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First results of fission-track thermochronology in the Albanides

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Abstract: Albania, situated at the boundary between the Dinaric and the Hellenic branchs of the Dinaro-Hellenic fold belt, has experienced a multiphase geodynamic evolution. The internal zones show a Mid-Jurassic episode of deformation characterized by ophiolite obduction, followed by development of a fold-and-thrust belt in the external zones during the Cenozoic. More recently, Albania has experienced a tensional regime. We present apatite and zircon fission-track (AFT and ZFT) measurements for 22 samples, and seven measurements of track-length distributions to elucidate the thermal evolution. AFT ages vary from 10.8 ± 0.7 Ma to 50.5 ± 5.7 Ma. The oldest ages (Eocene) occur in the western Albanides, corresponding to Eocene emplacement of the internal zones over the external ones. Neogene ages in the eastern Albanides suggest rapid exhumation, which we relate to an extensional regime. The ZFT ages show that the internal Albanides did not reach temperatures >200 °C during the Cenozoic.

Albania occupies a critical position within the Dinaro-Hellenic Alpine fold belt, at the boundary between the Dinarides and Hellenides (Fig. 1). The Dinaro-Hellenic orogen is characterized by three fundamental components: a western (external) fold-and-thrust belt, a central belt characterized by ophiolitic nappes, and an eastern (internal) complex (Aubouin *et al.* 1970; Meço & Aliaj 2000; Robertson & Shallo 2000).

Some key points of the geodynamic evolution of the Albanides remain controversial, partly because of limited well-constrained geochronological data, mainly concerning Mid-Jurassic ophiolite obduction, which was dated using the $^{40}Ar/^{39}Ar$ method on the amphibolitic metamorphic sole of the ophiolitic nappe (Dimo 1997; Dimo-Lahitte *et al.* 2001). Apatite and zircon fission-track (AFT, ZFT) thermochronology is an invaluable tool to decipher the low-temperature history of orogenic belts (Gallagher *et al.* 1998). Here, we report 18 AFT ages and four ZFT ages, together with seven measurements of track-length and track-width distributions to help determine the low-temperature history of the Albanides.

Geological setting of Albania

Present-day structure of Albania

Geological and gravimetric data, combined with velocity determination for P and S waves, indicate a thickening of the Albanian crust (Fig. 2a and b), from a normal thickness of about 30 km in western Albania, to 45–50 km in the eastern part, near the Macedonian and Greek borders (Frasheri *et al.* 1996; Papazachos *et al.* 2002; Cavazza *et al.* 2004). Seismological data (Aliaj 1991; Muço 1994; Frasheri *et al.* 1996; Louvari *et al.* 2001) characterize a gently east-dipping slab with compressional mechanisms for up to 50 km located beneath the Albania–Macedonia border (Fig. 2c). Eastern Albanian is characterized by extensional mechanisms down to 15 km (Fig. 2c). Tomographic imagery (Wortel & Spakman 1992, 2000; Cavazza *et al.* 2004) shows a cold lithospheric slab dipping gently eastward below the Dinaro-Hellenic belt (Fig. 2c); this represents the subducting Apulian lithosphere. Modern stress field data in the Dinaric belt (Mariucci & Miller 2003; Cavazza *et al.* 2004), indicate a more or less NE–SW-oriented compressional stress field in the external zones and a tensional one in the internal areas. Global motion vectors (DeMets *et al.* 1990), as well as more recent kinematic models (Altamimi *et al.* 2002; Sella *et al.* 2002), are compatible with the existence of a Dinaric compressive boundary. Published global positioning system (GPS) data for the Dinaric and northern Hellenic areas are sparse (Khale *et al.* 2000; McClusky *et al.* 2000; Anzidei *et al.* 2001; Bertran 2003; Hollenstein *et al.* 2003), but show, in a North European fixed frame, a NE-oriented displacement of the

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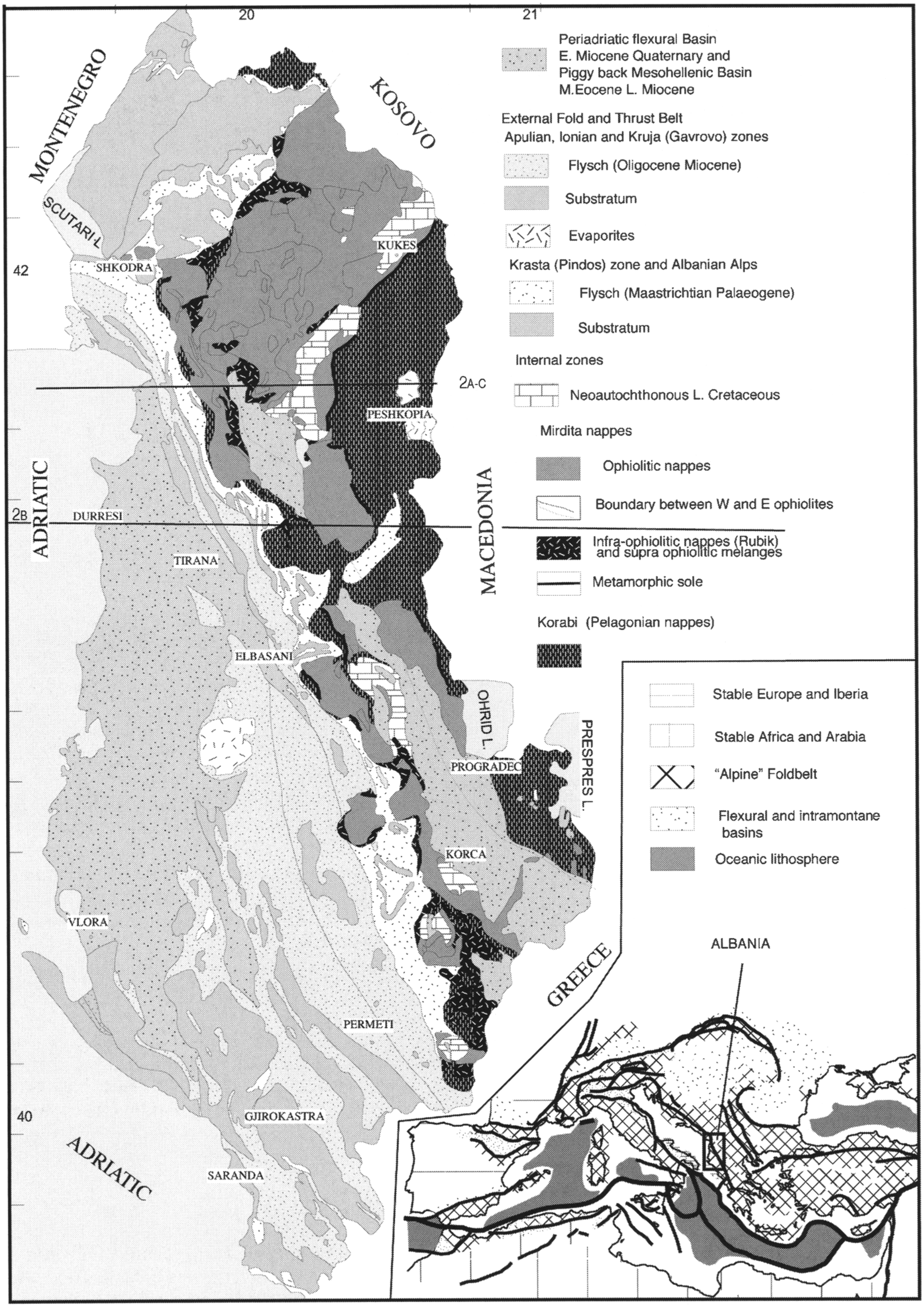

Fig. 1. Setting of the Albanides in the Mediterranean and simplified geological map of Albania. After ISPGJ–IGJN (1982, 1985, 2003); the cross-sections 2A-C and 2B are shown in Figure 2.

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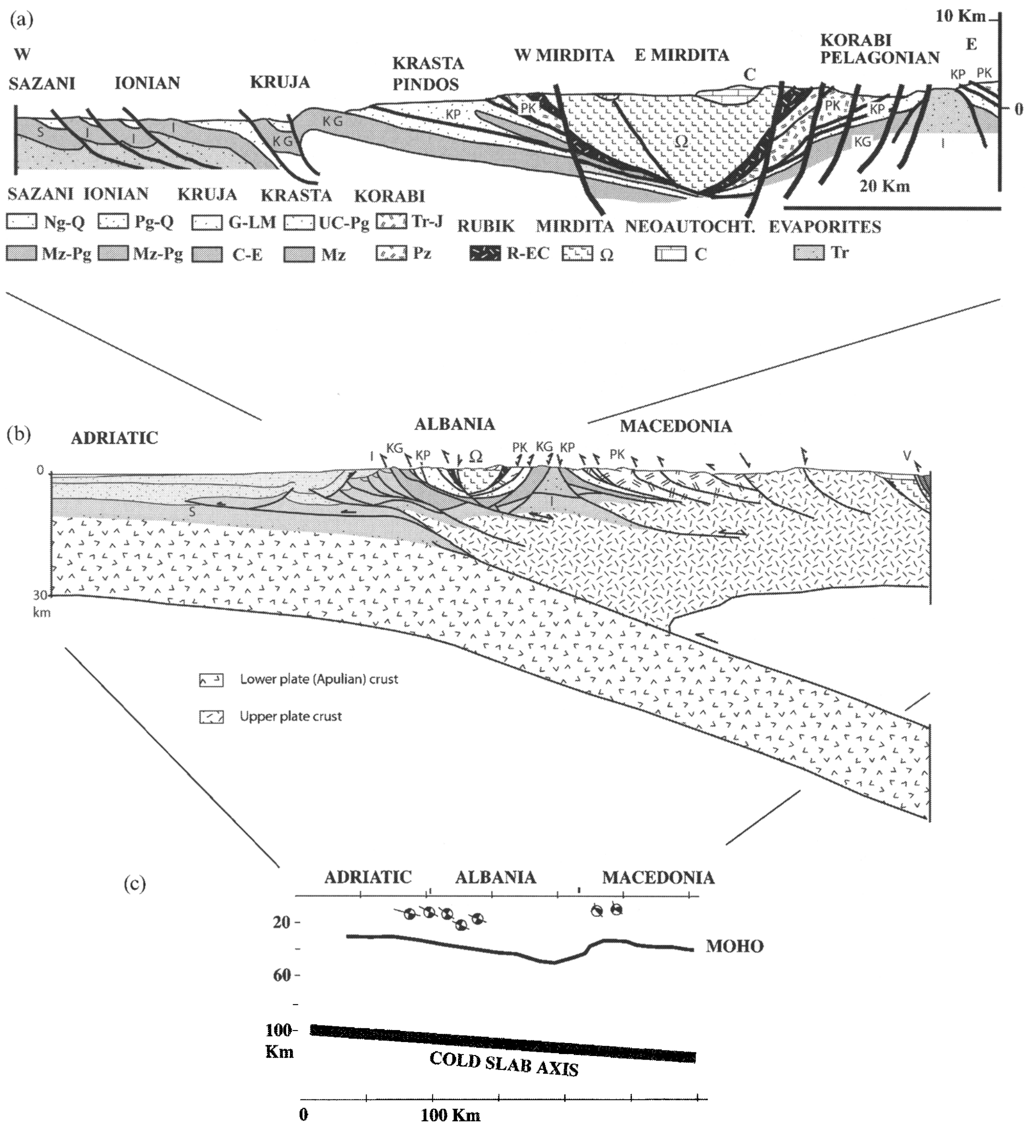

Fig. 2. (**a**) General cross-section of the Albanides (modified after Collaku *et al.* 1990). (**b**) Geodynamic section of the Helleno-Dinaric belt at the latitude of central Albania (modified after Transmed 2004; Carazza *et al.* 2004). I, Ionian; KG, Kruja–Gavrovo; KP, Krasta–Pindos; PK, Korabi–Pelagonian; S, Sazani–Preapulian; V, Vardar; Ω, Mirdita. (**c**) The subducting Apulian lithosphere from tomographic imagery and seismicity (data from Muço 1994; Frasheri *et al.* 1996; Wortel & Spakman, 2000; Louvari *et al.* 2001; Papazachos *et al.* 2002).

external Dinaric units (Fig. 1) at a velocity of 5 mm a^{-1}, whereas the internal Dinaric units move in the same direction but slightly faster, in good agreement with the existing tensional regime of both areas. For example, at the Ohrid station (Macedonia), the displacement is eastward, at a velocity of 2 mm a^{-1} (Fig. 1). Therefore, all the present-day data suggest the existence of a compressional regime in western Albania, related to the subduction of the Apulian lithosphere and a tensional regime in eastern Albania.

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Geological subdivision of Albania

The external fold-and-thrust belt. This covers (Figs 1 and 2) about half of the surface of Albania. The thrust belt is located west of a line joining Skodra to Elbasani and to Permeti, near the Greek border, and reappears in eastern Albania as indicated by the Peskopi tectonic window (Collaku *et al.* 1990). The westernmost unit (Sazani) is characterized by a neritic platform succession (of Late Triassic to Oligocene age) and a foreland complex (of Early Miocene to Pliocene age; mainly redeposited carbonate facies), deformed into large ramp anticlines with westward displacement (Frasheri *et al.* 1996); this unit is correlated with the Apulian carbonate platform (Meço & Aliaj 2000; Robertson & Shallo 2000; Kilias *et al.* 2001; Cavazza *et al.* 2004). The Ionian zone constitutes a thin-skinned fold-and-thust belt, overthrusting the Apulian unit aided by an evaporitic basal décollement (ISPGJ–IGJN 1982, 1985, 2003; Frasheri *et al.* 1996; Kilias *et al.* 2001; Cavazza *et al.* 2004). The stratigraphical section consists of an evaporitic Permo-Triassic sole, an Upper Triassic–Middle Liassic carbonate platform, a pelagic basinal sequence (of Dogger–Late Eocene age), and an Oligocene–Miocene foreland complex. This unit is also mainly redeposited carbonate facies, showing westward progradation with progressive unconformities; thrusting occurred during the Messinian. According to Collaku *et al.* (1990), the evaporitic diapirs of the Peskopia tectonic window represent the eastern prolongation of the Ionian Zone, which reappears some 60 km east of the Kruja thrust. The Ionian Zone is overthrust by the Kruja unit, corresponding to the Greek Gavrovo and Dalmatian zones (Meço & Aliaj 2000; Robertson & Shallo 2000). This unit is characterized by Mid–Upper Cretaceous platform carbonates, Upper Cretaceous–Palaeocene pelagic facies, and a thick (up to 5 km) Upper Eocene–Miocene turbiditic sequence. Thrust sheets of a similar turbiditic sequence are observed in the Peshkopi tectonic window (Collaku *et al.* 1990; ISPGJ–IGJN 2003). The Kruja Zone is itself overthrust by the Pindos nappe (Krasta Zone) represented by Cretaceous turbiditic sandstones and mudstones, followed by Upper Cretaceous pelagic facies (scaglia), and overlain by Maastrichtian–Eocene turbidites (Pindos flysch) (Meço & Aliaj 2000; Robertson & Shallo 2000). In northern Albania, the Maastrichtian–Eocene flysch sequence overlies a thin pelagic radiolarite–siliceous–carbonate sequence of Mid-Triassic–Late Cretaceous age (Cukali Zone, Meço & Aliaj 2000).

The central belt. This shows a very complex structural arrangement (Figs 1 and 2). North of the SW–NE Shkodra–Peć line, the Albanian Alps represent the southern continuation of the Dinaric nappe system (Meço & Aliaj 2000); the lowermost nappe (Malesia e Madhe; High Karst) shows a Permian–Middle Triassic terrigenous formation (Verrucano), a thick Middle Triassic–Cretaceous platform carbonate sequence, and Paleocene–Lower Eocene flysch. The second unit (Valbona; pre-Karst) is similar up to the Upper Jurassic sequence, followed by a mixed turbiditic pelagic Kimmeridgian–Cretaceous sequence and Maastrichtian flysch. The third unit (Vermoshi; Bosnian) shows a strongly folded Tithonian–Valanginian flysch sequence. South of the Shkodra–Peć line, the Mirdita Zone is characterized by a huge ophiolitic nappe (Mirdita ophiolite), up to 13 km thick in the Tropoja massif (Llangora & Bushati 1990), which represents the largest European ophiolitic complex. Between the ophiolitic sequence and the Krasta (Pindos) Zone there exists a strongly deformed tectonic complex, variously interpreted (and named as) the peripheral complex by Robertson & Shallo (2000); or the Hajmeli, Querreti-Miliska and Gjallica unit of Kodra *et al.* (1993) and Meço & Aliaj (2000). This tectonic complex may be subdivided into three main units. The lowermost one is characterized by a thick sequence of Triassic platform carbonates (Hajmeli in western Mirdita and Gjallica in eastern Mirdita following Kodra *et al.* 1993). In our opinion these units belong to the Pelagonian Korabi Zone. The Triassic platform is overthrust by a Permo-Triassic pelagic and volcanic complex, termed the Rubik complex, which is well dated in various places by microfauna (Kodra *et al.* 1993; Meço & Aliaj 2000). This unit appears not only on both sides of the ophiolitic nappes (Rubik and Mirake on the western side; Gjegjan on the eastern one), but also in several tectonic windows below the ophiolitic pile (Fushe Arresi, Blinishti–Reps). Copper mineralization is associated with Triassic alkali lavas (Gjegjan, Rubik). The unit is strongly tectonized, forming numerous thin thrust sheets. The Rubik complex is itself overthust by a thin metamorphic unit, which constitutes the amphibolitic metamorphic sole of the ophiolite nappe, dated as Mid-Jurassic in age using the $^{40}Ar/^{39}Ar$ method (Dimo 1997; Dimo-Lahitte *et al.* 2001). The Mirdita ophiolitic complex is itself subdivided into two belts, the western (WOM) and the eastern (EOM) belts (Shallo *et al.* 1987; Beccaluva *et al.* 1994; Tashko 1996), with mainly tectonic relationships. However, Bébien *et al.* (1998) reported a possible continuity between the two belts. The WOM is characterized

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by a lherzolitic mantle sequence, followed by a thin gabbroic troctolitic sequence and pillow lavas of normal mid-ocean ridge basalt (N-MORB) type (Beccaluva *et al.* 1994; Tashko 1996; Robertson & Shallo 2000, and references therein). Accociated pelagic sediments have yielded a Bathonian age (Marcucci *et al.* 1994). The EOM is thicker and is characterized by a harzburgitic mantle sequence, well-developed gabbronoritic plutonic sequence, a dyke complex, and island are tholeiite (IAT) to boninite extrusive rocks (Shallo *et al.* 1995; Tashko 1996; Bébien *et al.* 1998; Robertson & Shallo 2000, and references therein). Pelagic sediments have yielded a Late Bathonian to Mid-Callovian age (Marcucci *et al.* 1994). As shown by dating their tectonic sole, the Mirdita ophiolitic nappes were emplaced during the Mid-Jurassic (Dimo 1997; Dimo-Lahitte *et al.* 2001). After tectonic emplacement, the ophiolites underwent erosion, as shown in the EOM by intense lateritic alteration, and in the WOM by the existence of a regional unconformity below the post-obduction sediments (ISPGJ–IGJN 1982, 1985, 2003). The post-obduction sedimentary cover includes a succession of 'chaotic' sediments that rework the internal units including these beneath ophiolite. Ophiolitic clasts are, however very uncommon, probably as a consequence of the prevalent climatic conditions, which caused lateritization of the EOM. The chaotic sequence is followed by turbidites of Tithonian–Early Cretaceous age (ISPGJ–IGJN 1982, 1985, 2003), and then by shallow-water carbonates of Hauterivian–Barremian to Late Cretaceous age (ISPGJ–IGJN 1982; Peza 1985; Shallo 1990).

The eastern internal complex. North of the Shkodra–Peć line (Figs 1 and 2), this corresponds to the Gashi Zone, characterized by a Siluro-Devonian terrigenous formation, intruded by the large Trokuzi granodioritic batholith, and followed by a succession of dacitic and andesitic rocks, with limestone intercalations (of Late Permian to Early Triassic age), and ending with a conglomeratic sequence (Verrucano) (Meço 1991; Meço & Aliaj 2000). This Unit is correlated with the Durmitor Zone of Montenegro. South of the Shkodra–Peć line, the internal complex corresponds to the Korabi Zone, which is correlated with the Golia Zone in the Dinarides, or the Drina Zone of former Yugoslavia, and the Pelagonian Zone in the Hellenides (Robertson & Shallo 2000). The section, strongly deformed in several tectonic slices, shows a succession of quartzites, shales and minor carbonates, with some volcanic intercalations of Ordovician to Devonian age (Melo 1970; Meço 1988, 1991; Meço & Aliaj, 2000). These sequences underwent low-grade metamorphism and were intruded by monzosyenites and lamprophyres, dated by the K/Ar method at 373 ± 50.7 Ma, 294 ± 47.04 Ma and 241 ± 28.9 Ma, respectively (Shallo 1992). A weakly metamorphosed sequence of sandstones and conglomerates, with typical Verrucano facies, unconformably overlies the Palaeozoic succession. This passes upwards into a calc-alkaline volcano-sedimentary unit of Early–Mid-Triassic age, and then into platform carbonates of Mid-Triassic to Early Jurassic age. This platform sequence is identical to the Gjallica sequences, which form the lowermost tectonic slice below the EOM; therefore, following Kilias *et al.* (2001), we interpret the Gjallica sequence as the uppermost tectonic slice of the Korabi Zone, and adopt the same interpretation for the Hajmeli sequence, situated below the WOM. The platform sequence is overlain by a pelagic sequence of Late Liassic–Late Jurassic age (Shallo, 1992). An erosion surface truncates the Mesozoic sequence with local bauxitic pockets. The erosion surface is transgressed by a chaotic and turbiditic sequence of Ťithonian–Early Cretaceous age (Shallo 1992) that reworks the ophiolites and their tectonic substratum (Rubik unit). The section continues with shallow-water carbonates of Barremian to Albian age, which are locally transgressed by Palaeogene terrigenous turbidites.

The Albano-Thessalian depression. The NNW–SSE-oriented Albano-Thessalian depression (Fig. 1) crosscuts both the Korabi and the Mirdita zones. It shows a shallow-marine and continental clastic sequence of late Eocene to Tortonian age. The basin represents the northern continuation of the Meso-Hellenic Trough of northern Greece, interpreted as a piggyback basin developed behind the compressional front of the external fold-and-thrust belt (Ferrière *et al.* 2004).

The Neogene–Quaternary graben. A north–south-oriented Neogene-Quaternary graben system crosscuts the entire regional structure (Korabi, Mirdita and Albano-Thessalian basin) from Korca to Progradec lake and continues into Macedonia (Fig. 1). The fault system has been activated several times, involving Late Tortonian SE–NW extension, Early Pliocene ENE–WSW compression, Late Pliocene east–west extension, early Pleistocene east–west transpression and SE–NW to east–west Quaternary extension (Tagari *et al.* 1993).

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Geodynamic evolution of Albania

Although there is a general consensus as to a westward transported fold-and-thrust belt, a controversy exists concerning the deep structure of the ophiolite, which is considered either as a far-travelled nappe originating in the Vardar Zone (Collaku *et al.* 1990), as a locally rooted zone reversely faulted on both sides (Kodra *et al.* 1993), or as a twice-deformed moderately displaced unit (Robertson & Shallo, 2000). For Collaku *et al.* (1990), the existence of the Peshkopia tectonic window indicates the allochthony of the ophiolite. For Kodra *et al.* (1993), the thickness of the Tropoja ophiolite is not compatible with an allochthonous massif, and there exist kinematic indicators of reverse faulting on both sides of the ophiolite, west-directed on the western side and east-directed on the eastern side. The model of Robertson & Shallo (2000), is based on the petrological and geochemical differences between the WOM, seen as a MOR-type ophiolite, and the EOM, interpreted as a supra-subduction-type ophiolite. Robertson & Shallo inferred two-phase emplacement history in which eastward-dipping Jurassic subduction was followed by westward transport related to Early Tertiary collision. In our opinion, the structure of Albania has resulted from several structural episodes. The first well-characterized one is the obduction of the Mirdita ophiolite, well dated as Mid-Jurassic, either by geochronology (Dimo 1997; Dimo-Lahitte *et al.* 2001) or by the sedimentary evolution of the internal units (ISPGJ–IGJN 1982, 1985, 2003; Shallo 1992; Kodra *et al.* 1993; Robertson & Shallo 2000). The ophiolites were thrust over the Rubik complex, locally metamorphosed (metamorphic sole), and emplaced over the Korabi sequences. Some kinematic data from the ophiolite (Tashko *et al.* 1996; Robertson & Shallo 2000), or the metamorphic sole (Dimo 1997; Dimo-Lahitte *et al.* 2001) suggest a northeastward transport direction (in present-day orientation). However, this model does not explain the existence of calc-alkaline volcanic rocks in the Korabi and Gashi Triassic units, which possibly related to an earlier tectonic regime characterized by northward subduction. A second well-defined major tectonic episode resulted in the construction of the fold-and-thrust belt, characterized by west-southwestward transport, beginning in Eocene time with deformation of the Krasta (Pindos) Zone, then progressively affecting the more external domains. In our opinion, the previously structured internal complex (Mirdita ophiolite, Rubik complex and Korabi unit) was passively transported on top of the Krasta (Pindos) nappes at the start of this tectonic episode, resulting in the complete uprooting of the ophiolites (Fig. 2a and b).

Fission track data

Fission-track thermochronology

Apatite and zircon fission-track (AFT, ZFT) thermochronology is widely used for reconstruction of low-temperature thermal histories of upper crustal rocks. This method allows one to estimate the temperature history and long-term denudation rates in orogenic mountain belts, rifted margins and more stable continental areas (e.g. Green *et al.* 1989; Wagner & Van den Haute 1992; Gallagher *et al.* 1994; Fitzgerald *et al.* 1995; Carter 1999; Zarki-Jakni *et al.* 2004).

The apatite partial annealing zone (PAZ) is considered to extend from 120 to 60 °C (Gleadow & Fitzgerald 1987; Green *et al.* 1986, 1989). Confined tracks formed below 60 °C are characterized by a mean track length (MTL) of *c.* 15 μm and a standard deviation (SD) of their distribution <1 μm. Within the PAZ, tracks shorten at highly temperature-dependent rates. The relationship between track shortening, time and temperature has been quantified by laboratory experiments (e.g. Laslett *et al.* 1987; Carlson *et al.* 1999). Therefore, the track-length distribution within an apatite sample can be inverted to determine its thermal history experienced (e.g. Gallagher 1998; Ketcham *et al.* 1999). However, the annealing kinetics is dependent on apatite chemistry; an efficient measure of annealing kinetics is obtained by measuring the width of fission-track etch pits parallel to the *c*-axis (D_{par}; Carlson *et al.* 1999; Barbarand *et al.* 2003).

The PAZ of zircon is in the range of 200–250 °C and the temperature of 90% track retention is *c.* 240 °C in most cases (Brandon & Vance 1992; Brandon *et al.* 1998). Annealing of fission tracks in zircon during reheating is partially a function of alpha damage in the zircon. Highly damaged zircons will anneal at lower temperatures, whereas more pristine crystals may anneal only at temperatures of >250 °C, depending on heating time.

Sampling and analytical procedures

Lithologies suitable for FT thermochronology are present in the external fold-and-thrust belt (clastic sequences of the foreland complex and flysch sequences), in the central complex (basement of the Rubik nappes, metamorphic sole and Mirdita ophiolite), in the internal complex (magmatic intrusions and Verrucano), and in

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the clastic sequences of the Albano-Thessalian depression. After initial wide-mesh sampling, we concentrated our attention on the central belt and the internal complex. Twenty-eight samples were collected from different magmatic bodies and terrigenous formations of the Korabi, Rubik and Gashi zones, 19 from the amphibolitic metamorphic sole and 15 from gabbroic and plagiogranitic bodies within the Mirdita ophiolite. Twenty-two samples were collected from clastic layers of the external flysch units and the foreland complex and from the Albano-Thessalian depression.

Apatite and zircon were separated using standard magnetic and heavy liquid separation techniques. After separation, apatites were mounted in epoxy, polished and etched in 5M HNO_3 solution at 20 °C for 20 s. All samples were dated by the external detector method, using a zeta calibration factor for Fish Canyon Tuff (FCT) and Durango Tuff age standards (Hurford 1990). Samples were irradiated at the well-thermalized ORPHEE facility of the Centre d'Etudes Nucléaires in Saclay, France, with a nominal fluence of 5×10^{15} neutrons cm^{-2}. Neutron fluence was monitored using CN5 and NBS962 dosimeter glasses.

For calibration of confined track length measurements, we measured confined track lengths in apatite from the Durango and FCT age standards. We obtained an MTL of 14.2 and 14.4 μm for Durango and FCT, respectively, with standard deviations (SD) of 1.0 and 1.1 μm, respectively (see Fig. 6).

Results

We have so far dated 22 samples from the inner Albanides. AFT and ZFT data are summarized in Tables 1 and 2. All AFT ages are quoted as central ages (Hurford 1990) with $\pm 1\sigma$ uncertainties throughout and range from 10.8 ± 0.7 to 50.5 ± 5.7 Ma. All samples show a very low age dispersion ($D < 6\%$, $P(\chi^2) \geq 90\%$), suggesting that chemical heterogeneity of the apatite is not a problem in the crystalline rocks that we sampled (Fig. 3). The MTLs for our samples vary between 10.2 ± 0.3 μm (AM12-02) and 13.0 ± 0.2 μm (AM13-02), with standard deviations (SD) between 1.3 and 3.0 μm.

The youngest AFT ages (<20 Ma) are along the eastern border of the Mirdita Zone and in the Korabi Zone. Amphibolites, from the base of the ophiolites in the eastern Mirdita Zone, and micaschists from Gjegjani have AFT ages between 20 and 15 Ma (Table 1 and Fig. 3). In the Korabi Zone we dated monzonite, lamprophyre granite and Palaeozoic sandstones, and found AFT ages between 17 ± 1 and 11 ± 1 Ma.

We also analysed one granitoid from the Trokuzi massif in the Gashi Zone, which yielded an AFT age of *c.* 40 Ma. This age is close to the range of ages between 40 and 50 Ma that we observed in the western Mirdita Zone from amphibolites at the base of the ophiolitic nappe, and from plagiogranites in the western part of the ophiolites, and granite in the Rubik nappe. All AFT ages are significantly younger than the $^{40}Ar/^{39}Ar$ ages of 165–175 Ma determined from the metamorphic base and some intrusions into the ophiolites (Dimo-Lahitte *et al.* 2001).

We also dated four zircon samples from different locations: the Trokuzi massif (Gashi Zone); one granite in the Rubik area, and two samples from the Korabi Zone. The zircon FT ages (Table 2) range between 100 and 174 Ma, a considerably older age spectrum than the AFT ages.

Discussion

Our AFT ages show a clear regional trend. They are very similar from north to south but change significantly from west to east in the inner Albanides (Figs 3 and 4). The samples with young AFT ages (<15 Ma) are located in the eastern part of Albanides (Korabi and eastern Mirdita). They show an interesting age–elevation relationship; the ages are constant and independent of elevation (Fig. 5). Such an age–elevation trend is generally considered as being developed during a period of very fast tectonic denudation (exhumation) or erosion. These ages are significantly younger than the results (35–40 Ma) obtained in the Pelagonian domain of Macedonia and northern Greece, east of Korabi (Most *et al.* 2001); this suggests that relatively recent exhumation was localized near the western boundary of the Korabi Zone.

The MTL of the young samples in the eastern Albanides are relatively short, around 10–12 μm. One sample from the Peladhi granite (AM12-02), situated on the western border of the Korabi zone, shows a bimodal track-length distribution with an MTL of 10.2 ± 0.3 μm (SD = 3.0 μm) (Fig. 6). Other samples from the Korabi Zone do not show bimodal distributions, but do have similarly short MTL and wide track-length distributions. This suggests that all of the Korabi samples were maintained for a long time at a temperature of 90 ± 10 °C, within a PAZ, and that fast exhumation, as suggested by the age–elevation relation of the samples, affected the region recently.

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Table 1. *Apatite fission-track data from the Albanides*

Sample	Grid reference	Altitude (m)	n	ρ_s (10^5 cm^{-2})	N_s	ρ_i (10^5 cm^{-2})	N_i	ρ_d (10^5 cm^{-2})	N_d	$P(\chi^2)$ (%)	D (%)	$t \pm 1\sigma$ (Ma)	MTL (μm)	SD (μm)	No. (lengths)	D_{par}	Observer
Korabi																	
AM1-00	41.962365 20.585784	1295	27	1.83	(574)	9.68	(3029)	3.524	(15097)	96	0	11.3 ± 0.6	10.43	2.9	103		1
AM8-00	41.962471 20.585321	1300	21	2.6	(486)	12.9	(2410)	3.524	(15097)	91	6	11.9 ± 0.7	12.21	2.1	135	1.7	1
AM20-00	41.894265 20.501213	1750	26	0.366	(97)	1.968	(521)	3.524	(15097)	>99	0	11.1 ± 1.2	11.05	2.6	78		1
			23	0.325	(76)	2.498	(584)	5.121	(15671)	>99	0	11.2 ± 1.4					1
			6	0.407	(22)	2.18	(118)	3.524	(15097)	98	0	11.6 ± 2.7	12.18	2.2	107		2
AM9-00	42.025532 20.52856	750	20	1.36	(326)	7.49	(1797)	3.524	(15097)	>99	0	10.8 ± 0.7	12.21	2.1	124		1
			20	1.56	(308)	9.08	(1787)	3.524	(15097)	>99	0	10.7 ± 0.7	11.92	2	108		2
			15	1.76	(236)	12.89	(1728)	5.345	(16698)	72	1	12.3 ± 0.9					1
AM26-02	42.025532 20.52856	750	20	2.3	(359)	15.13	(2364)	5.345	(16698)	90	0	13.7 ± 0.8					1
AM27-02	42.005008 20.523131	800	22	2.51	(378)	13.342	(2009)	5.345	(16698)	92	0	17 ± 1.0					1
AM25-02	42.058534 20.504297	750	13	1.39	(80)	11.56	(665)	5.411	(11155)	96	0	11 ± 1.3					1
AM12-02	41.516216 20.334951	680	23	1.146	(186)	9.558	(1551)	5.411	(11155)	>99	0	11 ± 0.9	10.20	3.0	107	1.4	1
			24	1.435	(269)	9.896	1855	5.345	16698	>99	0	13.1 ± 0.9					1
Eastern Mirdita																	
AM15-02	41.762162 20.225728	875	26	0.356	(68)	2.215	(423)	5.411	(11155)	>99	0	14.7 ± 1.9					1
AM23-02	42.09646 20.478896	476	21	1.017	(175)	6.396	(1101)	5.411	(11155)	95	0	14.5 ± 1.2					1
AM02-03	41.483787 20.3699	792	17	0.256	(21)	1.477	(121)	5.345	(16698)	>99	0	15.7 ± 3.7					1
AM10-03	42.09105 20.48668	521	19	2.126	(325)	8.95	(1368)	5.345	(16698)	94	0	21.4 ± 1.4					1
Western Mirdita																	
AM16-00	42.247311 20.048543	305	24	1.83	(373)	2.21	(451)	3.524	(15097)	91	1	49 ± 3.5					1
AM30-02	42.100103 20.114121	841	17	1.08	(127)	1.95	(229)	5.411	(11155)	>99	0	50.5 ± 5.7					1
AM13-02	41.403603 20.192961	760	24	1.439	(148)	3.131	(322)	5.345	(16698)	>99	0	41.4 ± 4.2	12.96	1.3	30	1.7	1
AM14-02	41.455855 20.138349	450	8	2.02	(96)	4.129	(196)	5.411	(11155)	>99	0	44.6 ± 5.6					1
AM18-03	42.070176 19.75966		19	0.712	(84)	1.593	(188)	5.345	(16698)	>99	0	40.2 ± 5.3					1
Gashi																	
AM15-00	42.517921 20.036764	1865	7	0.869	(47)	1.33	(72)	3.524	(15097)	95	0	38.7 ± 7.3					1
			7	1.19	(51)	2.556	(109)	5.121	(15671)	86	0	40.3 ± 6.9					1

n, number of counted grains; ρ_s, spontaneous track density; ρ_i, induced track density; ρ_d, dosimeter track density; N_s, N_i, N_d, number of tracks counted to determine the reported track densities; $P(\chi^2)$, chi-square probability that the single grain ages represent one population; *D*, age dispersion; MTL, mean horizontal confined track length; SD, standard deviation of horizontal confined track-length distribution; No. lengths, number of measured horizontal confined track lengths. All ages are central ages (Galbraith & Laslett 1993). D_{par}, mean fission-track etch pit diameter parallel to the crystallographic *c*-axis for each apatite grain (e.g. Carlson *et al.* 1999; Donelick *et al.* 1999). Observer: 1, measurements by B. Muceku; 2, measurements by E. Labrin.

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Table 2. *Zircon fission-track data from the Albanides*

Sample	Grid reference	Altitude (m)	n	ρ_s (10^5 cm^{-2})	N_s	ρ_i (10^5 cm^{-2})	N_i	ρ_d (10^5 cm^{-2})	N_d	$P(\chi^2)$ (%)	D (%)	$t \pm 1\sigma$ (Ma)	Observer
Korabi													
AM8-00			4	450.00	(1118)	48.309	(120)	1.696	(16271)	84	0	125.1 ± 12.9	1
			4	464.674	(1197)	55.124	(142)	1.696	(16271)	75	0	116.8 ± 10.7	2
AM03-03	41.5001 20.34192	750	10	97.968	(1216)	7.734	(96)	1.76	(13753)	>99	0	156 ± 17	1
Eastern Mirdita													
AM13-03	42.2975 20.1442	370	15	112.773	(2493)	7.871	(174)	1.744	(13753)	>99	0	174.3 ± 15	1
Gashi													
AM15-00	42.517921 20.036764		8	32.039	(1182)	4.174	(154)	1.969	(16271)	92	0	103.2 ± 9.6	1

Symbols are as in Table 1.

Our samples collected from west of the Mirdita Zone, with AFT ages of 40 Ma or older, do not show any significant age–elevation relationship (Fig. 5). There, we were able to measure confined track lengths on one sample (AM13-02), and found an MTL of 13.0 μm with SD 1.3 μm (Fig. 6). The inferred cooling history appears to be different.

Our zircon FT results indicate that the internal Albanides have in general not reached a temperature high enough (>200 °C) to reset zircon. The zircon FT ages of the granite from the Rubik area (174 Ma) are compatible with K/Ar ages of 165 to 175 ± 6 Ma for the same rock, as reported by Castorina *et al.* (1995). This suggests that the maximum temperatures in the Albanides remained well below 200 °C since the Mesozoic, and particularly during the Eocene deformation (see Fig. 8).

Thermal modelling

To explore in more detail the cooling history, we used the multi-kinetic model of AFTsolve of Ketcham *et al.* (1999, 2000). The chemical composition of apatite may vary strongly, even for crystalline basement samples from the same lithology (Crowley *et al.* 1991; O'Sullivan & Parrish 1995). As a control of chemical variability we measured D_{par} (Table 1). D_{par} is the mean fission-track etch pit diameter parallel to the crystallographic *c*-axis for each apatite grain, and is specified in units of microns (e.g. Carlson *et al.* 1999; Donelick *et al.* 1999). We also measured the orientation of confined track length to the crystallographic *c*-axis for each track length, and corrected for this in the thermal history modelling (see Donelick *et al.* 1999).

To test this modelling approach, we first used grain-age, track-length (MTL 14.4 μm) and D_{par} (2.1 μm) measurements of FCT apatite. The aim was to compare the modelling results with a sample with a known cooling history. The results are shown in Figure 7. The thermal model of FCT shows very fast cooling (Fig. 7d) through the PAZ between 27 and 28 Ma; this corresponds well to the known thermal history of these volcanic rocks. Encouraged by these results, we modelled two samples from the Korabi Zone (Fig. 7a and b), and one sample of amphibolite from the western Mirdita Zone (Fig. 7c). For these samples we assumed that they cooled from temperatures of *c.* 120 °C since the last heating event.

To translate these cooling histories into exhumation rates, we needed to have an estimate of the geothermal gradient. Frasheri *et al.* (1996)

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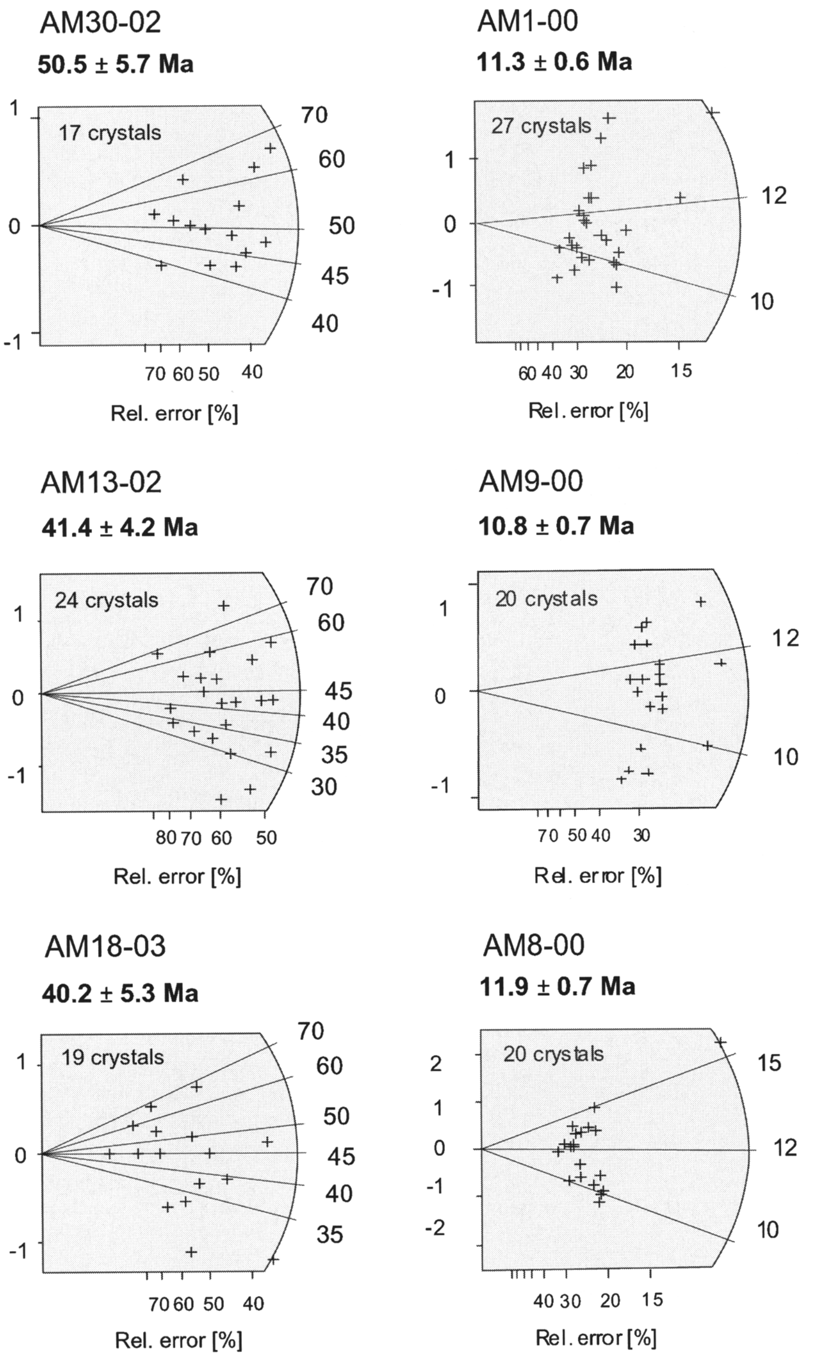

Fig. 3. Apatite fission-track (AFT) ages: radial plots of some representative samples from the western Mirdita and Korabi zones.

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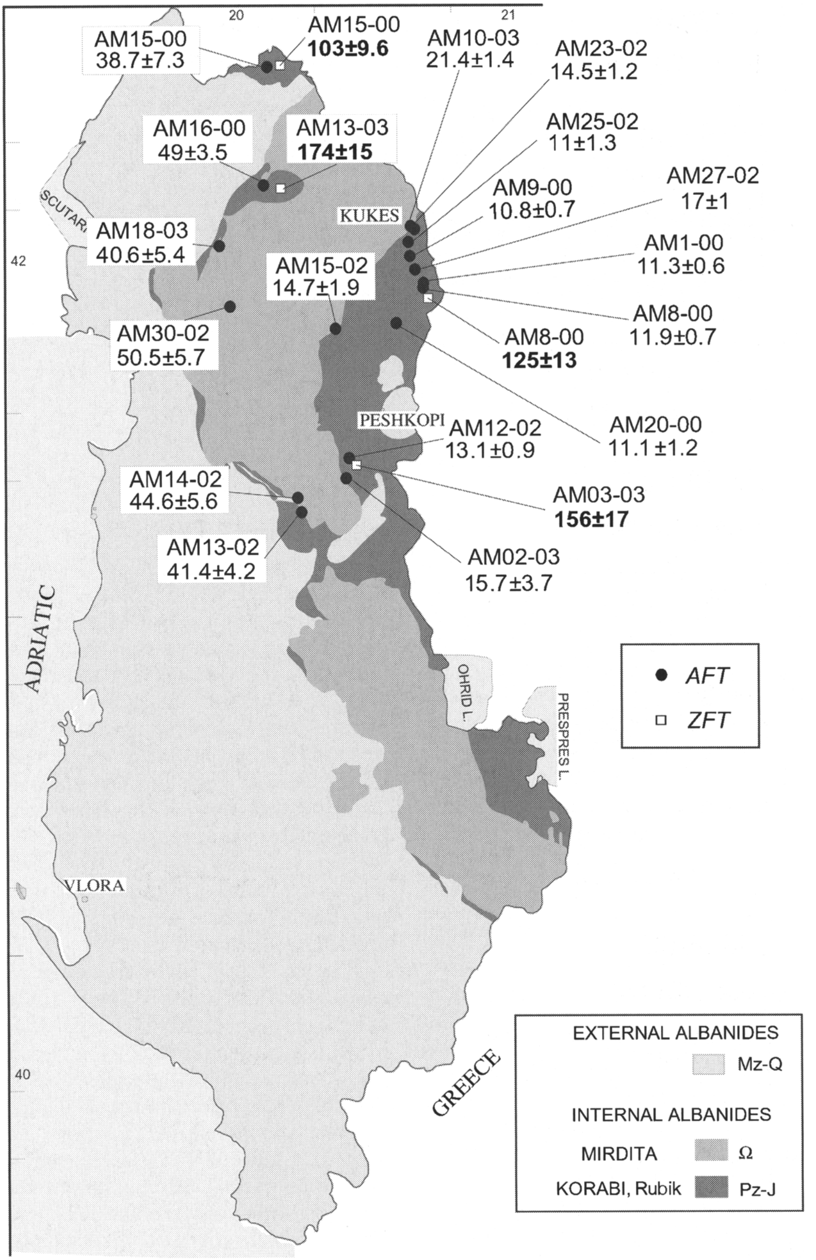

Fig. 4. Apatite fission-track (AFT) and zircon fission-track (ZFT) ages for the Albanides.

reported two different geothermal gradients: 15 °C km^{-1} for the external Albanides and 20–30 °C km^{-1} for the internal Albanides. We, therefore, believe 25 °C km^{-1} is a reasonable approximation for modelling the pre-fast exhumation cooling history of the Korabi Zone samples.

At about 30 Ma, sample AM12-02 was near or even at the surface (Fig. 7b). Subsequently the Korabi Zone was buried to about 4 km depth (assuming a palaeo-geothermal gradient of 25 °C km^{-1} and 10 °C surface temperature) to reach temperatures of 110–120 °C, allowing FT annealing. In contrast, sample AM8-00 experienced

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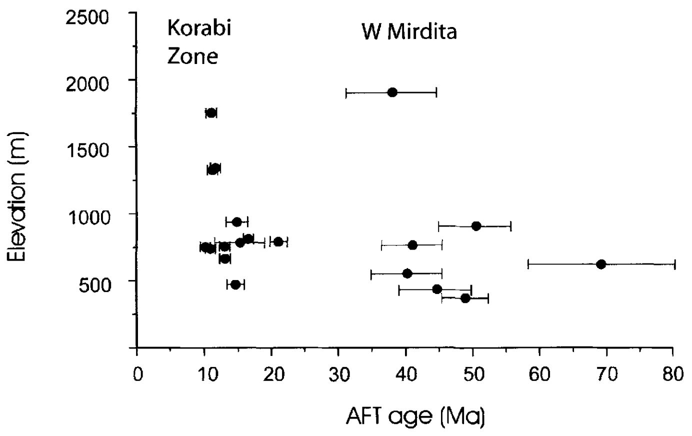

Fig. 5. Relationship between AFT age and sample elevation.

slow cooling from about 16 to 15 Ma (Fig. 7a), at an average rate of 5 °C Ma^{-1}, suggesting rapid exhumation after 2.3 Ma.

Comparing our result from multi-kinetic modelling of sample AM8-00 (Ketcham *et al.* 1999) with the results we obtained using mono-kinetic modelling (Laslett *et al.* 1987) for four other monzonite and lamprophyre samples of the Korabi Zone (Muceku *et al.* 2003), we then found a similar evolution. We believe that this is caused by the similarity of the chemical composition of these samples to the Durango standard, as we measured D_{par} values of 1.7 µm and 1.8 µm, respectively, in these samples.

The oldest AFT ages (40–50 Ma) are situated in the western part of the Mirdita Zone. They document an Eocene cooling event that corresponds well in time to the Eocene emplacement of the internal zones onto the external zones. Nowadays, the region has a geothermal gradient of 15–20 °C km^{-1} (Frasheri *et al.* 1996). However, for the Cenozoic deformation history we assume that the palaeo-geothermal gradient was probably between 20 and 25 °C at 40–50 Ma. Therefore, the 40–50 Ma AFT cooling ages of the western Mirdita rocks suggest that these rocks were not buried deeper than *c.* 4–5 km since that time (Fig. 8). The multi-kinetic thermal modelling of sample AM 13-02, even if not very well constrained by a sufficient number of track-length measurements, suggests a fast cooling since 49 Ma (Fig 7c).

Geodynamic interpretation

Figure 8 is a tentative synthesis based on our FT data and the small amout of reliable published Albanian geochronological data. First, our zircon FT results indicate that maximum temperatures in the central and eastern Albanides stayed well below 200 °C since Mesozoic time; in particular, there is no indication of deep burial despite the Eocene deformation, supporting the idea that the tectonic pile created during the Jurassic ophiolitic obduction (ophiolitic nappe–metamorphic sole–Rubiku nappe–Korabi Zone) was more or less passively transported, with only minor reworking of some tectonic contacts. Similarly, deformation in the Albanian Alps took place under upper crustal conditions.

Second, the AFT results document two very different vertical evolutions. In the western part of the belt (western Mirdita and Albanian Alps) the rocks were uplifted above 4–2.5 km depth during the Early to Mid-Eocene and possibly exposed at the surface before the Oligocene. The uplift rate was of the order of 0.1–0.2 mm a^{-1}. For this area the chronology agrees well with the Mid-Eocene age for the uppermost layers of the Pindos flysch, representing the tectonic substratum just below the Mirdita nappes. Therefore, we relate the uplift of the western area to the crustal thickening that occurred as a consequence of the first step of the fold-and-thrust belt construction.

The eastern part of the belt shows a very different evolution. The rocks underwent slow cooling during Mid–Late Miocene time, reaching a 4–2.5 km depth only in the Late Pliocene, at an uplift rate of the order of 0.1 mm a^{-1}. Since the Late Pliocene the uplift rate has accelerated about 12 times. The first episode, well documented in sample 12-02, may correlate with the emplacement of the Albano-Thessalian inferred piggyback basin at the rear of the propagating fold-and-thrust belt. Therefore, we consider this episode to be a consequence of the crustal

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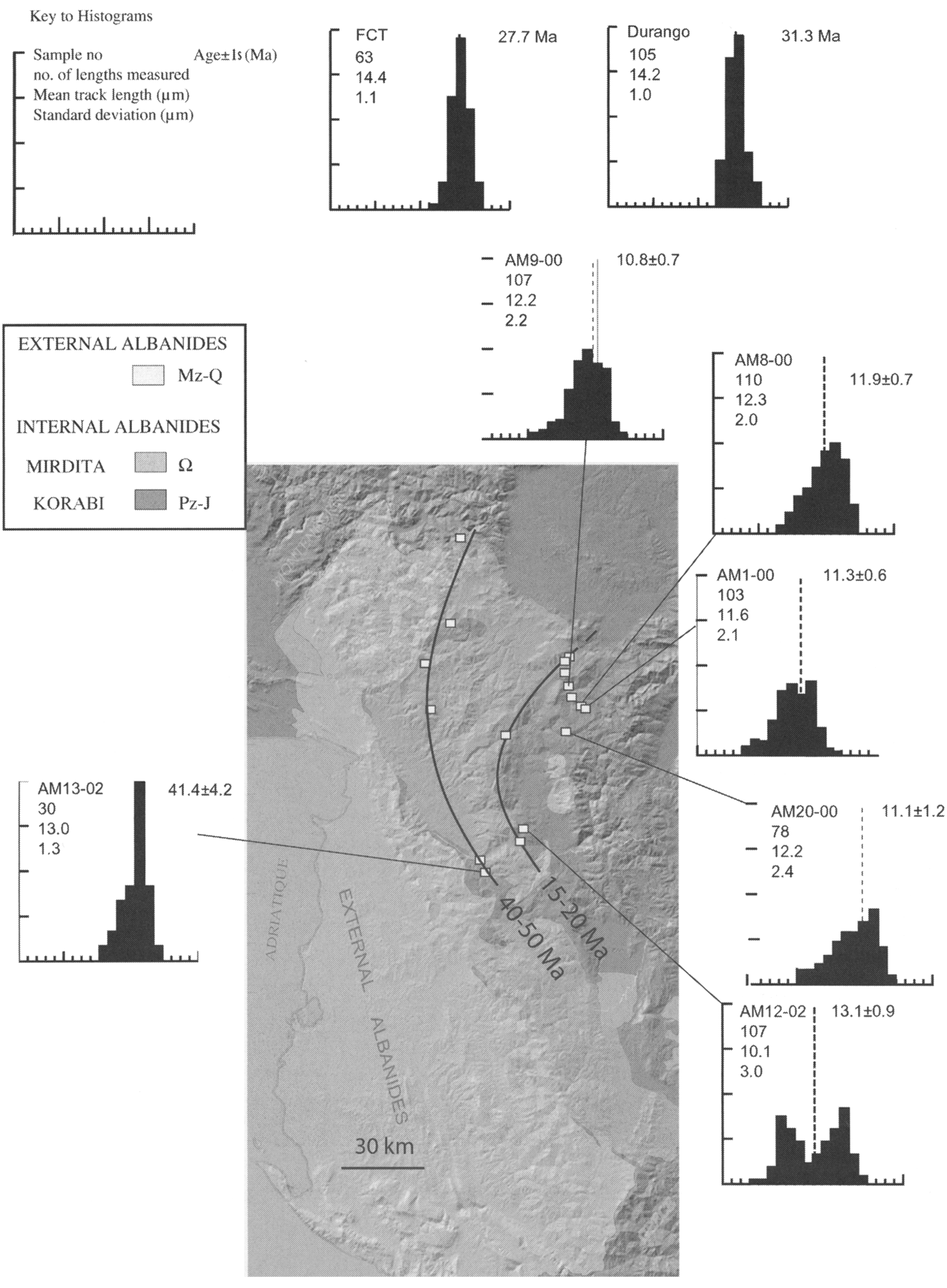

Fig. 6. Distribution of AFT ages and representative horizontal confined track-length distributions for some selected samples.

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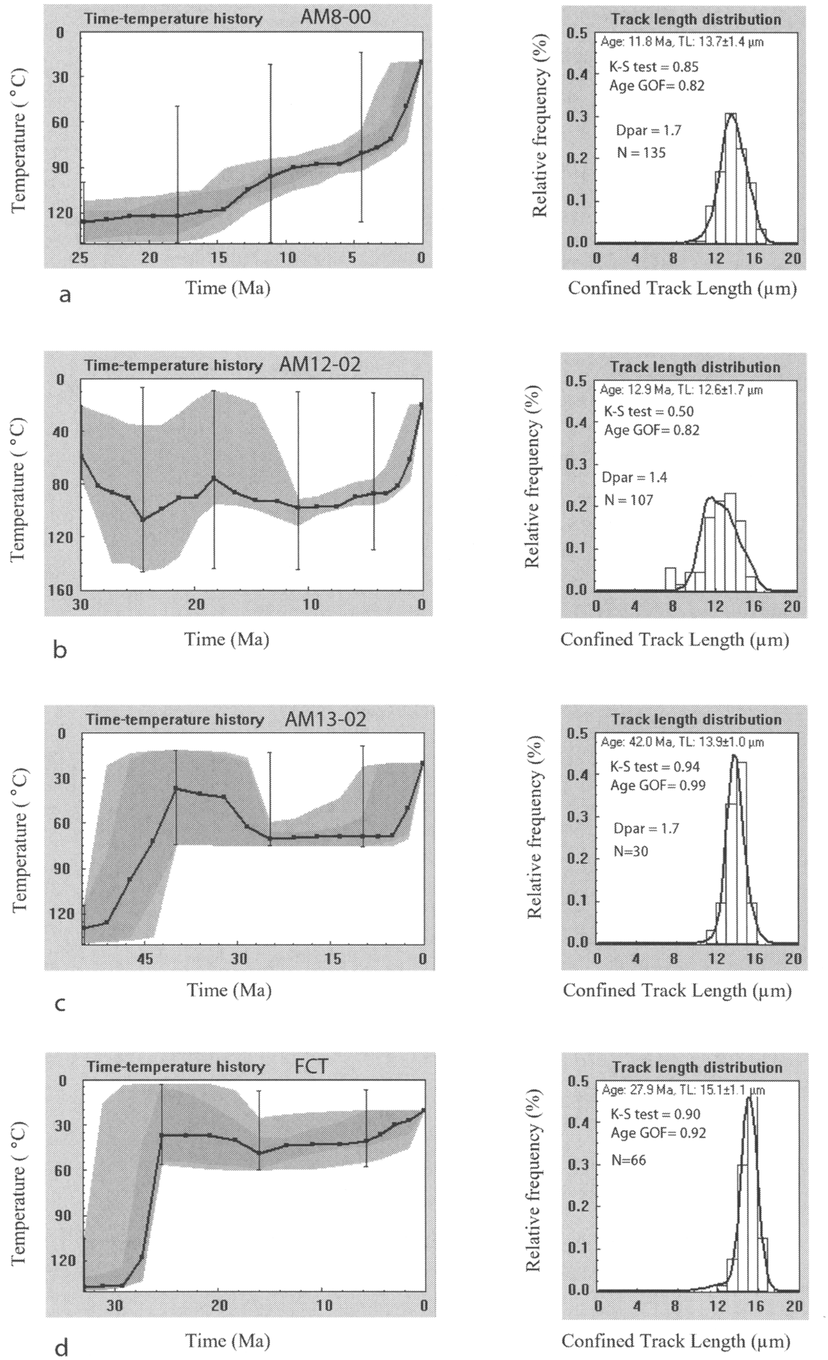

Fig. 7. Time–temperature histories of selected samples. Time–temperature histories were calculated by the inversion of track-length distribution (using AFTsolve software). The shaded areas on the time–temperature plots represent solutions that statistically fit the observed data (sample age and track distribution); the continuous black line is the overall 'best fit' solution for the sample. The plots at the right show the observed track-length distribution as a histogram and the modelled distribution as a continuous line. The 'K-S test' is the Kolmogorov–Smirnov test; the age 'GOF' is the goodness of fit between the age data and age predicted by the model. FCT is the Fish Canyon Tuff standard; *N*, number of measured track lengths.

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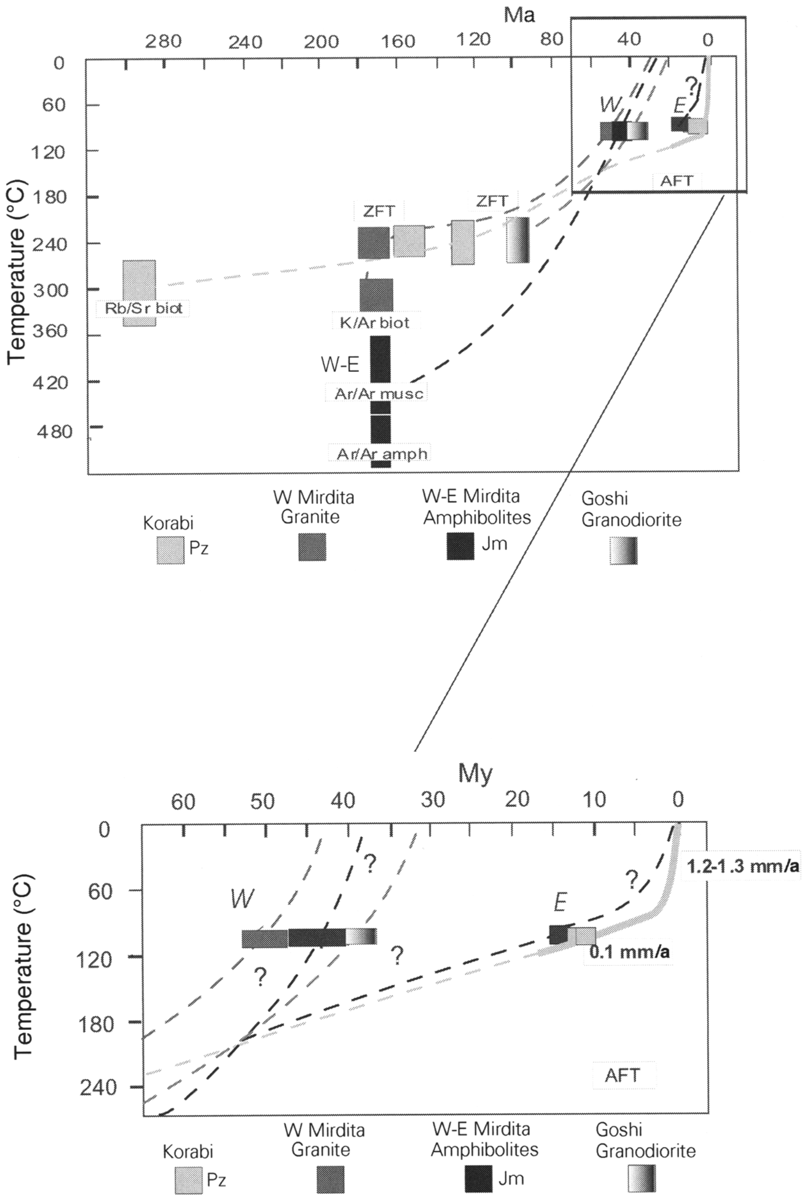

Fig. 8. Thermal evolution of Albanides: tentative synthesis based on our AFT and ZFT results and ages in literature.

thickening; the preliminary results of Most *et al.* (2001) for the internal Pelagonian domain suggest that the whole area underwent general uplift at this time. The Late Pliocene episode corresponds well in time to the evolution of the Neogene–Quaternary graben system, and specifically the Late Pliocene east–west extension event of Tagari *et al.* (1993). We propose that the recent acceleration of uplift at the eastern boundary of the Mirdita belt can be related to a recent tensional regime of crustal thinning, as documented by the formation of the graben system and the tensional focal mechanisms in the upper crust.

Conclusions

Our AFT data provide clear evidence for differential cooling and erosional denudation of the

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internal Albanides. Near their frontal thrust, the internal Albanides record cooling and denudation during Late Eocene–Early Oligocene times, contemporaneously with their tectonic emplacement onto the external fold-and-thrust belt. In this area, the cooling and denudation are clearly related to isostatic uplift as a consequence of crustal thickening in relation to subduction of Apulian lithosphere. The internal part of the internal Albanides records a more complex cooling evolution: a first stage of early Late Eocene–Early Oligocene cooling was followed by Early Neogene burial, also related to a crustal thickening regime; a second stage of Late Neogene cooling, characterized by recent acceleration, can be related to a still-active period of crustal thinning. Thinning is a common tendency for over-thickened crust. In the present case this could either be a local effect or a northward extension of the regional Aegean thinning regime. Our zircon fission track results indicate that the at present exposed internal Albanides did not reach high temperatures during their Tertiary deformation.

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