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# $^{207}$Pb-$^{206}$Pb, $^{40}$Ar-$^{39}$Ar and Apatite Fission-Track Geothermochronology Revealing the Emplacement, Cooling and Exhumation History of the Karaçayır Syenite (N Sivas), East-Central Anatolia, Turkey

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**Abstract:** The Karaçayır syenite, intruding the Palaeozoic crustal metamorphics and unconformably overlain by Upper Paleocene to Eocene Tokuş formation in the north of Sivas (east-central Anatolia), has been studied with respect to $^{207}$Pb-$^{206}$Pb single zircon evaporation, biotite $^{40}$Ar-$^{39}$Ar, and apatite fission-track geothermochronology. $^{207}$Pb-$^{206}$Pb single zircon evaporation dating yields an age of 99.0±11.0 Ma (Cenomanian–Turonian) which is considered to be the intrusion age. Biotite $^{40}$Ar-$^{39}$Ar age determination gives a cooling age of ca. 65 Ma. Apatite fission-track dating, combined with T-t modeling based on track-length distribution data, determines a fast tectonic exhumation with an uplift rate of > 1 mm/a which occurred 58–61 Ma ago. This Middle Paleocene fast tectonic uplift is considered to have resulted from a compressional regime induced by the collision between the Tauride-Anatolide platform (TAP) and the Eurasian plate (EP) along the İzmir-Ankara-Erzincan (İAE) suture zone following the closure of the north-dipping subducted İAE ocean which belongs to northern Neo-Tethyan realm. This compressional regime has also formed the peripheral foreland basins in central Anatolia.

Key Words: single zircon $^{207}$Pb-$^{206}$Pb, biotite $^{40}$Ar-$^{39}$Ar, apatite fission-track, exhumation history, Karaçayır syenite, Sivas, Turkey

## Karaçayır Siyenitinin (K Sivas) $^{207}$Pb-$^{206}$Pb, $^{40}$Ar-$^{39}$Ar ve Fizyon İzi Jeotermokronolojisi Yöntemleriyle Yerleşme, Soğuma ve Yüzeylenme Tarihçesinin İncelenmesi, İç-Doğu Anadolu, Türkiye

**Özet:** Sivas (İç-Doğu Anadolu) yöresinde Paleozoyik yaşlı kabuksal metasedimanter kayaçları sıcak dokanakla kesen ve Geç Paleosen–Eosen yaşlı Tokuş formasyonuyla uyumsuz olarak örtülen Karaçayır siyeniti tek zirkon $^{207}$Pb-$^{206}$Pb buharlaşma, biyotit $^{40}$Ar-$^{39}$Ar ve apatit fizyon izi jeotermokronolojisi yöntemleriyle incelenmiştir. Tek zirkon $^{207}$Pb-$^{206}$Pb buharlaşma yaş tayini çalışmaları sonucunda Karaçayır siyenitinin intrüzyon yaşı 99.0±11.0 My (Senomaniyen–Turoniyen) olarak belirlenmiştir. Biyotit $^{40}$Ar-$^{39}$Ar yaş tayini çalışmaları ~65 My civarında bir soğuma yaşı vermiştir. Apatit fizyon izi yaş tayini ve iz uzunluk ölçüm çalışmalarına dayalı sıcaklık-zaman (T-t) modelleme verileri, Karaçayır siyenitinin 58 ile 61 My aralığında (Orta Paleosen) yıllık 1 mm'den daha hızlı olan tektonik yükselme ile yüzeylendiğini ortaya koymuştur. Orta Paleosen yaşlı bu tektonik yükselmenin, Avrasya levhasının (AL) altına ve kuzeye doğru dalmakta olan İzmir-Ankara-Erzincan (İAE) okyanusunun kapanması sonucu, İAE kenet kuşağı boyunca meydana gelen ve AL ile Torid-Anatolid platformunun (TAP) kenetlenmesini sağlayan kıta-kıta çarpışması ile meydana gelen sıkışma rejiminden kaynaklandığı ileri sürülmektedir. Bu sıkışma rejimi, aynı zamanda, Orta Anadolu önülke havzalarının gelişimini de sağlamıştır.

Anahtar Sözcükler: tek zirkon $^{207}$Pb-$^{206}$Pb, biyotit $^{40}$Ar-$^{39}$Ar, apatit fizyon izi, yüzeylenme tarihçesi, Karaçayır siyeniti, Sivas, Türkiye

## Introduction

In the central Anatolia region (Turkey), there are numerous granitoids generated in a post-collisional extensional setting in relation to the evolution of the İzmir-Ankara-Erzincan ocean, belonging to the northern Neo-Tethyan domain (e.g., Boztuğ 2000; Bozkurt & Mittwede 2001; Önal *et al.* 2005; Boztuğ & Arehart 2007; Boztuğ & Harlavan 2008). High-T geothermochronology data, consisting of Rb-Sr whole-rock isochron (Göncüoğlu 1986; Kuruç 1990), zircon U-Pb SHRIMP (Whitney *et al.* 2003), titanite U-Pb (Köksal *et al.* 2004) and single zircon $^{207}$Pb-$^{206}$Pb (Boztuğ *et al.* 2007a), reveal that they fall into three groups with different emplacement ages: (1) Cenomanian–Turonian (94.9±3.4 Ma); (2) Turonian–Santonian (85.5±5.5 Ma); (3) Campanian (74.9±3.8 Ma). Hornblende and biotite K-Ar (Göncüoğlu 1986; Yalınız *et al.* 1999; İlbeyli *et al.* 2004; Tatar & Boztuğ 2005; Boztuğ & Harlavan 2008; Boztuğ *et al.* 2007b) and $^{40}$Ar-$^{39}$Ar ages (Kadıoğlu *et al.* 2003; Whitney *et al.* 2003) cluster around 75 to 65 Ma indicating rapid exhumation of a mid-crustal section. Geothermobarometric studies (Boztuğ *et al.* 2007c, 2008) indicate solidification between 5.0 kb (~15 km) and 695 °C to 2.0 kb (~7 km) and 600 °C. The east-central Anatolian granitoids consist of, from west to east, the Upper Cretaceous Davulalan, Yücebaca, Banaz, Karaçayır, Kuluncak, Yellice, Yüceşafak, Mursal, Dumluca, Murmana, Karakeban granitoids; and the Eocene Çaltı, Bizmişen, Çöpler and Kösedağ granitoids (Figure 1, Table 1). The Cretaceous plutons intrude the imbrication zone between the high- to medium-grade crustal metasediments (Whitney & Dilek 1998; Whitney *et al.* 2003; Whitney & Hamilton 2004) of the Tauride-Anatolide Platform (TAP) and the supra-subduction zone type central Anatolian ophiolites (SSZ-type CAO) (Yalınız *et al.* 1996, 2000; Floyd *et al.* 2000; Garfunkel 2004). They are unconformably overlain by Upper Paleocene to Middle Eocene sediments deposited in peripheral foreland basins (Görür *et al.* 1998; Gürer & Aldanmaz 2002). The Eocene granitoids intrude the same imbrication zone that includes an additional Eocene volcano-sedimentary sequence and are unconformably covered by Lower Miocene to Mio–Pliocene sedimentary rocks.

The Karaçayır pluton, among these east-central Anatolian granitoids, was first described by Schuiling (1961) as containing pegmatitic carbonatite-like occurrences found at the syenite-marble contact. Later, this small syenitic intrusion has been studied with respect to its mineralogical-petrographical and geochemical (Boztuğ *et al.* 1996) compositions. Boztuğ (1998) determined it as being part of central Anatolian alkaline plutonism. The aim of this paper is to present a new $^{207}$Pb-$^{206}$Pb single zircon evaporation age, biotite $^{40}$Ar-$^{39}$Ar cooling ages, and apatite fission-track ages of the Karaçayır pluton, combined with track-length data in order to get the crystallization, cooling and exhumation ages and temperature-time modeling during uplift with a special emphasize on geodynamic setting.

## Regional Geology

The geological evolution of central Anatolia is governed by the evolution of the northern branch of Neo-Tethys which is further subdivided in two oceanic realms: the İzmir-Ankara-Erzincan (İAE) ocean between the Eurasian plate (EP) in the north and the Tauride-Anatolide platform (TAP) in the south and the Inner Tauride (IT) ocean located within the TAP (Şengör & Yılmaz 1981; Bozkurt & Mittwede 2001; Boztuğ & Jonckheere 2007). Garfunkel (2004) proposed that these Neo-Tethyan seaways began to close in the Cenomanian–Turonian (95–90 Ma). When convergence set in, a subophiolitic metamorphic sole formed as a result of intra-oceanic thrusting in the İAE (Dewey *et al.* 1973; Le Pichon *et al.* 1988; Parlak & Delaloye 1999). Around the Cenomanian–Turonian, the oceanic island arc docked onto the TAP (Parlak & Delaloye 1999; Dilek *et al.* 1999; Floyd *et al.* 2000; Garfunkel 2004; Robertson & Ustaömer 2004; Parlak *et al. 2006;* Boztuğ & Jonckheere 2007). The supra-subduction zone (SSZ) type central Anatolian Ophiolites (CAO) seems to be the result of the associated obduction of ophiolitic rocks. Slab break-off and/or lithospheric delamination/detachment in the Turonian–Campanian installed an extensional post-collisional regime accompanied by medium- to high-grade metamorphism in the central Anatolian crystalline complex (CACC) and the emplacement of diverse granitoids which are called post-collisional central Anatolian granitoids (CAG) (Boztuğ & Jonckheere 2007; Boztuğ *et al.* 2007a, b, c). The Karaçayır syenite is one of the member of the CAG cropping out in the northern part of Sivas city in central Anatolia, Turkey, which constitutes the main subject of this study.

## Geological Setting and Petrography

The Karaçayır syenite (Figure 1), intrudes the Palaeozoic Akdağmadeni lithodem unit consisting of white coloured marbles, and is unconformably overlain by the Upper Paleocene–Middle Eocene Tokuş formation comprising, from bottom to top, conglomerate, sandstone, limestone, marl and siltstone alternations (İnan & İnan 1999).

The major fault in the mapped area is a NE–SW-trending normal fault developed between the

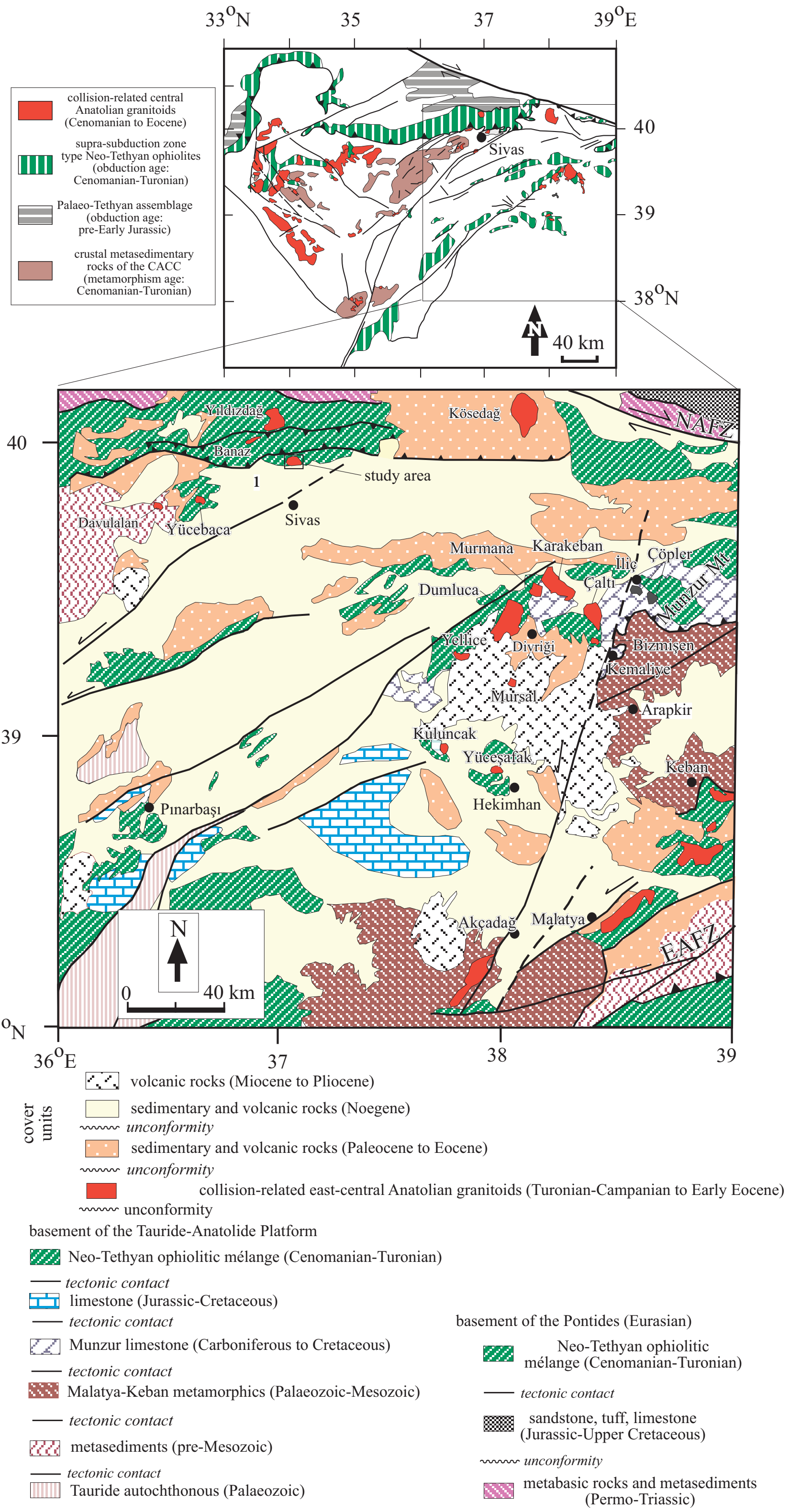

Figure 1. Location map and regional geological setting of the east-central Anatolian granitoids (modified after Boztuğ & Jonckheere 2007).

**Table 1.** The compilation of main characteristics of the east-central Anatolian granitiods, Turkey.

| Terrain | Granitoid type | Name of granitoid | Age | Wall and cover rocks | Main mineralogical-geochemical characteristics | Reference |
|---|---|---|---|---|---|---|
| East-Central Anatolia | S-type | Yücebaca | Late Cretaceous | intrusive within the medium- to high-grade metasediments unconformably covered by the Paleocene–Eocene Konaközü member and Mio–Pliocene Yuvalıçayır formation | high-K calc-alkaline, two-mica leucogranites | Alpaslan & Boztuğ (1997);<br>Boztuğ (2000) |
| | A-type | Dumluca, Murmana, Karakeban, Mursal, Yellice, Kuluncak, Karaçayır, Davulalan, | Early to Late Cretaceous | intruding the medium- to high-grade metasediments and central Anatolian ophiolite unconformably covered by the Paleocene–Eocene Tokuş formation and Mio–Pliocene terrigenous-lacustrine sediments | felsic, silica oversaturated alkaline rocks (ALKOS) bearing quartz in modal mineralogical composition | Zeck & Ünlü (1988);<br>Boztuğ *et al.* (1996, 1997, 2007a);<br>Boztuğ (1998, 2000) |
| | | Dumluca, Murmana | | | mafic, feldspathoid-bearing silica undersaturated alkaline rocks (ALKUS) | Zeck & Ünlü (1988);<br>Boztuğ *et al.* (1997, 2007a);<br>Boztuğ (1998, 2000) |
| | | Kösedağ | Eocene | a shallow-seated batholith intruding the Eocene volcano-sedimentary sequence unconformably covered by the Early Miocene lagoonal limestones | felsic, silica-oversaturated alkaline rocks (ALKOS) bearing quartz in modal mineralogical composition | Boztuğ *et al.* (1994);<br>Boztuğ (2008) |
| | I-type | Çaltı, Bizmişen | Eocene | intruding the central Anatolian ophiolite unconformably covered by the Mio–Pliocene lacustrine sediments | low to medium-K, calc-alkaline | Avcı & Boztuğ (1993);<br>Önal *et al.* (2005) |

Akdağmadeni marbles and the early Late Cretaceous (Cenomanian) ophiolitic mélange of the Tekelidağ complex (Figure 2). In addition to this normal fault, there are also some possible faults with NE–SW, N–S and NW–SE trends that can be located by the existence of crushed rocks (Figure 2).

Detailed petrographical descriptions can be found in Boztuğ *et al.* (1996) and Boztuğ (1998). However, it can briefly be summarized here. The Karaçayır pluton comprises medium- to coarse-grained syenites. The felsic components are K-feldspar (orthoclase, microcline) and plagioclase (albite) among which the microcline minerals are always associated with cataclastic zones that are considered to be formed by later cataclastic deformation. The mafic minerals are represented by hastingsitic amphibole, aegirine-augite, biotite, secondary muscovite, secondary calcite and some accessory phases such as allanite, monazite, xenotime, apatite, zircon and opaque minerals. Some minerals, recognizable only by their short prismatic pseudomorphs, are replaced by zeolite, sericite, calcite and clay. Apart from some fresh biotite which is reddish-brown in colour, other biotite and muscovite flakes exhibit evidence of deuteric processes. Deuteric biotites are green, and muscovites are clearly derived from the feldspar minerals, or, with coarse euhedral calcites, have crystallized from late stage hydrothermal magmatic fluids. These hydrothermal solutions have already interacted with marbles and other crustal metasediments of the basement rocks (Schuiling 1961). Some syenites include fluorite, distinguishable even in hand specimen. All these mineralogical-petrographical data reflect that the Karaçayır syenite has been affected by deuteric alteration processes. This is also compatible with the observation of Schuiling (1961) who found thorianite in some of these rocks. In addition to these mineralogical characteristics, the peraluminous chemistry of the Karaçayır syenite is attributed to assimilation of, and magma-wall-rock interaction with crustal metasediments of the Kırşehir block (Boztuğ *et al.* 1996). Similar magma-wall rock interaction has been ascribed to the formation of carbonatite-looking rocks in the Karaçayır pluton by Schuiling (1961).

## Analytical Techniques

All the rock samples were crushed, ground and sieved, then processed using bromoform in order to extract mafic phases (amphibole and biotite) and accessory minerals (zircon, titanite and apatite) in the laboratories of the Department of Geological Engineering, Cumhuriyet University (Sivas, Turkey). The extraction of zircon and apatite from these mineral separates was performed at the laboratories of the Mineralogisches Institute and Geologisches Institute of the TU Bergakademie Freiberg, Germany, respectively, using a magnetic separator and then extraction using diiodomethane heavy liquid.

Single zircon $^{207}$Pb-$^{206}$Pb evaporation dating (Table 2) was performed in the laboratories of the Mineralogisches Institute of the TU Bergakademie Freiberg, Germany. A zircon separate extracted from the rock sample of BAL-74 includes some 40–50 zircon grains. Individual zircons of similar physical appearance (colour, shape, morphology and transparency) were handpicked under a binocular microscope under high magnification. Grains were chosen which were euhedral, elongate prismatic, colourless, fully transparent and without any relict nucleus. Pb evaporation analysis of single zircon grains was carried out using a FINNIGAN MAT 262 mass spectrometer, according to the method of Kober (1986, 1987).

$^{40}$Ar-$^{39}$Ar age determination of purified biotite separates was performed at the New Mexico Geochronology Research Laboratory (NMGRL, USA) (Table 3). Following irradiation the mineral separates were step-heated using a Mo double vacuum resistance furnace. The biotites were analyzed using a 11-step heating schedule, however results for high temperature steps that yielded only blank level argon signals were omitted from the dataset. More details of the overall operation of the NMGRL can be found at internet site: http://geoinfo.nmt.edu/publications/ openfile /argon / home/html.

Apatite fission-track geothermochronology studies (Table 4) were conducted at the Geological Institute of the TU Bergakademie Freiberg, Germany. Analytical details can be found in Boztuğ *et al.* (2004) and Boztuğ & Jonckheere (2007).

## Emplacement Age

The Karaçayır syenite yields a $^{207}$Pb-$^{206}$Pb single-zircon evaporation age of 99.0±11.0 Ma indicating intrusion during the Cenomanian–Turonian (Middle Cretaceous) (Table 2, Figure 3). The $^{207}$Pb-$^{206}$Pb single-zircon evaporation age of the Karaçayır syenite is within the error range of the Rb-Sr whole-rock isochron ages of the bimodal A-type granites of the Divriği-Sivas region in

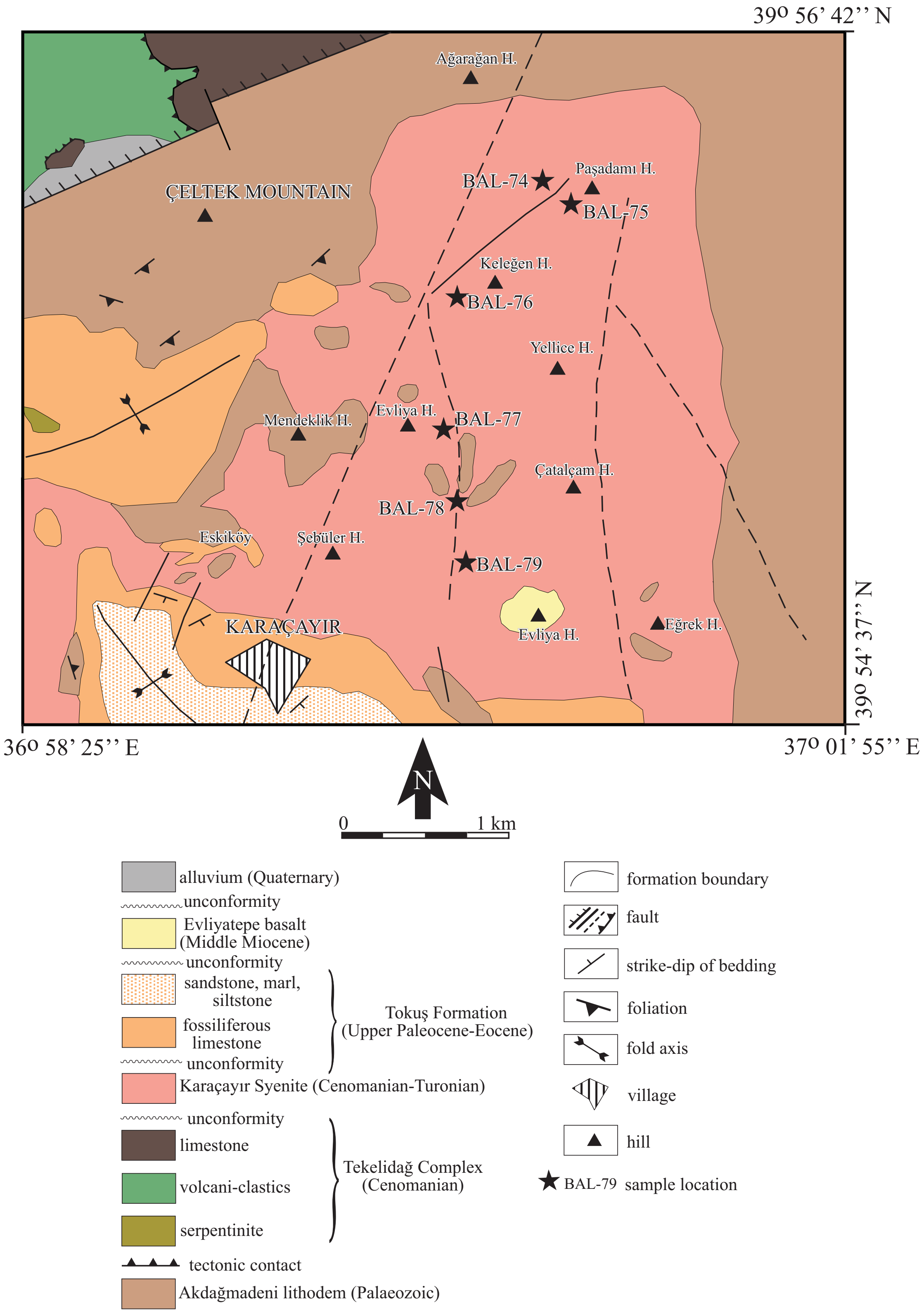

**Figure 2.** Geological map of the Karaçayır syenite (revised from Boztuğ *et al.* 1996).

Table 2. Single-zircon $^{207}$Pb / $^{206}$Pb evaporation ages.

| Sample-zircon no | Number of scans | $^{207}$Pb / $^{206}$Pb | $^{204}$Pb / $^{206}$Pb | $^{207}$Pb / $^{206}$Pb$_{corr}$ | $^{207}$Pb / $^{206}$Pb Age (Ma ± 2σ error) | Weighted mean age (Ma ± 2σ error) |
|---|---|---|---|---|---|---|
| BAL74-Z2 | 90 | 0.053043±0.0000625 | 0.000371±0.00000456 | 0.047805±0.0000637 | 89.6±8.4 | 99.0±11.0 |
| BAL74-Z5 | 89 | 0.072498±0.00122 | 0.0017±0.0000856 | 0.04794±0.000118 | 96.2±11.0 | |
| BAL74-Z6 | 88 | 0.07438±0.00065 | 0.00182±0.0000807 | 0.048088±0.000572 | 103.5±33.3 | |
| BAL74-Z1 | 88 | 0.078598±0.000267 | 0.0021±0.0000175 | 0.048159±0.0000917 | 107.0±9.7 | |
| BAL74-Z8 | 53 | 0.062455±0.00072 | 0.000973±0.0000665 | 0.048239±0.000803 | 110.9±44.5 | |
| BAL74-Z12 | 90 | 0.074932±0.0005 | 0.00183±0.0000424 | 0.048427±0.000247 | 120.1±17.2 | |

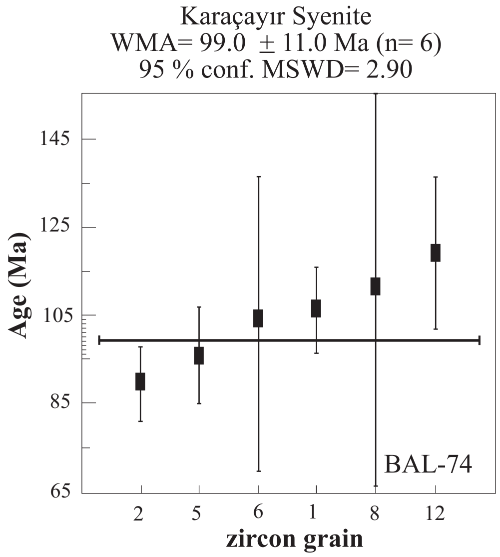

Figure 3. $^{207}$Pb-$^{206}$Pb single zircon evaporation ages of the Karaçayır syenite. WMA– weighted mean age; MSWD– mean square weighted deviate.

east-central Anatolia (Zeck & Ünlü 1988: 110±5 Ma), and the I-type Ağaçören intrusive suite in central Anatolia (Güleç 1994: 110±14 Ma). The $^{207}$Pb-$^{206}$Pb single-zircon evaporation age of the Karaçayır syenite is also close to the zircon U-Pb SHRIMP ages of the Üçkapılı two mica-granite (92–85 Ma; Whitney *et al.* 2003) in the Niğde Massif in central Anatolia.

## Cooling Age

$^{40}$Ar-$^{39}$Ar age data of two biotite separates are reported in Table 3, and the plateau age spectra are shown in Figure 4. The biotite separate extracted from sample BAL-76 of the Karaçayır syenite gives a plateau age of 65.1±0.3 Ma (MSWD= 3.59) and a total gas age (TGA) of 64.9±0.3 Ma (Table 3, Figure 4a). Another biotite separate extracted from sample BAL-78 does not yield a plateau age, but a TGA of 66.6±0.2 Ma (Table 3, Figure 4b). These two biotite separates indicate a cooling age of latest Maastrichtian at depths in the crust corresponding to ca. 300 °C (which is assigned as the closing temperature of $^{40}$Ar-$^{39}$Ar biotite geothermochronology methods, e.g., McDougall & Harrison 1999).

Such a latest Maastrichtian cooling age of the Karaçayır syenite seems to be consistent with the amphibole/biotite K-Ar cooling ages of other central and east-central Anatolian granitoids which range from 65 Ma to 80 Ma (e.g., Yalınız *et al.* 1999; Kadıoğlu *et al.* 2003; İlbeyli *et al.* 2004; Tatar & Boztuğ 2005; Boztuğ & Harlavan 2008; Boztuğ *et al.* 2007a).

## Exhumation Age and Uplift Rate

Apatite fission-track age and track-length data are given in Table 4. The rock samples, collected from the Karaçayır syenite, represent an elevation difference of ca. 400 m between the samples taken from the lowest and highest altitudes in the field (Table 4). All the rock samples yield very similar apatite fission-track ages, regardless of altitude, that range from 58.4±2.3 Ma to 61.1±2.6 Ma (Table 4). The age vs elevation plot shows a typical fast exhumation with an uplift rate of > 1 mm per year (Figure 5). This Early to Middle Paleocene rapid uplift is also supported by T-t modeling, based on track length data, which describes a rapid undercooling from the total annealing zone (TAZ; Wagner & Van den Haute 1992; Wagner 1998) through the partial annealing zone (PAZ; Wagner & Van den Haute 1992; Wagner 1998) to the total stability zone (TSZ; Wagner & Van den haute 1992; Wagner 1998) in a time span between 58 and 61 Ma (Figure 6). The mean-track-length versus standard-

**Table 3.** $^{40}$Ar–$^{39}$Ar analytical data.

| ID | Temp (°C) | $^{40}$Ar/$^{39}$Ar | $^{37}$Ar/$^{39}$Ar | $^{36}$Ar/$^{39}$Ar (x $10^{-3}$) | $^{39}$Ar$_K$ (x $10^{-15}$ mol) | K/Ca | $^{40}$Ar* (%) | $^{39}$Ar (%) | Age (Ma) | ±1σ (Ma) |
|---|---|---|---|---|---|---|---|---|---|---|
| | **BAL-76**, Biotite, 12.09 mg, J= 0.0036056±0.46%, D= 0.998±0.001, NM-194J, Lab#56179-01 | | | | | | | | | |
| xA | 650 | 19.30 | 0.2073 | 39.90 | 12.3 | 2.5 | 39.0 | 1.4 | 48.25 | 0.55 |
| B | 750 | 10.39 | 0.0277 | 0.7776 | 238.7 | 18.4 | 97.8 | 28.0 | 64.884 | 0.081 |
| C | 850 | 10.31 | 0.0054 | 0.3592 | 145.9 | 94.0 | 99.0 | 44.3 | 65.097 | 0.084 |
| D | 920 | 10.35 | 0.0301 | 0.5063 | 94.5 | 17.0 | 98.6 | 54.8 | 65.116 | 0.096 |
| E | 1000 | 10.30 | 0.0384 | 0.3261 | 206.3 | 13.3 | 99.1 | 77.9 | 65.172 | 0.080 |
| F | 1075 | 10.31 | 0.0541 | 0.2825 | 155.0 | 9.4 | 99.2 | 95.2 | 65.312 | 0.082 |
| xG | 1110 | 10.41 | 0.0819 | 0.4624 | 25.5 | 6.2 | 98.8 | 98.0 | 65.64 | 0.14 |
| xH | 1180 | 10.44 | 0.1535 | 0.3256 | 17.7 | 3.3 | 99.2 | 100.0 | 66.06 | 0.18 |
| Integrated age ± 1σ | | | n= 8 | | 895.7 | 13.5 | $K_2O$= 7.89% | | 64.90 | 0.30 |
| Plateau ± 1σ Steps B-F | | | n= 5 | MSWD= 3.59 | 840.3 | 28.5 | | 93.8 | 65.12 | 0.30 |
| | **BAL-78**, Biotite, 10.21 mg, J= 0.0036212±0.29%, D= 0.998±0.001, NM-194J, Lab#56184-01 | | | | | | | | | |
| xA | 650 | 12.89 | 0.1212 | 38.17 | 14.1 | 4.2 | 12.5 | 1.5 | 10.50 | 0.51 |
| xB | 750 | 12.17 | 0.1233 | 11.13 | 67.2 | 4.1 | 73.0 | 8.5 | 57.09 | 0.18 |
| xC | 850 | 11.12 | 0.0113 | 2.510 | 181.9 | 45.1 | 93.3 | 27.4 | 66.529 | 0.098 |
| xD | 920 | 11.31 | 0.0179 | 2.102 | 149.1 | 28.6 | 94.5 | 42.9 | 68.463 | 0.095 |
| xE | 1000 | 11.43 | 0.0342 | 1.880 | 233.3 | 14.9 | 95.2 | 67.2 | 69.667 | 0.092 |
| xF | 1075 | 10.95 | 0.0187 | 0.8999 | 174.9 | 27.3 | 97.6 | 85.4 | 68.413 | 0.088 |
| xG | 1110 | 10.81 | 0.0287 | 0.8667 | 87.5 | 17.8 | 97.7 | 94.5 | 67.605 | 0.095 |
| xH | 1180 | 10.76 | 0.1167 | 0.7122 | 47.6 | 4.4 | 98.1 | 99.5 | 67.63 | 0.11 |
| xI | 1210 | 10.89 | 0.6351 | 1.134 | 4.85 | 0.80 | 97.4 | 100.0 | 67.97 | 0.34 |
| Integrated age ± 1σ | | | n= 9 | | 960.5 | 13.2 | $K_2O$= 9.98% | | 66.63 | 0.21 |
| Plateau ± 1σ no plateau | | | | | | | | | | |

Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interfering reactions. Errors quoted for individual analyses include analytical error only, without interfering reaction or J uncertainties. Integrated age calculated by summing isotopic measurements of all steps. Integrated age error calculated by quadratic summation of the errors of all steps. The plateau age and associated error are the weighted means for the selected steps (Taylor 1982). Decay constants and isotopic abundances after Steiger & Jäger (1977). x symbol preceding sample ID denotes analyses excluded from plateau age calculations. Weight percent $K_2O$ calculated from $^{39}$Ar signal, sample weight, and instrument sensitivity. Ages calculated relative to FC-2 Fish Canyon Tuff sanidine inter-laboratory standard at 28.02 Ma (Renne *et al.* 1998). Decay constant: $\lambda_K$ (total)= 5.543 $10^{-10}$ $a^{-1}$ (Steiger & Jäger 1977). Correction factors: $(^{39}Ar/^{37}Ar)_{Ca}$= 0.00067±0.00005; $(^{36}Ar/^{37}Ar)_{Ca}$= 0.00028±0.00001; $(^{38}Ar/^{39}Ar)_K$= 0.01077; $(^{40}Ar/^{39}Ar)_K$= 0.01±0.002

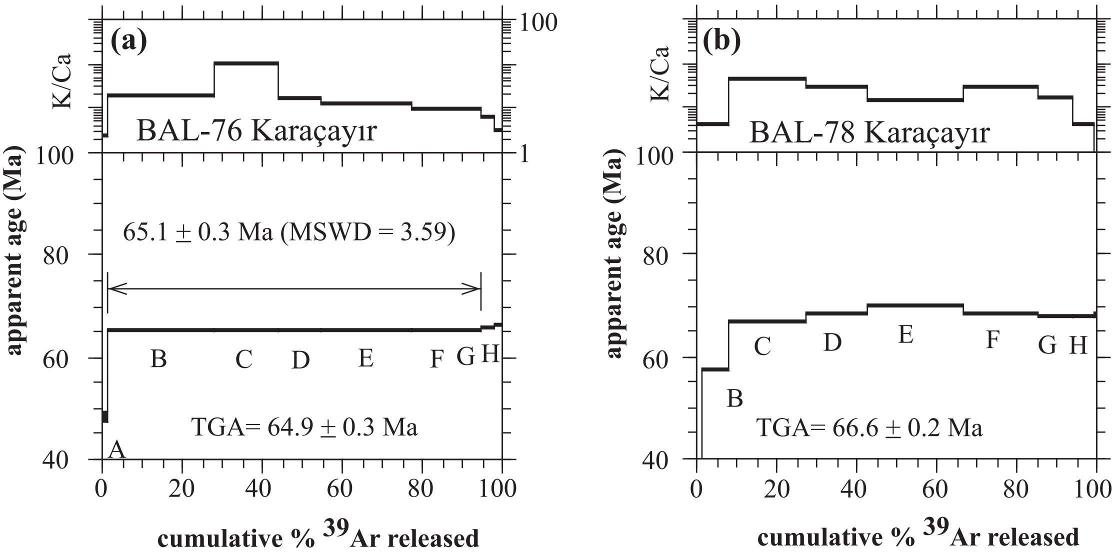

**Figure 4.** Biotite $^{40}$Ar-$^{39}$Ar cooling age spectra of the rock sample BAL 76 (a) and BAL-78 (b) from the Karaçayır syenite. MSWD– mean square weighted deviate; TGA– Total gas age.

Table 4. Apatite fission-track data.

| Sample | Elevation (asl) (m) | Irradiation step | Grains | $\rho_s \pm 1\sigma$ | $N_s$ | $\rho_i \pm 1\sigma$ | $N_i$ | P ($\chi^2$) | $\rho_d \pm 1\sigma$ | $N_d$ | $\xi$Age±1 $\sigma$ (Ma) | Numb. of length | Mean track length | Stand. dev. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BAL-74 | 1975 | FG-02 | 20 | 1.169±0.035 | 1127 | 1.273±0.036 | 1227 | 100.00 | 0.416±0.003 | 16955 | 59.5±2.8 | 120 | 13.97 | 1.03 |
| BAL-75 | 1987 | FG-02 | 20 | 3.296±0.089 | 1371 | 3.495±0.092 | 1454 | 100.00 | 0.416±0.003 | 16955 | 61.1±2.6 | 171 | 14.00 | 1.06 |
| BAL-76 | 1928 | FG-02 | 20 | 2.416±0.046 | 2802 | 2.622±0.048 | 3041 | 100.00 | 0.416±0.003 | 16955 | 59.7±2.0 | 141 | 13.96 | 1.09 |
| BAL-77 | 1780 | FG-02 | 20 | 1.856±0.046 | 1626 | 2.042±0.048 | 1789 | 100.00 | 0.416±0.003 | 16955 | 58.8±2.4 | 190 | 13.97 | 1.02 |
| BAL-78 | 1714 | FG-02 | 20 | 1.487±0.036 | 1701 | 1.651±0.038 | 1889 | 100.00 | 0.416±0.003 | 16955 | 58.4±2.3 | 208 | 13.68 | 1.06 |
| BAL-79 | 1671 | FG-02 | 20 | 2.341±0.053 | 1976 | 2.570±0.055 | 2169 | 100.00 | 0.416±0.003 | 16955 | 59.1±2.2 | 172 | 13.76 | 1.01 |

$\rho_S$= spontaneous track density ($10^6$ cm$^{-2}$), $N_S$= number of spontaneous tracks; $\rho_I$= induced track density ($10^6$ cm$^{-2}$), $N_I$= number of induced tracks in external detector; $\rho_d$= density ($10^6$ cm$^{-2}$), $N_d$= number of induced tracks in muscovite external detector irradiated against IRMM 540R; $\chi^2$ value in (%);. $t_\zeta$ (Ma): pooled fission-track age calculated with $\zeta$= 313 ± 6.1 a/cm$^2$ for IRMM 540R (Boztuğ & Jonckheere 2007); $N_C$– number of measured confined track lengths; $L_M$– mean confined track length (µm); $S_L$– standard deviation of the confined track length distribution (µm).

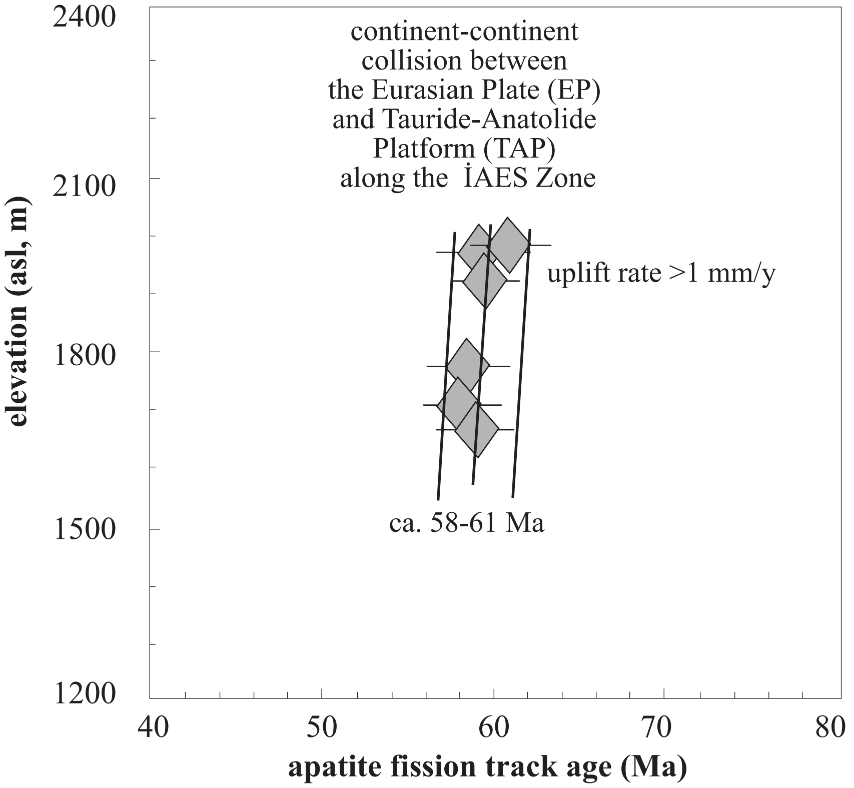

Figure 5. Age vs elevation diagram of the apatite fission-track data of the Karaçayır syenite.

deviation plot (Gleadow *et al.* 1986) shows an 'undisturbed-basement' field for all the rock samples from the Karaçayır syenite that is consistent with the exhumation history of a plutonic body (Figure 7).

## Discussion

Complementary geothermochronological data characterizing almost the whole temperature range from intrusion ($^{207}$Pb-$^{206}$Pb single zircon evaporation age)

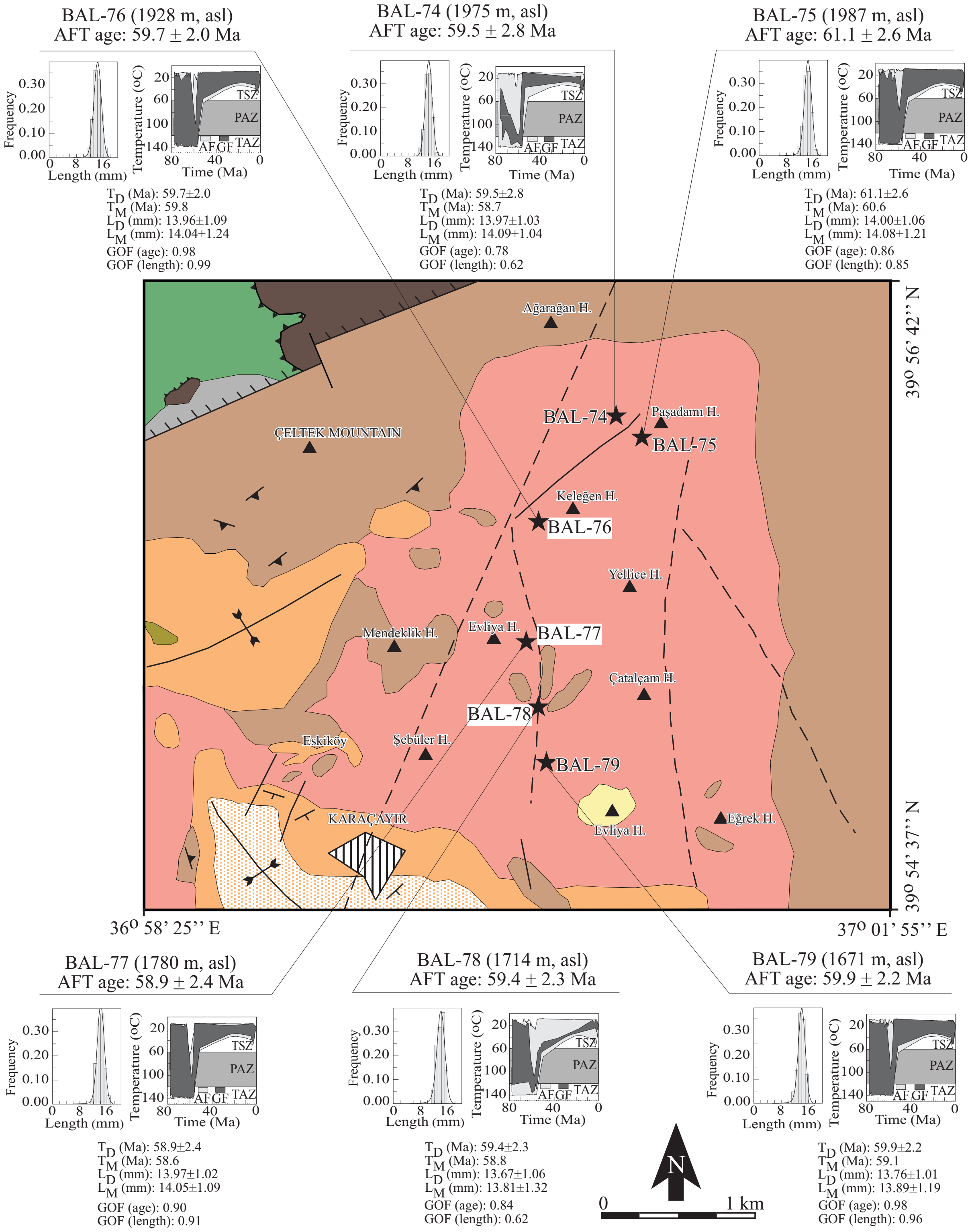

Figure 6. T-t modelling of the cooling history of the Karaçayır syenite with HeFTy 4.0 (Ketcham 2005). TD– data age, TM– modelled age, LD– measured mean track length, LM– model mean track length, GOF– goodness of fit, AF– acceptable fit, GF– good fit, TAZ– total annealing zone, PAZ– partial annealing zone, TSZ– 'total' stability zone.

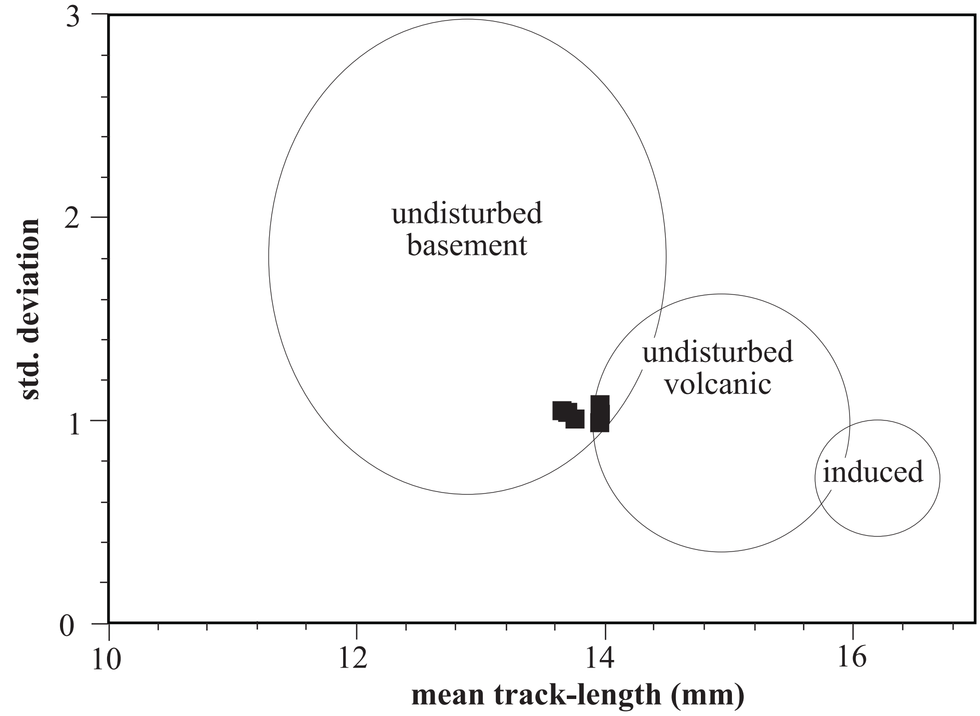

**Figure 7.** Plot of the standard deviation vs the mean of the confined track length distributions (Gleadow *et al.* 1986).

through cooling (biotite $^{40}$Ar-$^{39}$Ar cooling ages) to exhumation history (apatite fission-track ages) have been evaluated to determine the rate of cooling of the Karaçayır syenite. Subsequently, the timing of the intrusion, cooling and exhumation of the Karaçayır syenite has been interpreted with respect to the geodynamic evolution of the İzmir-Ankara-Erzincan (İAE) ocean which is the part of northern Neo-Tethyan domain.

### *Cooling Rate*

The cooling rate of the Karaçayır syenite is based on a temperature (°C) versus age (Ma) plot of the $^{207}$Pb-$^{206}$Pb single zircon evaporation age (high-T geothermochronology), biotite $^{40}$Ar-$^{39}$Ar cooling ages (medium-T geothermochronology) and apatite fission-track ages (low-T geothermochronology) (Figure 8). The temperature values in Figure 8 correspond to the closing temperature of each geothermochronology method. For example, the closing temperature of the $^{207}$Pb-$^{206}$Pb single zircon method is regarded as ~800 °C on the basis of considerations given by Lee *et al.* (1997) and Cherniak & Watson (2000). The closing temperatures of biotite $^{40}$Ar-$^{39}$Ar and apatite fission-track methods are considered to be ~300 °C (McDougall & Harrison 1999) and ~120 °C (Wagner & Van den Haute 1992; Wagner 1998), respectively.

Temperature vs age plot of the Karaçayır syenite reveals a very slow cooling rate of 14.7 °C/Ma in a time interval between 99 Ma (i.e. crystallization age) and 65 Ma (biotite cooling age) (Figure 8), however, the cooling rate between high and medium temperatures should be treated with caution given that the error in the crystallization age is subject to large errors (±11 Ma). In contrast, a relatively high cooling rate of 33.3 °C/Ma is observed in a time interval between 65 Ma and ca. 59 Ma (apatite fission-track ages) (Figure 8). It is interesting to note that biotite $^{40}$Ar-$^{39}$Ar cooling ages and apatite fission-track ages are close each other (Tables 3 & 4, Figure 8). On the assumption that apatite fission-track ages determine the tail end of exhumation of any plutonic body, the fast uplift of the Karaçayır syenite could have commenced sometime around 65 Ma, and then accelerated towards 60 Ma.

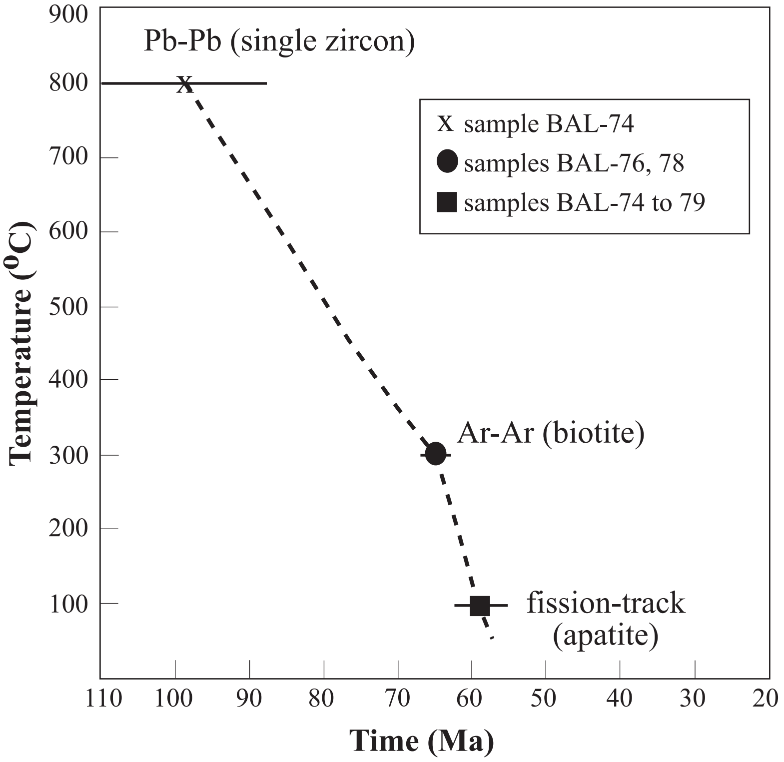

**Figure 8.** Cooling history of the Karaçayır syenite based on the age (Ma) vs closing temperature of each geothermochronology data (°C). See text for explanation of closing temperatures.

### *Geodynamic Interpretation*

The Neo-Tethyan geodynamic evolution of central Anatolia and surroundings has been intensively studied by various authors (e.g., Şengör & Yılmaz 1981; Okay & Tüysüz 1999; Yalınız *et al.* 2000; Floyd *et al.* 2000; Fayon *et al.* 2001; Whitney *et al.* 2003; Robertson & Ustaömer 2004; Boztuğ & Harlavan 2008; Boztuğ *et al.* 2007a; Boztuğ & Jonckheere 2007). Taking into account these studies, the following geodynamic model is suggested to explain the generation of the Karaçayır syenite in connection with the evolution of the İAE ocean in central and east-central Anatolia (Figure 9). The north-dipping subduction of the İAE oceanic crust (part of northern Neo-Tethys) beneath the Eurasian plate (EP) generated the well-known eastern Pontide arc magmatism (Okay & Şahintürk 1997; Boztuğ *et al.* 2004, 2006, 2007d) in the active continental margin, whereas an intra-oceanic subduction zone produced the supra-subduction zone type central Anatolian ophiolite (SSZ-type CAO) within the ocean itself before Cenomanian–Turonian time, i.e., ca 100–95 Ma (Figure 9a). The collision between the TAP and oceanic island arc, consisting of the SSZ-type CAO, may have generated intra-oceanic thrusting and formation of the sub-ophiolitic metamorphic soles (Parlak & Delaloye 1999), and then obduction of the SSZ-type CAO onto the crust, accompanying crustal metamorphism in the CACC (Whitney *et al.* 2003; Whitney & Hamilton 2004) during the Cenomanian–Turonian (Floyd *et al.* 2000; Garfunkel 2004; Robertson & Ustaömer 2004). The initiation of a regional extensional setting can be maintained after the obduction of the SSZ-type CAO onto the TAP. Such a regional extension can result from lithospheric detachment or delamination due presumably to a slab break-off mechanism (Davies & von Blanckenburg 1995; von Blanckenburg & Davies 1995) (Figure 9b). The proposed post-collisional lithospheric-delamination or slab breakoff-related genesis of the central Anatolian granitoids has already been suggested by Boztuğ (1998), Düzgören-Aydın *et al.* (2001), İlbeyli *et al.* (2004), İlbeyli

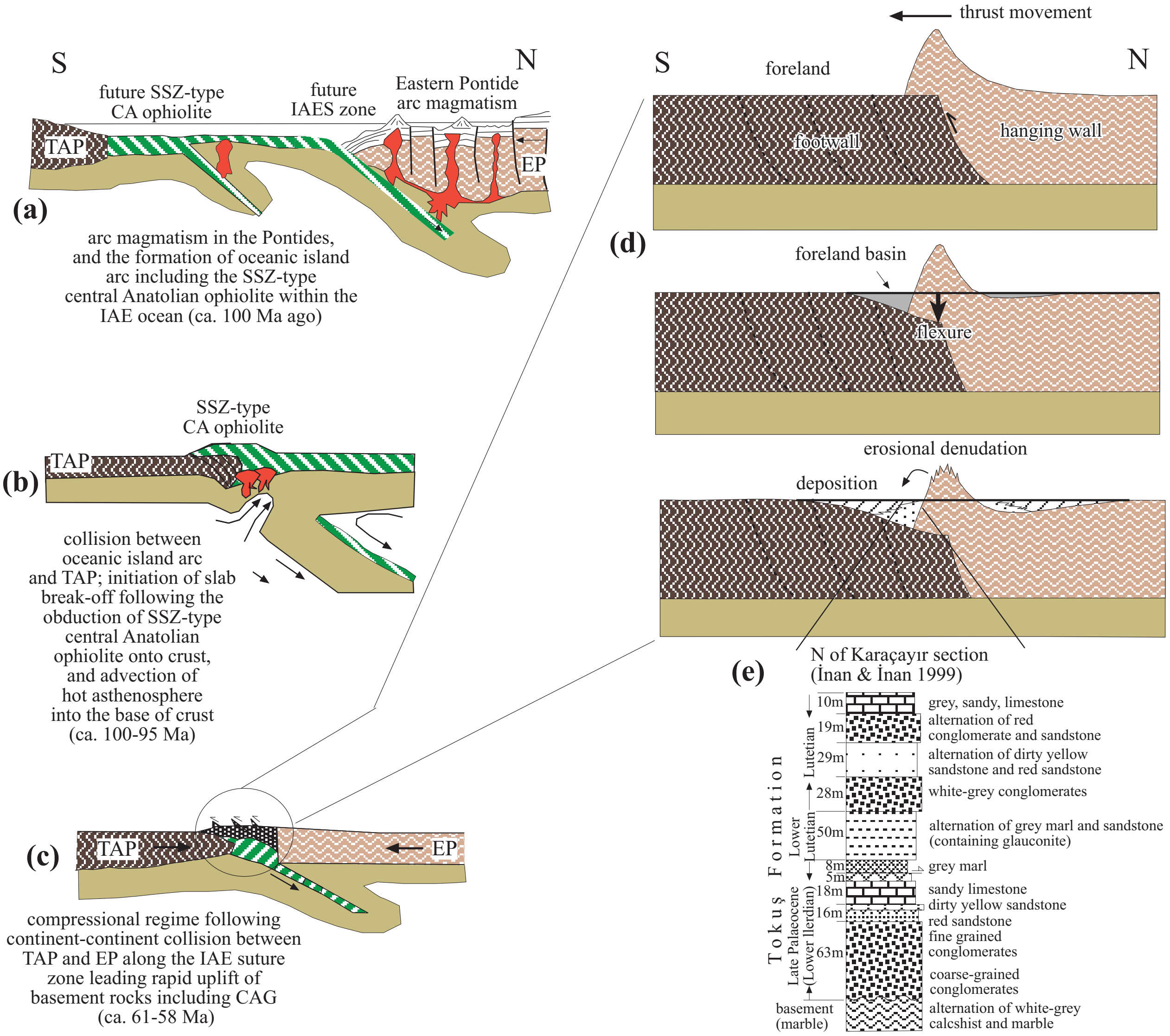

Figure 9. Suggested geodynamic model for the intrusion **(a, b)** and cooling-exhumation history **(c)** of the Karaçayır syenite (based on data given by Boztuğ & Jonckheere 2007); formation of foreland basins (Egan & Williams 2007) due to thrust faults along which basement rocks (including Karaçayır syenite) were tectonically exhumed; **(d)** and Late Paleocene–Eocene infilling (Tokuş formation); **(e)** which is issued from rapid erosional denudation triggered by fast tectonic uplift of the basement.

(2005) and Boztuğ *et al.* (2007a). The simultaneous formation of the high- to medium-grade crustal metamorphism and the emplacement of Cenomanian–Turonian granitoids could have occurred in such a regional extensional setting (Figure 9b). The continent-continent collision, following the closure of the İAE ocean, is proposed to have occurred sometime around latest Cretaceous to Early/Middle Paleocene on the basis of biotite $^{40}$Ar-$^{39}$Ar cooling and apatite fission-track ages, which made the Karaçayır syenite uplift rapidly under the compressional regime (Figure 9c). The fast uplift of the Karaçayır syenite and basement rocks, consisting of imbricated crustal metasediments and ophiolitic rocks, is also accompanied by development of peripheral foreland basins (Figure 9 d-e) in central and east-central Anatolia, Turkey (Gürer & Aldanmaz 2002; Boztuğ *et al.* 2008).

## Conclusions

The geothermochronology data, comprising the single zircon $^{207}$Pb-$^{206}$Pb (high-T), biotite $^{40}$Ar-$^{39}$Ar (medium-T) and apatite fission-track ages (low-T), combined with regional and local geology can lead us to propose the following conclusions.

1. Karaçayır syenite, a member of the east-central Anatolian granitoids, intrudes the Palaeozoic marbles and is unconformably overlain by Upper Paleocene to Eocene Tokuş formation. $^{207}$Pb-$^{206}$Pb single zircon evaporation age determination of one rock sample from the Karaçayır syenite yields an age of 99.0±11.0 Ma which is considered to be the intrusion or crystallization age.
2. Biotite $^{40}$Ar-$^{39}$Ar ages reveal a cooling age of ~65 Ma for the Karaçayır syenite. An age vs elevation plot of apatite fission-track ages and T-t modelling of track-length data determine a fast tectonic exhumation with an uplift rate of > 1 mm/a that occurred 58–61 Ma ago. Very similar biotite $^{40}$Ar-$^{39}$Ar and apatite fission-track ages are considered to be evidence of a rapid exhumation that commenced ~65 Ma ago (biotite cooling ages), and then accelerated ~58–61 Ma (apatite fission-track ages) ago.
3. There is an apparent spatial and temporal relationship between the intrusion-cooling-exhumation of the Karaçayır syenite and the evolution of the İzmir-Ankara- Erzincan (İAE) ocean belonging to the northern Neo-Tethyan oceanic domain. The intrusion of the Karaçayır syenite is proposed to have occurred in a post-collisional extensional geodynamic setting following the Cenomanian–Turonian collision between the Tauride-Anatolide platform (TAP) and oceanic island arc, comprising the supra-subduction zone type central Anatolian ophiolite (SSZ-type CAO). The commencement and then acceleration of the exhumation of the Karaçayır syenite seems to be connected with continent (TAP) – continent (Eurasian plate) collision along the İAE suture zone. The formation of peripheral foreland basins in central Anatolia is also triggered by compression due to this continent-continent collision.

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