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ORIGINAL PAPER

Titanite and zircon fission-track dating resolves successive igneous episodes in the formation of the composite Kaçkar batholith in the Turkish eastern Pontides

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Abstract The Kaçkar batholith in the Turkish eastern Pontides comprises several intrusive units with distinctive textural, mineralogical and geochemical characteristics. Their titanite and zircon fission-track ages confirm that the different lithodem units result from consecutive igneous episodes, establish their emplacement sequence and, together with geochemical data, help to relate them to their geodynamic context. The Çamlıkaya granitoid (112.4 ± 1.6 Ma) was emplaced during an immature-arc magmatic episode of early Cretaceous age. The Sırtyayla (57.1 ± 1.2 Ma) and Marselevat (52.9 ± 1.3 Ma) granitoids are late products of a late-Palaeocene mature-arc episode. The Ayder granitoid (46.4 ± 1.0 Ma) is the result of middle- to late-Eocene post-collisional magmatism related to slab break-off. The Halkalıtaş quartz diorite (43.7 ± 2.3 Ma) and the Güllübağ monzonite (38.1 ± 0.9 Ma) document a middle- to late-Eocene episode related to post-collisional extension. The data reveal the advantages of dense sampling, spanning a maximum range of elevations. Apart from the increased precision on the mean, redundant sampling allows to shift the basis for interpretation from a priori assumptions to a posteriori numerical criteria when using geochronometers with low to moderate closure temperatures, including apatite, titanite and zircon fission-tracks but also K–Ar (Ar–Ar) biotite, muscovite and K-feldspar.

Keywords Titanite · Zircon · Fission-track · Kaçkar batholith · Turkey

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Introduction

The Turkish eastern Black Sea mountains are geographically known as the Kaçkar region and geologically as the eastern Pontide arc, a product of Neo-Tethyan convergence in a region between the European Alps and the Himalayas (Şengör and Yılmaz 1981). They comprise comprehensive volcanics and plutonics derived from magmatism related to the northward subduction of the İzmir-Ankara-Erzincan (IAE) ocean, part of the northern branch of the Neo-Tethys between the Eurasian plate (EP) to the north and the Tauride-Anatolide platform (TAP) to the south (Şengör and Yılmaz 1981; Bozkurt and Mittwede 2001). Structural (Şengör and Yılmaz 1981; Yılmaz et al. 1997; Okay and Şahintürk 1997) and apatite fission-track data (Boztuğ et al. 2004) indicate that the ocean closed and the EP and TAP collided around the late Palaeocene to early Eocene. The main age constraints for the timing of arc magmatism between Samsun in the west and the Turkish-Georgian border in the east are founded on fossiliferous calcareous and pelagic limestones of middle Turonian to Maastrichtian age (Taner and Zaninetti 1978) that are interbedded with submarine volcanics (Fig. 1). There are several structural (Şengör and Yılmaz 1981; Korkmaz et al. 1995; Yılmaz et al. 1997; Okay and Şahintürk 1997) and petrological studies of the granitoid and volcanic rocks (e.g., Eğin and Hirst 1979; Manetti et al. 1983; Yılmaz and Boztuğ 1996; Aydın et al. 2003; Boztuğ et al. 2003; Yılmaz-Şahin et al. 2004; Karslı et al. 2004; Boztuğ et al. 2006; Arslan and Aslan 2006) of the eastern Pontide arc magmatism and some radiometric age determinations (Fig. 1; Table 1). Most regional studies place the beginning of arc magmatism in the Turonian/Cenomanian, while others suggest Early Cretaceous (Okay and Şahintürk 1997 and references therein).

This study presents 27 titanite and 2 zircon fission-track ages for different units along a north-south traverse through the Kaçkar batholith between Ardeşen (Rize) on the Black Sea coast and İspir (Erzurum) in the Çoruh river canyon, (Figs. 1, 2). In the light of geological, textural and geochemical data related to the petrogenesis of the Kaçkar batholith (Boztuğ et al. 2006), the fission-track ages are interpreted as emplacement ages dating subduction-, collision- and extension-related magmatic episodes of the Neo-tethyan convergence in the eastern Pontides.

Geological setting

The composite Kaçkar batholith consists of ten mapped lithological units that are assigned to five igneous episodes on the basis of their mineralogical and geochemical compositions (Boztuğ et al. 2006; Fig. 2). The Çamlıkaya granitoid represents the first episode; it is unconformably overlain by the Turonian Ardıçlı formation, consisting of red, coarse-grained sandstone, sandstone, siltstone, marl and, rarely coal. Widespread submarine arc volcanics associated with Maastrichtian epiclastic and calcareous sediments compose, from bottom to top, the Çatak, Kızılkaya and Çağlayan volcano-sedimentary formations. The Sırtyayla and Marselevat granitoids intrude the Çamlıkaya granitoid and Çağlayan Formation and represent the second igneous episode. The Çamlıkaya, Sırtyayla and Marselevat granitoids contain ovoid to ellipsoidal mafic microgranular enclaves (MME) of a few cm to 1–2 dm. The Asniyor leucogranite intrudes the Çamlıkaya and Marselevat granitoids and constitutes the third intrusive pulse. The Ayder granitoid and Sasmistal microgranite belong to the fourth igneous episode; the Ayder unit intrudes the Çağlayan Formation and the Marselevat

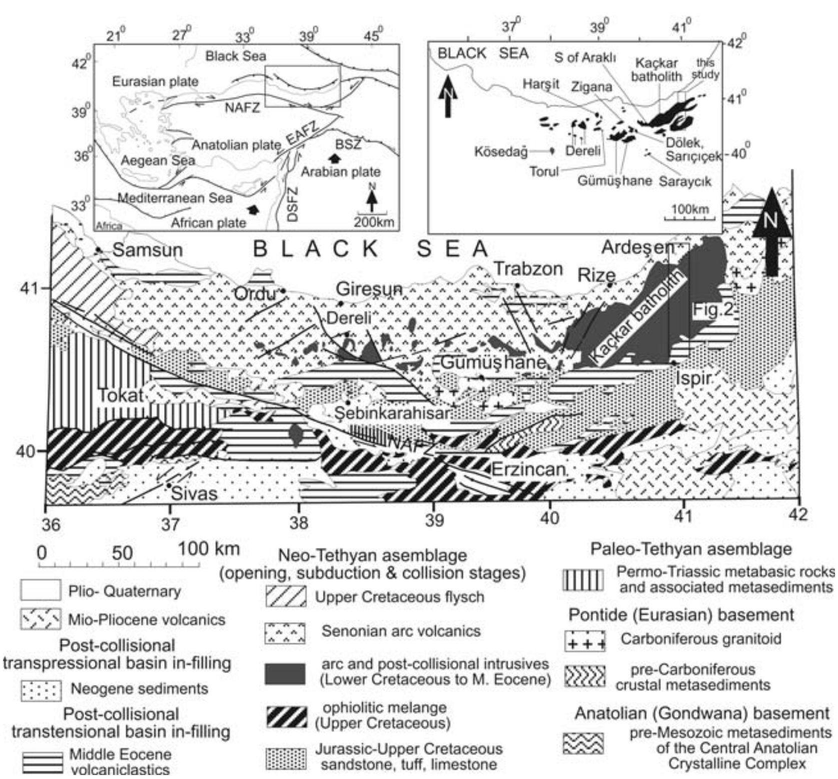

Fig. 1 Regional geological map of the Eastern Black Sea region and location of the study area. The *upper left inset* shows the main tectonic units of Turkey and surrounding area (after Bozkurt and Mittwede 2001), and the *upper right inset* represents the locations of dated rocks in the central and eastern Pontides (modified after Boztuğ et al. 2003, 2004). Abbreviations in the upper left inset; *NAFZ* north Anatolian fault zone; *EAFZ* east Anatolian fault zone; *BSZ* Bitlis suture zone; *DSFZ* Dead Sea fault zone

Table 1 Compilation of radiometric age data from the central and eastern Pontides

Unit	Method	Rock type	Age	Reference
Kösedağ	Rb-Sr (WR)	Sy	42 ± 4	Kalkancı (1974)
Dereli	K-Ar	Gd	71.4 ± 1.0–84.2 ± 3.2	Moore et al. (1980)
	FT (apatite)	gr, gd, qsy	47.8 ± 2.4–80.7 ± 3.2	Boztuğ et al. (2004)
Harşit	K-Ar	Gd, qd	65.3–115.9	Gedikoğlu (1979)
Torul	K-Ar	Gd	72.1 ± 3.6	JICA (1986)
Gümüşhane	K-Ar	Gr	162	Çoğulu (1975)
	U- (Th-Pb)	Gr	298–338	Çoğulu (1975)
	K-Ar	Gd	107	Moore et al. (1980)
	Rb-Sr (WR)	Gr	535 ± 74	JICA (1986)
	Rb-Sr (WR)	Gr	360 ± 2	Bergougnan (1987)
Dölek	K-Ar	Gd	42.9 ± 0.9–43.5 ± 0.9	Karslı et al. (2004)
	U-Pb (zircon)	Gd	44.0 ± 0.2	Arslan and Aslan (2006)
Sarıçiçek	K-Ar	Gd	42.7 ± 2.2–44.1 ± 1.1	Karslı et al. (2004)
Saraycık	Ar-Ar	Gd	52.2 ± 0.4–52.8 ± 0.7	Topuz et al. (2005)
Zigana	K-Ar	Gd	43.1 ± 2.2	JICA (1986)
Kaçkar	U-(Th-Pb)	mzd	29–56	Delaloye et al. (1972)
	K-Ar	gd	127–132	Giles (1974)
	K-Ar	gd, to	39.9 ± 0.3–211.3 ± 2.8	Taner (1977)
	U-(Th-Pb)	gr	142 ± 12–237 ± 5	Yılmaz (1977)
	K-Ar	gd	79.3 ± 1.0	Moore et al. (1980)
S of Araklı	K-Ar	gd, gr	41.2 ± 0.89–75.7 ± 1.55	Yılmaz-Şahin et al. (2004)
	K-Ar	gd	138.5 ± 2.2	Boztuğ and Harlavan (2006)

WR whole-rock; *Sy* syenite; *gd* granodiorite; *gr* granite; *qsy* quartz syenite; *qd* quartz diorite; *mzd* monzodiorite; *to* tonalite. See the *upper-right* inset in Fig. 1 for location of unit

and Sırtyayla granitoids. The Güllübağ monzonite and the Halkalıtaş quartz diorite are exposed as porphyritic small stocks and N-S, NE-SW, NW-SE and E-W oriented subvolcanic veins and represent an extension-related fifth intrusive pulse. Small mafic and basic porphyritic gabbroic stocks and veins with similar orientations (Ardeşen gabbro and İsina diabase) are also considered part of this igneous pulse. All the intrusives are unconformably overlain by Miocene molasse deposits consisting of alternating conglomerate, sandstone, siltstone, claystone and marl. The Guvant andesitic tuff, exposed along a major fault zone, can be correlated with the İkizdere-Rize volcanics in the eastern Pontides, which are of Plio-Pleistocene age based on fission-track dating of fracture-filling obsidians (Yeğingil et al. 2002). The major structural elements are NE-SW striking faults and NW-SE trending fold axes with secondary faults striking E-W. Miocene uplift, in which the Pontides functioned as a monolithic horst has been documented by Yılmaz et al. (1997) and by apatite fission-track data (Boztuğ et al. in review).

Petrographical, geochemical and geochronological data

The petrographical and geochemical characteristics of the composite Kaçkar batholith are described in Boztuğ et al. (2006). The textural features, mineralogical and geochemical compositions and available geochronological data of the lithological units for which titanite and zircon fission-track ages are reported here are summarized below.

The Çamlıkaya granitoid

The Çamlıkaya unit consists of granodiorites, minor granites, tonalites and quartz-diorites, made up of medium-grained equigranular quartz, plagioclase, orthoclase, hornblende, biotite, clinopyroxene and accessory apatite, titanite, zircon, epidote and opaque minerals. Mingling and mixing of coeval felsic and mafic magmas is evidenced by different MME (Didier and Barbarin 1991; Barbarin and Didier 1992), anti-rapakivi textures, blade-biotite, poikilitic/oikocrystic quartz and K-feldspar, biotite/hornblende zones in K-feldspar phenocrysts, small lath-plagioclase and boxy cellular plagioclase growth (Hibbard 1991). Major and trace-element data show a subalkaline-calcalkaline composition and early-arc characteristics (Boztuğ et al. 2006). Giles (1974) obtained biotite K-Ar cooling ages ranging from 127 to 132 Ma on granodiorite samples from the Çoruh river canyon around İspir, Erzurum; and Boztuğ and Harlavan (2006) obtained a hornblende K-Ar age of 138.5 ± 2.2 Ma for the Çamlıkaya granodiorite outcropping in the south of the Araklı-Trabzon region (Fig. 1; Table 1).

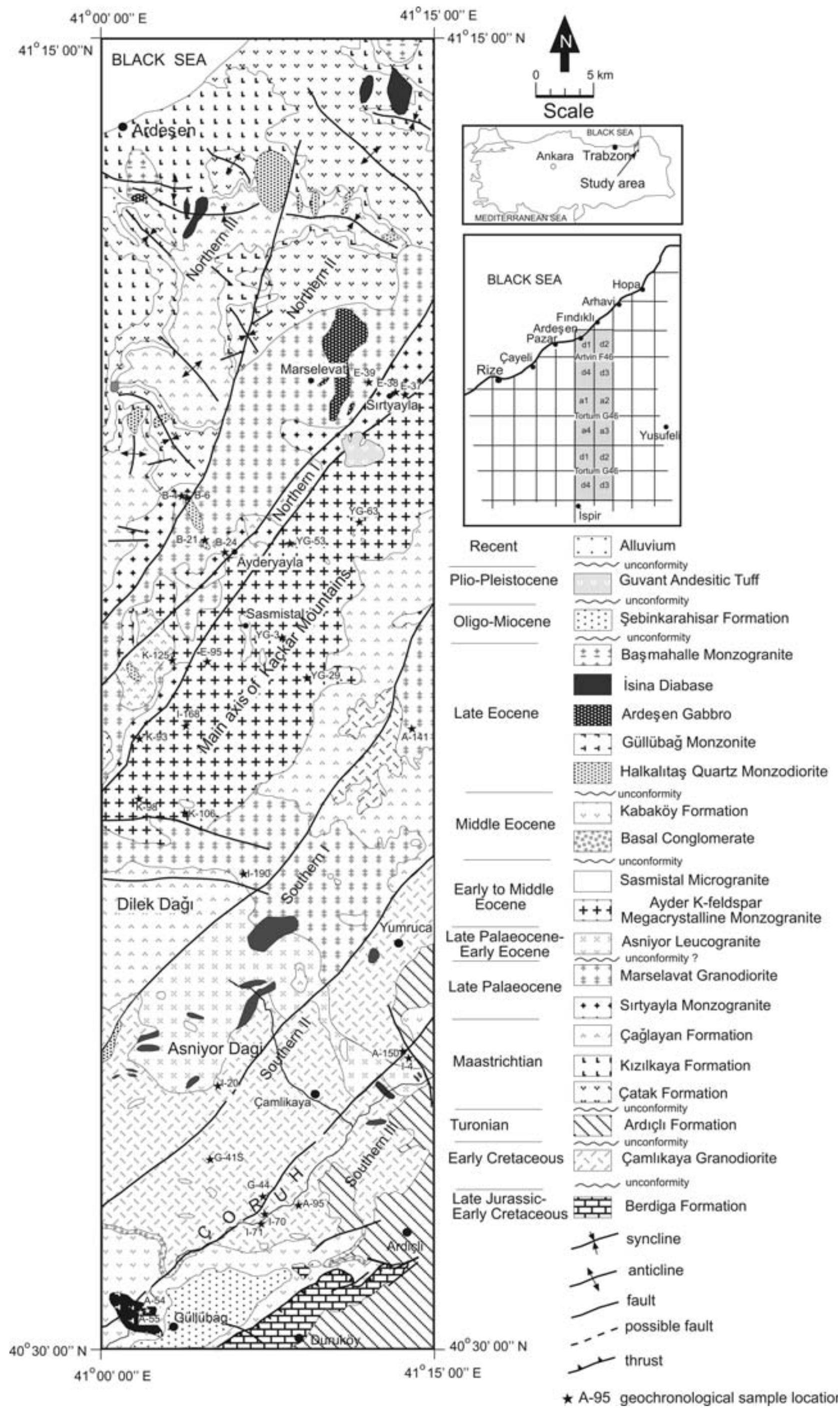

Fig. 2 Geological map of the composite Kaçkar batholith along a north-south transect between Ardeşen (Rize) and İspir (Erzurum), in the Turkish eastern Black Sea region (after Boztuğ et al. 2006). See Fig. 1 for location

The Sırtyayla and Marselevat granitoids

The Sırtyayla granitoid comprises coarse-grained granodiorites and monzogranites with large feldspars and, as a rule, more modal biotite than hornblende. It also contains MME and exhibits textures indicative of mingling and mixing of coeval felsic and mafic magmas. The major and trace element geochemical data indicate a subalkaline-calcalkaline mature-arc composition (Boztuğ et al. 2006). The Marselevat granitoid consists of granodiorites and minor granites, tonalites and quartz-diorites. Its texture and mineralogical composition are similar to those of the Çamlıkaya granitoid. Major and trace-element data indicate a mature arc and subalkaline-calcalkaline composition (Boztuğ et al. 2006). The published radiometric ages (Delaloye et al. 1972; Çoğulu 1975) do not distinguish between the Sırtyayla and Marselevat granitoids because they were considered as a single unit at the time. Delaloye et al. (1972) measured U/Th-Pb ages of 29 and 49 Ma, and Çoğulu (1975) obtained K-Ar ages of 30, 32 and 47 Ma (Fig. 1; Table 1). Delaloye et al. (1972), and Çoğulu (1975) dated samples from the south of Çamlıhemşin in the Rize area, which could be from either the Sırtyayla or Marselevat granitoids.

The Ayder granitoid

The Ayder granitoid has a porphyritic texture with K-feldspar megacrysts up to 4–5 cm long and 1–2 cm wide in a porphyritic quartz, K-feldspar, plagioclase, biotite and hornblende groundmass, indicative of shallow emplacement. MME sometimes include K-feldspar megacrysts. The textures described by Hibbard (1991) indicate thermal, mechanical and chemical interaction between coeval mafic and felsic magmas, resulting in mingling and mixing. Major and trace-element analyses show a post-collisional high-K cal-calkaline composition (Boztuğ et al. 2006). There are no published radiometric ages for the Ayder granitoid. However, a middle to late Eocene age is proposed for various intrusive rock units in different parts of the composite Kaçkar batholith (Fig. 1; Table 1). JICA (1986) give a K-Ar cooling age of 43 Ma for samples taken from the Zigana granitoid in the Gümüşhane region. Arslan and Aslan (2006) determined a U-Pb zircon age of 44.4 ± 0.3 Ma, and Karslı et al. (2004) reported biotite K/Ar ages of 42.9 ± 0.9 and 43.5 ± 0.9 Ma for the Dölek granitoid in the Gümüşhane region (Fig. 1; Table 1). Karslı et al. (2004) have determined biotite K/Ar ages of 42.7 ± 2.2 and 44.1 ± 1.1 Ma for the Sarıçiçek granitoid. Topuz et al. (2005) found an Ar/Ar age of 52 Ma for the Saraycık-Bayburt granitoid in the eastern Pontides. Yılmaz şahin et al. (2004) found middle Eocene amphibole K-Ar ages for a porphyritic granodiorite from the southern Araklı-Trabzon region in the eastern Pontides (Fig. 1; Table 1).

Halkalıtaş quartz diorite and Güllübağ monzonite

The Halkalıtaş quartz diorite and Güllübağ monzonite are exposed as small shallow stocks and dykes with a typical porphyritic texture, characterized by lath-shaped plagioclase in a groundmass of plagioclase, orthoclase, amphibole, augite and biotite in Güllübağ and by large plagioclase, hornblende and augite phenocrysts in a phaneritic groundmass of feldspar and mafic minerals in the Halkalıtaş quartz diorite. Major and trace-element data indicate a post-collisional extension-related high-K alkaline (Güllübağ) and medium-K subalkaline to slightly tholeiitic character (Halkalıtaş; Boztuğ et al. 2006). Delaloye et al. (1972) obtained U/(Th-Pb) ages of 33 and 56 Ma for monzodiorite samples south of Çamlıhemşin, in the Rize area (Fig. 1; Table 1).

Preparation of the fission-track samples

A total of 48 samples were collected for apatite, titanite and zircon fission-track dating from all the lithological units, except the aplitic veins of the Sasmital microgranite. The sample localities lie along a north-south traverse, perpendicular to the trend of the major structures, and their elevations range from 100 to 3200 m. The fission-track analyses were carried out at the Max-Planck Institute for Nuclear Physics in Heidelberg. The minerals were separated with standard electromagnetic and heavy-liquid techniques. Suitable apatite, titanite and zircon fractions were obtained from 39, 27 and 2 samples respectively; the apatite results are discussed in a companion paper (Boztuğ et al. in review). The 27 datable titanite separates are from the Çamlıkaya, Sırtyayla, Marselevat, Ayder and Halkalıtaş units. The samples from the Ardeşen gabbro, İsina diabase and Asniyor leucogranite contained neither apatite, titanite nor zircon. The Güllübağ monzonite unit yielded only zircon. Thus, five of the nine sampled lithological units have given titanites, one

Table 2 Calculation of the ζ-calibration factor for titanite

Sample	Reference age	Grains	ρ_s	N_s	ρ_I	N_i	P (χ^2)	ρ_d	N_d	*zeta*
MTD1-004	98.8 ± 0.6	20	6.0109	2263	4.6642	1756	86.00	1.0701	5036	144.4 ± 5.0
FCT1-004	27.8 ± 0.2	22	0.8959	643	2.7060	1942	99.54	1.0701	5036	155.9 ± 7.4
FCT2–005	27.8 ± 0.2	22	0.9302	591	2.6239	1667	100.00	1.1942	5620	129.9 ± 6.3
MTD2–005	98.8 ± 0.6	20	5.8989	2776	4.7662	2243	27.79	1.1942	5620	134.7 ± 4.2
MTD3–006	98.8 ± 0.6	15	4.9752	1756	4.6975	1658	76.27	1.2698	5976	148.1 ± 5.4

The reference ages for the Mount Dromedary and Fish Canyon Tuff have been taken after Williams et al. (1982), and Green (1985); ρ_s = density (10^6 cm^{-2}), N_s = number of spontaneous tracks in titanite minerals; ρ_i = density (10^6 cm^{-2}), N_i = number of induced tracks in external detector; ρ_d = density (10^6 cm^{-2}), N_d = number of induced tracks in dosimeter of standard glass CN1; zeta and χ^2 values are represented in (a cm^2) and (%), respectively (analyst: D. Boztuğ) zircon and three have given neither titanite nor zircon grains.

The titanites and zircons were mounted in epoxy and Teflon respectively, ground and polished. The fossil tracks in the titanites were etched for 20 min in $1HF:2HNO_3:3HCl:6H_2O$ at 20°C; the fossil tracks in the zircons were etched for 20 h in a eutectic mixture of NaOH and KOH at 210°C. The etched mounts were covered with 50 μm uranium-free muscovite external detectors and irradiated in Jülich, together with Fish Canyon Tuff, Mount Dromedary and Tardree Rhyolite age standards, prepared in the same manner as the samples, and Corning CN1 uranium glass. After the irradiation, the induced tracks in the external detectors were etched in 40% HF for 30 min. The track counts were carried out in transmitted light at a nominal magnification of 400 on a Leitz Aristomet microscope. The external detectors were repositioned track side down on the mounts, in the same position as during irradiation. The fossil tracks were counted by focusing on the mineral surface through the muscovite external detector and the induced tracks by focusing on the underside of the external detector (Jonckheere et al. 2003). The tracks were counted in scratched surfaces of titanite (Gleadow 1978) and prismatic faces of zircon. At least 20 grains were dated when possible; this was the case for all samples except TRB-21 (16 grains), TRI-20 (15 grains), and TRA-150 (13 grains). Seven standard mounts (2 Fish Canyon Tuff, 3 Mount Dromedary and 2 Tardree Rhyolite) irradiated in the course of five earlier irradiations in Jülich were counted for the determination of the ζ-calibration factors (Hurford and Green 1983) for titanite and zircon (Tables 2, 3). The unweighted rather than the weighted mean ζ-values were used because the error on the unweighted means better reflects the scatter of the data.

Results and discussion

The fission-track data for the dated samples are given in Table 4. Two main age groups can be distinguished in a radial plot (Galbraith 1990; Fig. 3): a Cretaceous group (120–88 Ma) with samples from the Çamlıkaya unit and a Palaeocene to Eocene group (57–37 Ma) made up of samples from the Güllübağ, Halkalıtaş, Ayder, Marselevat and Sırtyayla units. There appears to be additional structure in the data as well as outliers. The ages are plotted against elevation in Fig. 4. Except for one outlier (TRI-20; 88.4 ± 3.8 Ma), the ages of the Çamlıkaya samples range from 98.4 ± 5.3 to 122.0 ± 4.9 Ma. The location of TRI-20 is close to the contact with the Asniyor leucogranite (Fig. 2) so that its age could have been reset by the later intrusion of this unit. The Asniyor unit could not be dated but the 88.4 ± 3.8 Ma age of TRI-20 puts an upper limit on its emplacement that is consistent with the Palaeocene age inferred from field relationships (Boztuğ et al. 2006). The interpretation of the remaining Çamlıkaya ages hinges on whether the correlation with sample elevation is real. The regression line has a slope of 0.01 km/Ma and a correlation coefficient of 0.72, which might but need not be significant; the problem is compounded by the fact that these samples span a limited range of elevations (850–1300 m; Fig. 4).

Interpretation of the early Cretaceous ages

The doubtful age *versus* elevation trend poses an interpretation problem that has general implications for such data. If the apparent correlation is *not real* then the samples define an unweighted mean of 112.4 ± 3.2 Ma with a standard deviation of 8.6 Ma, i.e. somewhat greater than the calculated errors. This is a common observation in fission-track dating and not proof of systematic variation but due to the fact that the internal errors do not include extra-Poisson variation related to an inhomogeneous uranium distribution, variable etching characteristics and imperfect track identification criteria. In this case, the mean age of 112.4 ± 3.2 Ma dates the cooling *in situ* of the Çamlıkaya unit. This age is somewhat lower than the biotite K-Ar ages of Giles (1974) (127 and 132 Ma) for two samples to the west of the studied area and the hornblende K-Ar age of 138.5 ± 2.2 Ma (Boztuğ and

Table 3 Calculation of the ζ-calibration factor for zircon

Sample	Reference age	Grains	ρ_s	N_s	ρ_i	N_i	P (χ^2)	ρ_d	N_d	Zeta
TR1–007	58.7 ± 1.1	7	3.5895	549	5.8191	890	11.28	1.2834	6040	149.0 ± 8.3
TR2–008	58.7 ± 1.1	10	3.1980	602	5.9445	1119	34.13	1.4953	7037	146.6 ± 7.6

The reference age for the Tardee Rhyolite has been taken after Hurford and Green (1983), and Green (1985); ρ_s = density (10^6 cm^{-2}), N_s = number of spontaneous tracks in zircon minerals; ρ_i = density (10^6 cm^{-2}), N_i = number of induced tracks in external detector; ρ_d = density (10^6 cm^{-2}), N_d = number of induced tracks in dosimeter of standard glass CN1; zeta and χ^2 values are represented in (a cm^2) and (%), respectively (analyst: D. Boztuğ)

Table 4 Titanite and zircon fission-track data and ages for samples from the Kaçkar batholith; ages with asterisk have been the partially or totally reset

Sample	Unit	Irradiation step	Elevation (m)	Mineral	Grains	ρ_s	N_s	ρ_i	N_i	$P(\chi^2)$	ρ_d	N_d	ξAge ± 1σ (Ma)
TRB–6	Halkalıtaş	TR–005	750	Titanite	20	2.8353	1401	5.4965	2716	99.63	1.1942	5620	43.7 ± 2.3
TRYG–3	Ayder	TR–005	1650	Titanite	20	2.4972	1704	4.3026	2936	72.86	1.1942	5620	49.2 ± 2.6
TRK–93	Ayder	TR–004	2050	Titanite	20	2.7181	1471	4.8208	2609	100.00	1.0701	5036	42.8 ± 1.5
TRE–95	Ayder	TR–005	2100	Titanite	20	2.5601	1506	4.9010	2883	99.99	1.1942	5620	44.1 ± 1.5
TRYG–53	Ayder	TR–006	2120	Titanite	20	2.4912	1612	4.7722	3088	88.35	1.2698	5976	47.2 ± 2.5
TRI–168	Ayder	TR–006	2300	Titanite	20	2.7256	1443	4.9941	2644	93.35	1.2698	5976	49.4 ± 2.6
TRK–98	Ayder	TR–004	2400	Titanite	20	3.5160	1696	5.3072	2560	93.99	1.0701	5036	50.5 ± 2.7
TRYG–63	Ayder	TR–005	2400	Titanite	20	2.5726	1816	4.7755	3371	85.37	1.1942	5620	45.7 ± 2.3
TRYG–29	Ayder	TR–004	2550	Titanite	20	2.9647	1744	2.8466	2851	97.89	1.0701	5036	46.6 ± 2.4
TRK–106	Ayder	TR–004	3200	Titanite	20	2.5301	1280	4.5424	2298	100.00	1.0701	5036	42.3 ± 1.5
TRB–4	Marselevat	TR–005	750	Titanite	20	3.2041	1244	4.8268	1874	71.84	1.1942	5620	56.2 ± 3.1
TRB–21	Marselevat	TR–006	980	Titanite	16	2.4389	1033	4.9960	2116	95.71	1.2698	5976	44.2 ± 2.5*
TRB–24	Marselevat	TR–005	1100	Titanite	20	3.1615	1525	5.7902	2793	55.80	1.1942	5620	46.3 ± 2.4*
TRE–39	Marselevat	TR–005	2060	Titanite	20	3.1859	2174	4.8463	3307	99.98	1.1942	5620	55.4 ± 1.6
TRK–125	Marselevat	TR–004	2250	Titanite	20	2.9367	1382	4.5537	2143	99.83	1.0701	5036	49.1 ± 2.7
TRA–141	Marselevat	TR–006	2350	Titanite	20	2.5456	1767	4.4084	3060	73.99	1.2698	5976	52.2 ± 2.7
TRI–190	Marselevat	TR–006	2900	Titanite	20	3.3185	1835	5.8160	3216	81.51	1.2698	5976	51.6 ± 2.6
TRE–38	Sırtyayla	TR–006	2400	Titanite	20	3.3980	1799	5.4247	2872	99.99	1.2698	5976	56.6 ± 2.9
TRE–37	Sırtyayla	TR–005	2900	Titanite	20	3.3878	1674	4.9805	2461	99.74	1.1942	5620	57.6 ± 3.0
TRI–20	Çamlıkaya	TR–006	1850	Titanite	15	2.7360	1191	2.7704	1206	99.91	1.2698	5976	88.4 ± 3.8*
TRA–150	Çamlıkaya	TR–005	850	Titanite	13	3.6778	1125	2.7918	854	97.66	1.1942	5620	111.1 ± 6.9
TRI–4	Çamlıkaya	TR–004	950	Titanite	20	4.5738	1994	3.5331	1538	95.54	1.0701	5036	98.4 ± 5.3
TRA–95	Çamlıkaya	TR–004	1010	Titanite	20	3.5614	1676	2.5754	1212	97.65	1.0701	5036	104.9 ± 5.9
TRI–71	Çamlıkaya	TR–004	1070	Titanite	20	3.7422	1629	2.4994	1088	88.44	1.0701	5036	113.5 ± 6.5
TRI–70	Çamlıkaya	TR–006	1080	Titanite	20	4.4161	2338	3.4301	1816	99.96	1.2698	5976	115.1 ± 3.8
TRG–44	Çamlıkaya	TR–006	1150	Titanite	22	3.6832	1560	2.6987	1143	100.00	1.2698	5976	122.0 ± 4.9
TRG–41S	Çamlıkaya	TR–005	1300	Titanite	20	4.0819	2065	2.7891	1411	99.42	1.1942	5620	121.6 ± 4.4
TRA–54	Güllübağ	TR–008	1100	Zircon	20	2.2673	1067	6.4598	3040	100.00	1.4953	7037	38.6 ± 1.5
TRA–55	Güllübağ	TR–008	1100	Zircon	20	2.3456	1435	6.8636	4199	100.00	1.4953	7037	37.5 ± 1.2

ρ_s = density (10^6 cm^{-2}), N_s = number of spontaneous tracks; ρ_i = density (10^6 cm^{-2}), N_i = number of induced tracks in external detector; ρ_d = density (10^6 cm^{-2}), N_d = number of induced tracks in dosimeter; χ^2 value in (%). Ages are pooled ages and calculated using zeta = 142.6 ± 5.66 and 147.8 ± 7.95 for dosimeter glass CN1 for titanite and zircon, respectively. (analyst: D. Boztuğ)

Harlavan 2006) for a sample at a greater distance. The difference in K-Ar ages indicates cooling to 300°C at ca. 20°C/Ma. The cooling rate below 300°C is an order of magnitude lower, ca. 2°C/Ma (30°C in 15 Ma). The rapid decrease of the cooling rate suggests emplacement at a level at which the equilibrium isotherm is not much lower than the titanite fission-track closure temperature or just under 9 km for a geothermal gradient of 30°C/km. The sample textures support the notion that the Çamlıkaya samples solidified at such a depth.

If the correlation *is real*, then it indicates slow cooling due to relaxation of the isotherms (~0.3°C/Ma), exhumation (~0.01 km/Ma) or a combination of both. In the first case, the interpretation as post-emplacement cooling ages and the estimate of the emplacement depth is as before. In the second case, the exhumation rate can be regarded as a background rate that need not be associated with tectonic uplift but could reflect a period of comparative quiescence. The oldest fission-track age (122.0 ± 4.9 Ma) then sets a lower limit for the emplacement age and the 270°C equilibrium isotherm provides a lower limit for the emplacement depth: >9 km for a geothermal gradient of 30°C/km. The interesting question then arises whether the biotite ages of Giles (1974) are consistent with the uplift rate calculated from the fission-track data alone (~0.01 km/Ma). This is so if the K-Ar samples were collected ~1000 m below the level of the fission-track samples. In this case, the combined data document a 35 Ma period of slow exhumation, following emplacement prior to 127–132 Ma at >10 km depth. The early Cretaceous history of the Çamlıkaya unit could be better constrained from additional fission-track data, elevation data for the dated K-Ar biotite samples or from barometric constraints on the emplacement depth.

Differentiating the Palaeocene-Eocene ages

The cluster of late Palaeocene to late Eocene ages in Fig. 4 possesses insufficient structure to distinguish

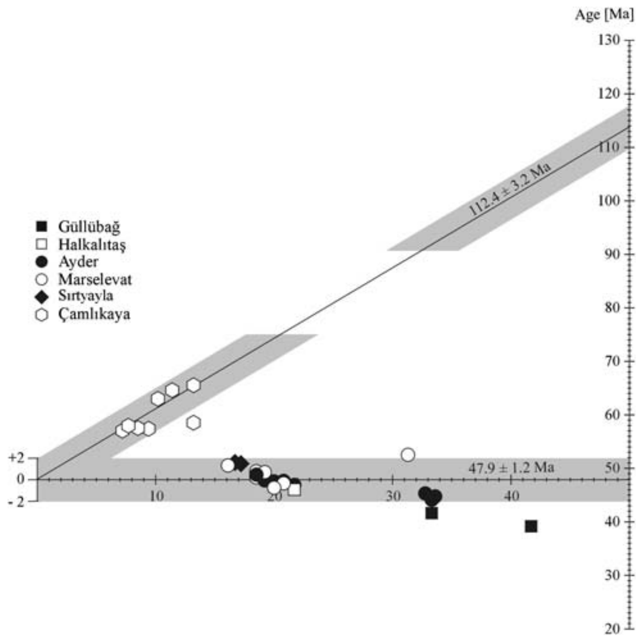

Fig. 3 Radial plot (Galbraith 1990) of the titanite and zircon fission-track ages revealing two principal age clusters; horizontal axis: x = 1/s; vertical axis: y = $(t_F - t_R)/s$; s = one-sigma absolute error on the sample age (t_F) = sample age; t_R = reference age (47.9 Ma)

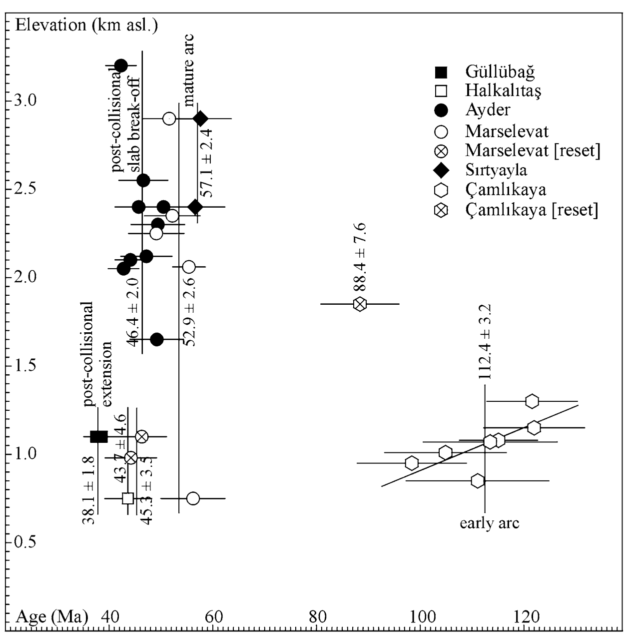

Fig. 4 Titanite and zircon fission-track ages plotted *versus* elevation and coded according to their respective lithodem units; error bars are 2σ. The numbers next to the vertical lines represent the weighted mean age and 2σ error of each unit

sub-clusters on the basis of the age data *alone* (Fig. 5) but a significant correlation emerges when the field, textural and geochemical criteria are used to allocate the samples to their different lithological units. A basic one-factor analysis of variance (Spiegel 1975) returns a probability of <1% that the correlation of the fission-track ages with the different lithological units is fortuitous. This is a clear indication that their ages must be interpreted as emplacement ages. This conclusion is corroborated by the lack of variation of the fission-track ages with elevation (Fig. 4). These facts indicate rapid cooling at a level well below that of the 270°C equilibrium isotherm, consistent with the textures of the Sırtyayla and Marselevat units and the vein or small-stock occurrences of the Halkalıtaş and Güllübağ units. The difference between the titanite and zircon closure temperatures (titanite: 250 ± 50°C: Gleadow and Brooks 1979; 240 ± 40°C: Harrison et al. 1979; 275 ± 25°C: Fitzgerald and Gleadow 1988; 275 ± 25°C: Kohn et al. 1993; 265–310°C: Coyle and Wagner 1998; ~285°C: Jacobs and Thomas 2002; zircon: 175–250°C: Harrison and McDougall 1979; Hurford 1986; 210 ± 40°C: Wagner and Van den Haute 1992; 210–310°C: Tagami et al. 1996, 1998; 180–240°C: Brandon et al. 1998) is of no consequence in this case.

The Sırtyayla granitoid, with a distinctive coarse-grained texture and more biotite than hornblende in its mineralogical composition has an unweighted mean age of 57.1 ± 1.2 Ma (2 samples; Table 4; Fig. 4). The Marselevat unit has an unweighted mean age of

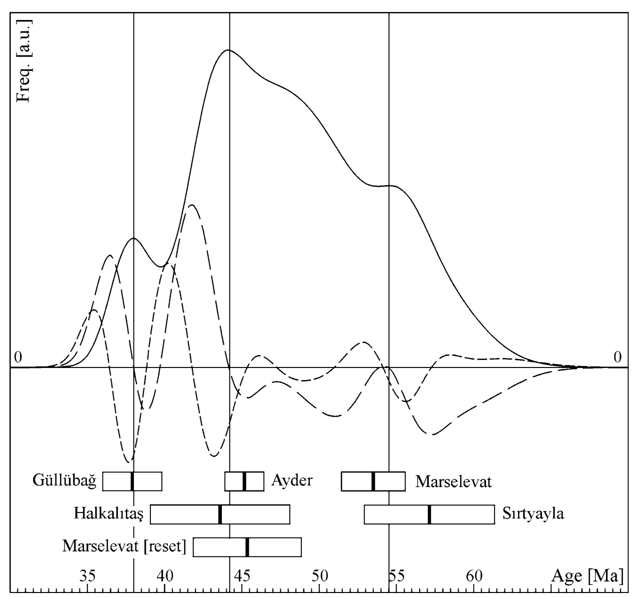

Fig. 5 Age spectrum (*solid line*) of the Palaeocene-Eocene age cluster and its first (*long-dash*) and second (*short-dash*) derivatives, illustrating the problem of distinguishing age components without considering all relevant information. The horizontal bars are the weighted mean ages and 2σ-errors of the sub-clusters distinguished after taking the mineralogical-petrological and geochemical characteristics of the samples into consideration

50.7 ± 1.7 Ma (7 samples). However, samples TRB-21 (44.2 ± 2.5 Ma) and TRB-24 (46.3 ± 2.4 Ma) have ages well below the mean and their locations are close to the contacts with the Ayder (46.4 ± 1.0 Ma; 9 samples) and Halkalıtaş (43.7 ± 2.3 Ma; 1 sample) units, emplaced within the Marselevat unit (Fig. 2). The ages of TRB-21 and TRB-24 are therefore considered to have been completely reset due to the intrusion of these later units. The recalculated unweighted mean age of the Marselevat granitoid, excluding TRB-21 and TRB-24, is 52.9 ± 1.3 Ma (5 samples; Fig. 4). With TRB-21 and TRB-24 excluded, the probability that the correlation of the individual sample ages with the lithological units is coincidental decreases to < 0.1% (Spiegel 1975).

The Ayder unit (46.4 ± 1.0 Ma; nine samples) is a shallow porphyritic intrusion. The Güllübağ monzonite is a shallow small porphyritic stock. Its unweighted mean zircon fission-track age (38.1 ± 0.9 Ma; two samples) is therefore also interpreted as an emplacement age. This late Eocene age is consistent with the fact that the Güllübağ unit intrudes the middle-Eocene volcano-sedimentary Kabataş Formation (Boztuğ et al. 2006; Fig. 2). Middle to late Eocene alkaline plutonism is widespread in the Turkish eastern Pontides. It is represented, among others, by the Kösedağ syenitic batholith with a whole-rock Rb-Sr isochron age of 42 ± 4 Ma to 37 ± 2.6 Ma (Kalkancı 1974); the Dölek granitoid with biotite K/Ar ages ranging from 42.9 ± 0.9 to 43.5 ± 0.9 Ma (Karslı et al. 2004), and a zircon U/Pb TIMS age of 44 ± 0.2 Ma (Arslan and Aslan 2006); the Sarıçiçek granitoid with K/Ar ages between 42.7 ± 2.2 and 44.1 ± 1.1 Ma (Karslı et al. 2004) and the Zigana granitoid with a K/Ar age of 43.1 ± 2.2 Ma (JICA, 1986; Fig. 1; Table 1). These values are statistically indistinguishable from the zircon fission-track ages of Güllübağ.

Regional geodynamic significance

Bingöl (1989) considered the Kaçkar batholith in the eastern Turkish Pontides as a monolithic granitic intrusion of late Cretaceous to early Tertiary age. It is represented as an undifferentiated granitoid on the geological map, with indications of a Carboniferous age in the region of Çamlıkaya and an upper Cretaceous age to the east and west (geological map of Turkey; Trabzon sheet 1:500.000; Akdeniz and Güven 2002). Boztuğ et al. (2006) reported field, mineralogical-petrographical and geochemical data indicating that this large batholith is composed of various rocks, including granite, granodiorite, tonalite and diorite. The present fission-track data confirm that the lithological units mapped by Boztuğ et al. (2006) correspond to separate intrusions emplaced at different crustal levels in two major episodes: early Cretaceous and Palaeocene-Eocene. The early Cretaceous age is consistent with published data proposing a Jurassic and even earlier onset of arc magmatism in the eastern Pontides (Adamia et al. 1977; Kazmin et al. 1986). Zankl (1962) and Okay (1993) also reported early Cretaceous basaltic rocks in the eastern Pontides. The early Cretaceous Çamlıkaya granitoid can be seen as part of pre-Turonian/Cenomanian arc magmatism and a western extension of the Caucasian region (Adamia et al. 1977; Kazmin et al. 1986). In view of its petrological and geochemical characteristics, it is proposed that the Çamlıkaya unit is derived from arc magmatism induced by the northward subduction of the İzmir-Ankara ocean beneath the Eurasian plate.

The absence of late Cretaceous ages is remarkable since late Cretaceous volcanic rocks are common in the eastern Pontides and all the units along a ~100 km N–S transect through the composite Kaçkar batholith that could be distinguished in the field have been sampled for this investigation. The reason is perhaps that not all these units could be dated and that our transect provides no data on along-strike age variations within the eastern Pontides.

The Sırtyayla (57.1 ± 1.2 Ma) and Marselevat (52.9 ± 1.3 Ma) units possess an equigranular texture reflecting solidification at mid-crustal level (>6–7 km). In view of their petrological and geochemical characteristics (Boztuğ et al. 2006), these units are derived from successive igneous episodes related to the latest mature stages of arc plutonism. The titanite fission-track ages of the Ayder granitoid (46.4 ± 1.0 Ma) and Halkalıtaş quartz diorite (43.7 ± 4.6 Ma) and the zircon fission-track age of the Güllübağ monzonite (38.1 ± 0.9 Ma) date their emplacement. These units consist of porphyritic rocks crystallized at shallow depths. The middle Eocene age of the Ayder granitoid is consistent with field evidence that it intrudes the Sırtyayla and Marselevat units. The middle-Eocene age of the Halkalıtaş quartz diorite is based on one sample and indistinguishable from the mean age of the Ayder unit. Halkalıtaş is nevertheless considered as a separate intrusion on the basis of its petrological and geochemical characteristics (Boztuğ et al. 2006). The titanite fission-track age of Halkalıtaş and the zircon fission-track age of Güllübağ just overlap within their 2σ errors. In view of their shallow emplacement, small volumes and consequent rapid cooling and considering their different petrological and geochemical characteristics, the difference is considered significant and a late Eocene age is proposed for the Güllübağ monzonite. The Ayder, Halkalıtaş and Güllübağ units are thought to be derived from successive post-collisional igneous episodes. Lithospheric attenuation following slab break-off or lithospheric delamination during the late to middle Eocene, perhaps triggered by regional extension, produced the magmas of the Halkalıtaş quartz diorite and the Güllübağ monzonite during the middle to late Eocene. The Ayder unit is similar to the high-K calc-alkaline K-feldspar-megacryst granitoids of central Anatolia (Boztuğ 1998, 2000; Düzgören-Aydın et al. 2001; İlbeyli et al. 2004) and a typical product of magma genesis triggered by post-collisional slab break-off or lithospheric delamination.

Thus the different units of the composite Kaçkar batholith in the Eastern Pontides are testimonies to different stages of plate-boundary magmatism associated with the closure of the Neo-Tethyan ocean and the Alpine-Himalayan orogeny: from subduction through collision to post-collisional extension (Şengör and Yılmaz 1981; Boztuğ et al. 2003, 2006).

Conclusions

The present fission-track data confirm that the lithological units of the composite Kaçkar batholith correspond to successive intrusions emplaced at different crustal levels in two major episodes: early Cretaceous and late Palaeocene to early Eocene; a detailed analysis allows to distinguish several pulses within the second episode. The Çamlıkaya unit (112.4 ± 3.2) is derived from the early stages of arc magmatism and emplaced at not much less than 9 km. The Sırtyayla (57.1 ± 1.2 Ma) and Marselevat (52.9 ± 1.3 Ma) units represent the latest stages of a mature arc plutonism. The Ayder granitoid (46.4 ± 1.0 Ma), Halkalıtaş quartz diorite (43.7 ± 4.6 Ma) and Güllübağ monzonite (38.1 ± 0.9 Ma) are part of a post-collisional igneous episode induced by slab break-off or lithospheric delamination.

These results confirm that titanite and zircon fission-track dating is useful for determining the emplacement ages of moderate to shallow intrusives. Thus, as for the composite Kaçkar batholith, titanite and zircon fission-track dating has the potential of contributing towards establishing the timing of different magmatic stages of the Alpine-Himalayan Neo-Tethyan convergence, not only in the Turkish Eastern Pontides but in other regions as well.

These results also reveal the advantage of high sampling densities, spanning a maximum range of elevations, which might at first appear redundant in the case of intrusives. However, the age versus elevation plot provides a qualitative a posteriori criterion for distinguishing cooling ages from uplift and exhumation ages. In addition, statistical techniques allow to calculate numerical probabilities that specific groups of fission-track ages are correlated with different intrusive units, shifting the basis for interpretation from a priori assumptions to a posteriori numerical criteria. This is most forcefully demonstrated by the biotite K-Ar ages discussed in this work. Isolated geochronological data referring to moderate closure temperatures, i.e. apatite, titanite and zircon fission-track ages but also K-Ar (Ar-Ar) biotite, muscovite and K-feldspar ages, with no information on the elevation of the dated samples, do not offer the possibilities of a posteriori analysis exploited in this work and can thus only serve to put a numerical value on an a priori assumption as to their geological significance.

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