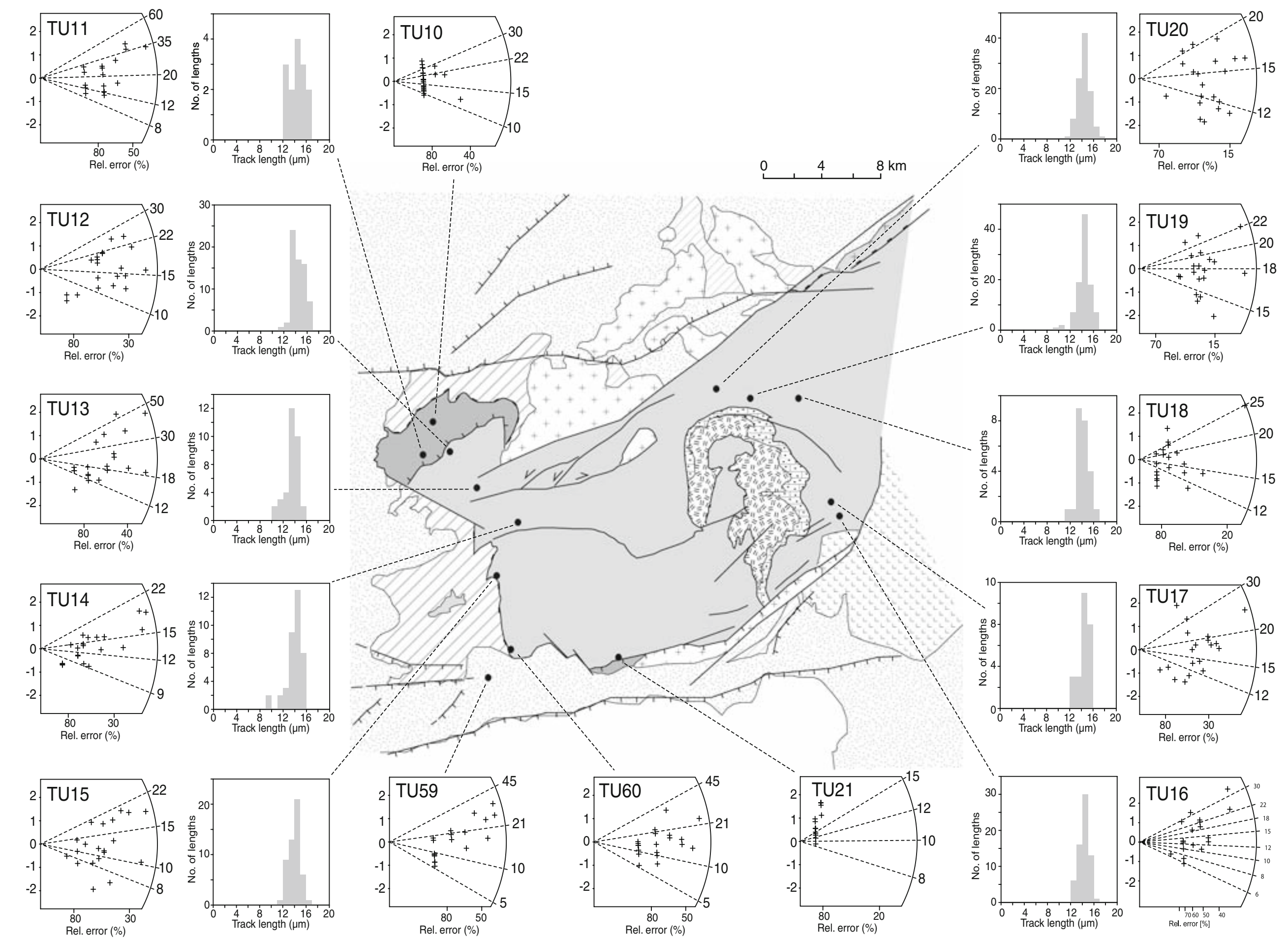

Fig. 4 Confined-track length histograms and radial plots of apatite samples. Radial plots show single grain ages; age precision is indicated on the *x*-axis (Galbraith 1990). See Table 1 for analytical data

leptokurtic (Fig. 4), thus indicating fast exhumation through the apatite partial annealing zone.

With the exception of TU21, all samples yielded good quality apatites, in some cases with high uranium content (TU19 and TU20). All samples passed the χ^2 test, thus pointing to a single grain population in each sample (Table 1). Therefore, the calculated FT ages represent well the time of cooling through the $\sim$110°C isotherm. This is confirmed by track length measurements that show a unimodal distribution with a mean higher than or very close to 14 μm.

Interpretation

Thermal history modelling

Quantitative evaluation of the thermal history can be carried out through modelling procedures, which find a range of cooling paths compatible with the FT data (Gallagher 1995; Willett 1997; Ketcham et al. 2000). During this research, inverse modelling of track length data was performed using the AFTSolve program (Ketcham et al. 2000), which generates the possible T–t paths by a Monte Carlo algorithm. Predicted FT data were calculated according to the Laslett et al. (1987) annealing model.

In order to constrain further the thermal histories, we applied an inverse modelling procedure to samples TU-12, TU-13, TU-16, TU-19, and TU20. Sample TU20 was collected in the same locality where samples for Rb/Sr dating were taken by Okay and Satır (2000). These radiometric ages were used to constrain the modelling. Although the match between synthetic and observed data is variable, the T–t paths thus produced (Fig. 6) consistently indicate a very fast rate of cooling through the PAZ, whose lower temperature boundary was reached between 17 and 13 Ma. After 13 Ma, the lack of important variations in temperature denotes the absence of vertical movements large enough to exhume a new PAZ. The data appear to be quite consistent for all the samples but TU13, whose thermal

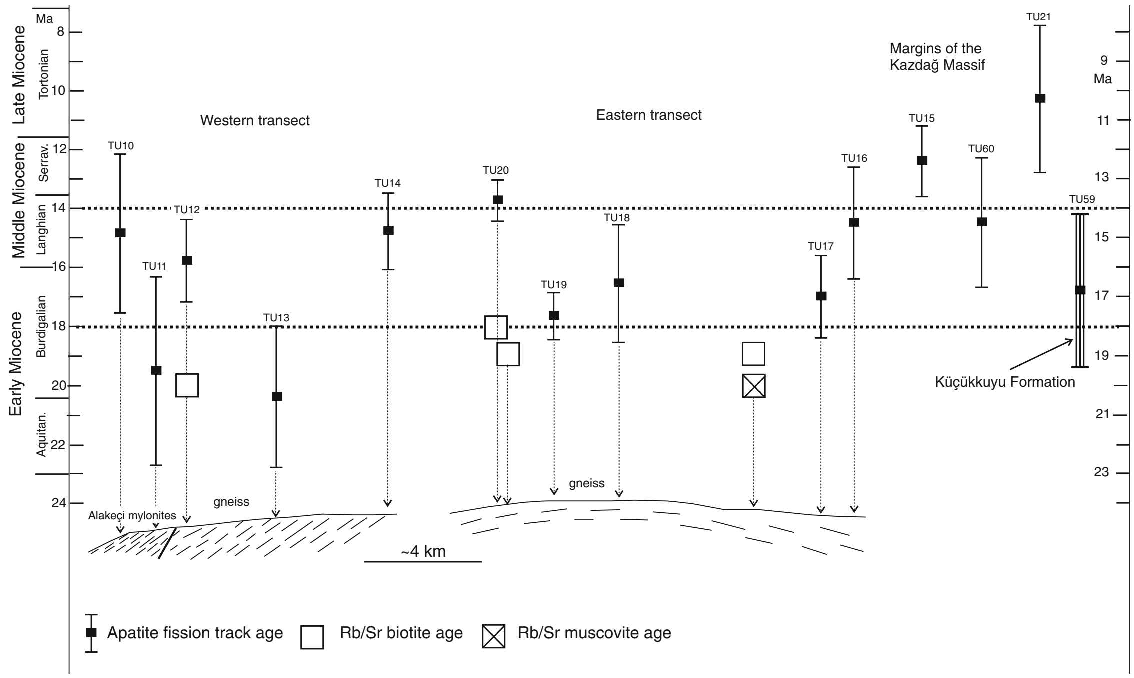

Fig. 5 Apatite fission track and Rb/Sr mica ages plotted against time, structural position and elevation. Rb/Sr ages are from Okay and Satir (2000)

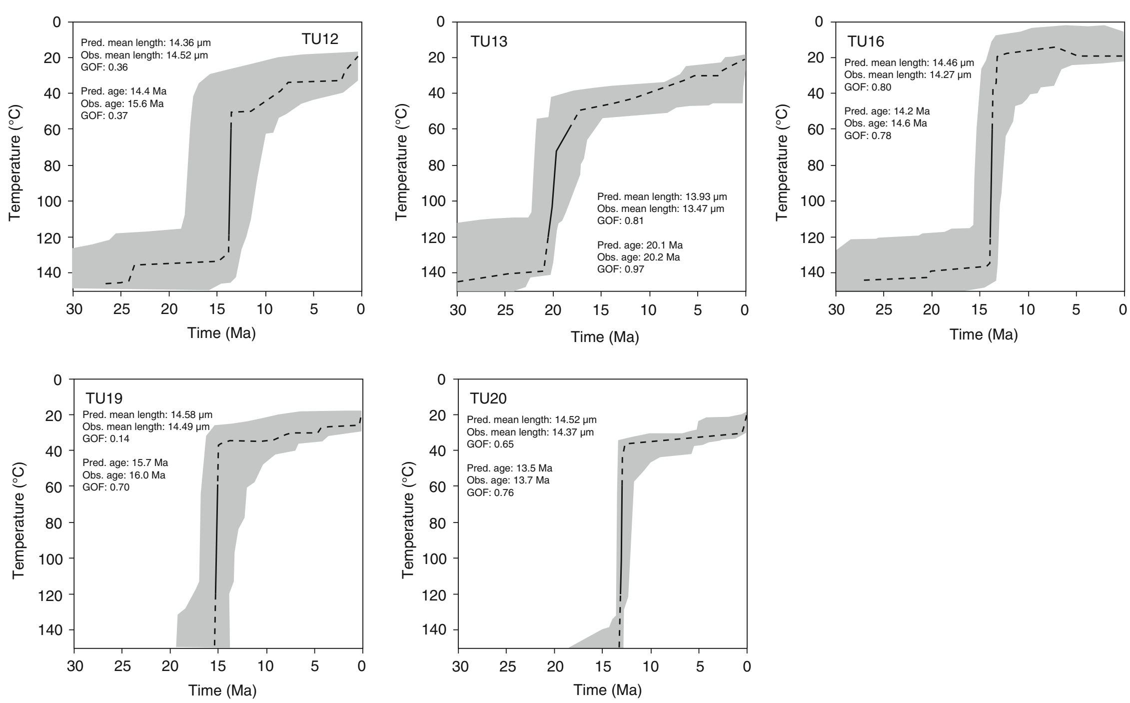

Fig. 6 Time-temperature paths obtained from inverse modelling. Shaded areas mark envelopes of statistically acceptable fit and the thick lines correspond to the most probable thermal histories. Thermal paths out of the partial annealing zone are largely inferential as fission-track data cannot give reliable information out of this temperature range. In each diagram, parameters related to inverse modelling are reported: *obs. age* observed age (in Ma); *pred. age* predicted age (in Ma); *obs. MTL* observed mean track length (in microns); *pred. MTL* predicted mean track length (in microns). GOF gives an indication about the fit between observed and predicted data (values close to 1 are best)

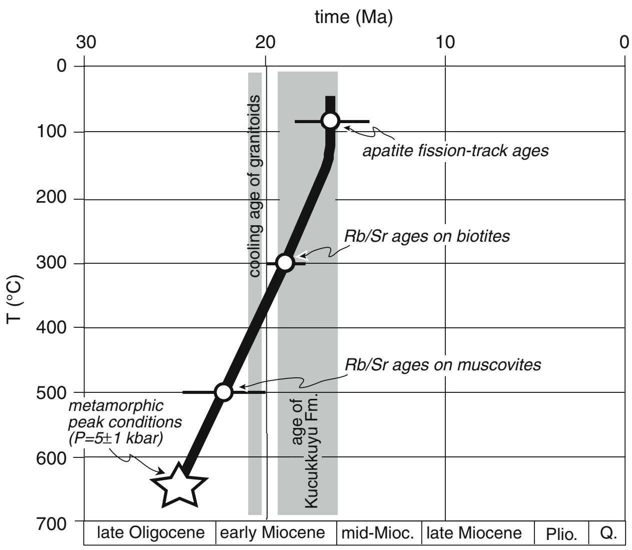

Fig. 7 Temperature-time path of Kazdağ massif. White dots indicate means, horizontal bars indicate one standard deviation from the means. Data souces: fission track data (this study); Rb/Sr ages (Okay and Satir 2000); age of Küçükkuyu Fm. (Beccaletto 2004; Beccaletto and Steiner 2005; this study); cooling age of granitoids and peak metamorphism (Okay and Satir 2000)

path suggests a slightly older exhumation. The reason for this apparent discrepancy is not clear, but could be related to some differences in the kinetics of apatites (unfortunately, no composition data are available) or, more probably, to some late tectonics (Plio-Quaternary?) as discussed in the following sections.

In summary, apatite FT ages collected across Kazdağ indicate that exhumation of the core complex to shallow crustal levels occurred during late Early–early Middle Miocene time (late Burdigalian-Langhian). FT ages of nine out of thirteen samples from the Kazdağ basement rocks cluster from 17.7 ± 0.8 to 13.7 ± 0.7 Ma.

Composite t–T paths

Integration of our new apatite FT results with preexisting radiometric data on the basement rocks of Kazdağ allows the construction of a detailed time-temperature path (Fig. 7). In addition to the FT data presented in this study, the path is constrained by (1) geothermometric and geobarometric estimates from metamorphic and granitic mineral assemblages and (2) $^{87}Rb/^{86}Sr$ geochronologic data on biotites and muscovites (Okay and Satır 2000). The cooling path thus obtained is coherent and points to a fairly constant cooling rate (ca. 60°C/Ma) between the time of peak metamorphism (latest Oligocene) and the late Burdigalian-Langhian, when Kazdağ basement rocks reached the base of the apatite partial annealing zone. Successively, FT data indicates a faster cooling rate across the apatite PAZ.

The perfect euhedral shape of apatite grains obtained from the tuffite sample (TU59) interbedded within the upper member of the Küçükkuyu Formation suggests that these mineral grains derive from synsedimentary volcanism. Thus the FT age (16.8 ± 2.6 Ma) yielded by such grains represents the depositional age of the upper member of the Küçükkuyu Formation.

The sense of shear in the Kazdağ metamorphic core complex is equivocal. Although there is a preponderance of top-to-the-north shear fabrics northwest of Kazdağ (Okay and Satır 2000), top-to-the-south fabrics are also present and dominate the southern part of the massif. This could be due to a major component of pure shear and/or bivergent extension. Apatite FT data do not show a clear pattern of directional younging; however those from the southern margin of the massif are generally younger than those from the north (Fig. 2). This implies a top-to-the-south sense of shear for the Şelale detachment fault. The older apatite FT ages in the northern part of Kazdağ combined with the dominance of top-to-the-north shear fabrics suggest that the Alakeçi shear zone with a top-to-the-north sense of shear may have predated the activity of the Şelale detachment fault. The absence of a thick mylonitic shear zone along the Şelale detachment fault also indicates that it is younger than the Alakeçi shear zone. However, the southern part of Kazdağ was exhumed more than the northern part during the Plio-Quaternary due to the footwall uplift along the active Edremit fault (Fig. 2), and this might have caused some younging in the apatite FT ages along the southern margin.

Discussion

Yilmaz and Karacik (2001) suggested that the Küçükkuyu Formation was deposited during a period of north–south contraction. However, the early Miocene age of the Küçükkuyu Formation, constrained by palinology (Inci 1984) and by the 16.8 ± 2.6 Ma apatite FT age from the tuff, overlaps the age of exhumation of the Kazdağ Massif (Figs. 6 and 7). This –together with the supradetachment setting of the Küçükkuyu Formation-clearly shows that the Küçükkuyu sediments were deposited during a period of north-south extension rather than contraction. The apatite FT age from gneisses directly underlying the Küçükkuyu Formation is also early to middle Miocene (14.7 ± 2.2 Ma) (Fig. 3). This indicates that a thick rock section is missing between the Küçükkuyu Formation and the Kazdağ Massif. Such section must have been tectonically removed during and/or after deposition of the Küçükkuyu Formation. The missing section most probably consisted of the Çetmi mélange, which forms the probable stratigraphic basement of the Küçükkuyu Formation (Fig. 8). From this viewpoint,

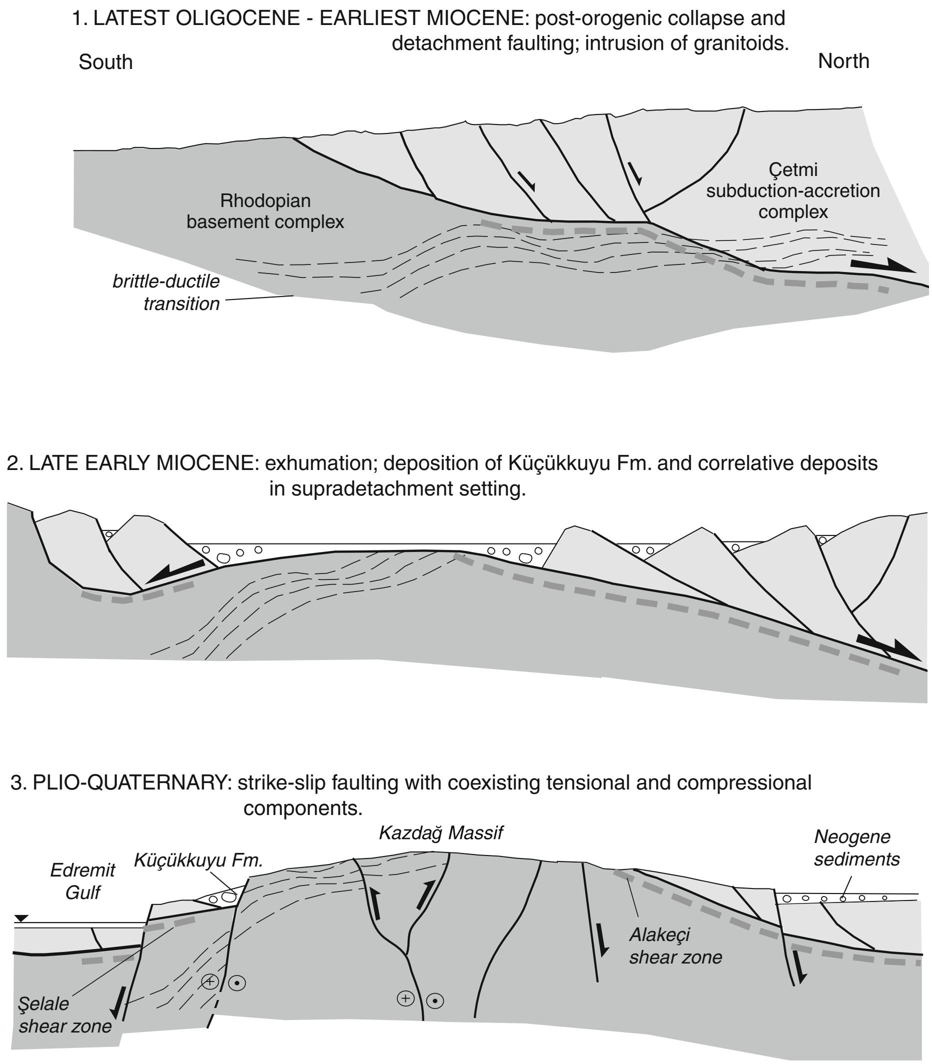

Fig. 8 Schematic N–S cross-sections across the southern Biga peninsula from early Miocene to Plio-Quaternary times. (1) Post-orogenic collapse of the Çetmi subduction-accretion complex and inception of detachment faulting. (2) Late early Miocene block faulting and deposition of Küçükkuyu Formation within supradetachment grabens. (3) Strike-slip faulting; precise location of strike-slip faults is speculative. The Alakeçi and Şelale shear zones represents discrete episodes of shearing at different crustal levels and with opposing movements

the Küçükkuyu Formation can be interpreted as the filling of a typical supra-detachment basin (Beccaletto and Steiner 2005). Sedimentation was synchronous with the ongoing deformation in the footwall along the N-dipping Alakeçi and S-dipping Şelale detachment faults. Cross-cutting relationships indicate that the age of the latter fault is younger than the intrusion of small granitic bodies (dated at 29.9 Ma with the U-Pb method; Beccaletto and Steiner 2005).

Although deposition of the Küçükkuyu Formation occurred during the exhumation of the Kazdağ Massif, detrital modes of the Küçükkuyu Formation are characteristically dominated by Çetmi mélange rock types (Beccaletto and Steiner 2005). Kazdağ gneiss clasts are first encountered in the fluviatile Plio-Quaternary conglomerates and sandstones of the Bayramiç area (Siyako et al. 1989), thus implying that Kazdağ basement rocks reached the surface well after deposition of the Küçükkuyu Formation. In addition, FT ages close to the Alakeçi and Şelale detachments range between 15 and 12 Ma -therefore younger than the upper member of the Küçükkuyu Formation- and confirm that exhumation at very shallow crustal levels was achieved only late in the activity of the detachments.

The Kazdağ Massif is bounded in the south by the active Edremit Fault, a predominantly normal fault with a dextral strike-slip component, whose inception probably dates back to the late Miocene (Boztepe-Güney et al. 2000; Yilmaz and Karacik 2001). Offshore data (seismic lines and the stratigraphy of the Edremit-1 well) show a >2,500 m thick section of Miocene and younger sedimentary and volcanic deposits in the Edremit basin (Siyako et al. 1989; Yilmaz and Karacik 2001). Such thickness - coupled with the present elevation of Kazdağ (1,766 m)- indicate a cumulative vertical offset in excess of 4.5 km across the southern margin of the Kazdağ Massif. Despite this considerable offset, the footwall uplift north of the Edremit fault in Kazdağ (0.5 km) was insufficient to exhume a new PAZ, as clearly shown in this study. At depth the steeply south-dipping active Edremit fault must cut and displace the much flatter (15–20°) Kazdağ detachment fault. A similar relation is observed between the active graben-bounding faults in western Anatolia and the gently dipping detachments (Bozkurt and Sözbilir 2004).

The Neogene tectonic evolution of the Kazdağ Complex involves rapid exhumation during the early to early middle Miocene (23 to 13 Ma) followed by quiescence, at least in terms of vertical tectonics. A similar thermochronological evolution has been deduced for the Simav metamorphic core complex, 170 km east of Kazdağ (Thomson and Ring 2006). The extension in the northern Aegean region appears to have been episodic rather than continuous, with a rapid phase of extension and associated sedimentation during the Early to Middle Miocene.

According to Okay and Satır (2000), (1) the estimated conditions of metamorphism and pluton emplacement at Kazdağ indicate that high-grade metamorphic rocks were rapidly exhumed starting at ∼24 Ma from a depth of ∼14 km to ∼7 km by activity along the Alakeçi shear zone, and (2) the subsequent exhumation of the metamorphic rocks to the surface occurred during Pliocene-Quaternary time in a transpressive ridge between two overstepping fault segments of the North Anatolian fault zone. Such structural configuration would be responsible for the present anomalously high topography of the Kazdağ range (1,767 m above sea-level, compared to an average elevation <500 m for the entire NE Aegean region). In fact, although most research on the Northern Anatolian Fault system is now focused on the northern Marmara Sea oversteps and the Ganos segment on land, which are considered the active strands of the fault system, it must be borne in mind that in the past 50 years several destructive earthquakes have occurred along the southern edge of the fault system not only along the northern shore of the Edremit Gulf (1944; Mw = 6.8), but also near Manyas Lake (1964; Mw = 6.9) and near Yenice (1953; Mw = 7.2), just about 30 km northeast of Kazdağ (Nalbant et al. 1998). The moment tensor solutions of these historical earthquakes show that these active segments have not only strike-slip but also normal fault characteristics (Herece 1990).

Based on the results of this research and the available literature on the study area, we propose the following evolutionary scheme for the region of the Kazdağ Massif (Fig. 8).

(1) We subscribe to the notion that the present-day scattered outcrops of the Çetmi mélange are remnants of a widespread subduction-accretion complex of Rhodopian affinity active at least until the Late Cretaceous (Beccaletto et al. 2005). Widespread contractional tectonism continued in the Paleogene in the north Aegean region and NW Anatolia, and came to an end with the sequential and progressive closure of the Vardar and Pindos oceans (Stampfli and Borel 2004). In addition, closure of the Intra-Pontide oceanic domain and coincident development of the Intra-Pontide Suture occurred during the Oligocene (Görur and Okay 1996). By late Oligocene time extensional tectonism is well documented all over the north Aegean region (see, for example, Gautier et al. 1999; Burchfiel et al. 2000) and must be considered as a viable mechanism for significant and widespread exhumation, in line with the results of this study.

(2) During late early Miocene time prolonged extensional tectonism and exhumation induced the development of a full-fledged core complex and associated supradetachment basin where the Küçükkuyu Formation was deposited (Beccaletto and Steiner 2005). At this time -despite rapid exhumation- the basement rocks of Kazdağ were not yet exposed at the surface, as shown by the absence of Kazdağ-derived detritus in the Küçükkuyu Fm. It must be noted that the Alakeçi and Şelale detachments are discrete structures with different timing and characteristics, and not two segments of a continuous, single detachment. The two detachments induced progressive exhumation along the northern and southern margins of the massif, as shown by the youngest FT ages along its present-day margins.

(3) During the Pliocene-Quaternary the region of the Kazdağ Massif has been affected by intense strike-slip tectonism associated with the development of the present-day North Anatolian fault system. A complex array of anastomosing faults induced localized subsidence/exhumation at releasing/constraining bends and oversteps. As clearly indicated by the results of this study, the vertical component of this later stage was insufficient to exhume a new PAZ. Nevertheless, in a few locations the horizontal component was large enough to juxtapose rock volumes originally located at distant sites across the Kazdağ domal structure, and thus characterized by different FT ages.

Widespread high-pressure metamorphic rocks in the central Aegean have been cited as evidence for a thick, and consequently topographically high, continental crust prior to the onset of extension. From this viewpoint, Aegean extension was driven by orogenic collapse. However, in NW Turkey there is no evidence for high topography during the Eocene and Oligocene. Rocks of this age are present in the northern Biga and Gelibolu peninsulae as well as in the Thrace basin and are predominantly marine. Paleoclimatological inferences based on paleobotanical evidence also rule out the existence of a high relief (Mädler and Steffens 1979; Ediger 1990). Such paleoenvironmental-paleotopographic considerations place important constraints on the tectonic mechanism responsible for Latest Oligocene extension in northwest Turkey–including the development of the Kazdağ metamorphic core complex. Orogenic collapse can be ruled out whereas Aegean and peri-Aegean extension could instead be the result of subduction roll-back of the Hellenic trench.

The Cycladic core complexes are similar to the Kazdağ core complex yet the age of metamorphism, extensional deformation and plutonism is younger (e.g., 16–10 Ma on the island of Naxos, Andriessen 1991) than in the Kazdağ and Rhodope core complexes. Exhumation of Kazdağ is also older than that of the Menderes metamorphic core complex to the south, where apatite fission-track ages from the lower plate cluster between ca. 15 and 5 Ma (Gessner et al. 2001). Such tendency toward an overall younging in exhumation going southward across the Aegean region (cf. also Walcott and White 1998) agrees well with the notion of slab roll-back along the eastern Mediterranean subduction zone as the driving mechanism for lithospheric extension in the Aegean (e.g., Jolivet 2001).

Conclusions

The Kazdağ Massif underwent high-temperature regional metamorphism at ~24 Ma at a depth of ~14 km. Ensuing exhumation took place along a couple of opposing detachments between 20 and 10 Ma (i.e. early-middle Miocene), with the majority of apatite FT ages at 17–14 Ma. The post-metamorphic evolution of Kazdağ encompasses two stages. The first stage comprises late Oligocene-early Miocene low-angle detachment faulting and early Miocene development of small supradetachment grabens filled with a mixture of epiclastic, volcaniclastic and volcanic rocks (Küçükkuyu Fm.). During this phase much of the rapid thermal evolution of the massif occurred, including the emplacement of a suite of granitoid stocks with cooling ages around 21 Ma. Younger fission-track ages are aligned along the borders of the massif, substantiating the notion of a progressive, bivergent denudation along opposing detachment faults whose remnants are still visible. The second stage (Plio-Quaternary) is dominated by strike-slip faulting related to the westward propagation of the North Anatolian fault system. The overall thermochronologic evolution of Kazdağ fits well in the framework of Aegean extensional tectonism, with exhumation ages becoming progressively younger from north to south.

Acknowledgments L. Beccaletto and G. Stampfli are thanked for fruitful discussions. Reviews by F. Lisker and D. Papanikolaou greatly improved the manuscript. This research was sponsored by MIUR (Italian Dept. of Public Education, University and Research) and in part by the Turkish Academy of Sciences.

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