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# Exhumation of HP-rocks accompanied by low-angle normal faulting and associated detachment fault of Milos Island – Evidence from zircon fission-track thermochronology

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**Abstract.** Southward roll-back and slab retreat of the subducting African plate has been the cause of extension and magmatism in the Aegean since the Early Miocene. The Hellenic subduction system has shown a progressive southward-migration provoking activity on a series of detachment faults and successive associated exhumation episodes of *HP*-rocks. Volcanism has been localized during Oligocene–Middle Miocene in central Aegean, and from Pliocene to Recent in the south Aegean. Plutonism, active during Early to Middle Miocene also shows a southward migration through time. Fission-track dating of detrital zircon from exhumed *HP*-rocks along the volcanic arc and the fore-arc ridge shows at least two zones of successive exhumation episodes of *HP*-rocks. Zircon fission-track (ZFT) dating from the small exposure of metamorphic basement in Paliochori, on Milos Island, located below the unmetamorphosed Neogene limestones and Pliocene to Recent volcanic rocks, documents an older exhumation episode active at ~16 Ma. In comparison, exhumation of metamorphic rocks on and near Kythera Island was active at ~11 Ma. In the southwestern part of Aegean the exhumation was accompanied by activity on two successive low-angle detachments. We infer that rapid roll-back and slab retreat resulted in the migration of the locus of exhumation of *HP*-rocks from the Cyclades towards the Peloponnese-Cretan fore-arc ridge of the southwest Aegean during the interval of 16-11 Ma. Fore-arc migration and overall extension of at least 150 km occurred in this interval, with rates up to ~30 mm/yr.

*Keywords: HP*-rocks, exhumation, roll-back, exhumation, zircon, fission-track

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**Антониос Е. Марселос, Уилиям С.Ф. Кид, Джон И. Гарвър, Костантинос Г. Кириакопулос. Ексхумация на високобарични скали, придружена от полегато разсядане, свързано с разлом на отделяне на о-в Милос (Гърция) – доказателства от термохронологията, получени по метода на следите в циркони**

**Резюме**. Отдръпването в южна посока на субдуктиращата Африканска плоча е причина за екстензията и магматизма в Егейския район, започнали от ранния миоцен. Елинидната субдукционна система показва една прогресираща, насочена на юг миграция, предизвикваща активността на серия от разломи на отделяне и асоцииращите с тях ексхумационни епизоди на високобарично метаморфозирани скали. Вулканизмът е бил локализиран през олигоцена – средния миоцен в Централна Егея, а от плиоцена до днес – в Южна Егея. Плутонизмът, активен през ранния до средния миоцен също темпорално мигрира на юг. Датирането по метода на следите (ZFT – zircon fission-track dating), приложен към детритни циркони от ексхумирани високобарични метаморфни скали от вулканската дъга и преддъговия хребет сочи най-малко две зони на последователно ексхумиране. Този метод, приложен към циркони от слаборазкрития метаморфен цокъл на о-в Милос, залягащ под неметаморфозирани неогенски варовици и плиоценски до съвременни вулканити, документира един по-стар ексхумационен епизод с възраст около 16 Ма. За сравнение ексхумацията на метаморфните скали на о-в Китера и около него е с възраст около 11 Ма. В ЮЗ част на Егея ексхумацията е била придружена от последователната активност на два полегати разлома на отделяне. Допуска се, че бързото отдръпване и изменение на наклона на субдукционната плоча е довело до миграция на мястото на ексхумация на високобаричните скали от Цикладите към Пелопонес-Критския преддъгов хребет в ЮЗ Егея във възрастовия интервал 16–11 Ма. Миграция на този хребет, както и цялостна екстензия, от порядъка поне на 150 km е извършена в този интервал със скорост до около 30 mm/год.

## Introduction and geologic background

Motion of Africa with respect to Europe in the Mediterranean region shows a deceleration since 35 Ma, and in the eastern Mediterranean by 10 Ma declined to a very low overall convergence rate of a few mm/yr (see Savostin et al. 1986; Rosenbaum et al. 2004 and references therein). Significant changes of the convergence rate between the African and European plate occurred at ~35 Ma, ~20 Ma, and ~10 Ma (Savostin et al. 1986). However, the roll-back of the Hellenic sector of the subducting African slab began in this interval causing localized more rapid subduction (presently ~35 mm/yr in the central part of the arc) and a broad extensional event in the Aegean occurred as a result (Jolivet et al. 1994a; McClusky et al. 2000).

Roll-back and slab retreat have been accommodated in the upper (Aegean) plate by a series of extensional detachment faults (e.g. Fassoulas et al. 1994; Kilias et al. 1994; Jolivet et al. 1996, 1998; Thomson et al. 1999; Marsellos 2006, 2008; Marsellos & Kidd 2008). *HP/LT* metamorphic rocks are widespread in the present back-arc and fore-arc regions beneath these detachment faults, and have been subducted beneath the orogenic wedge and then brought upwards dominantly by exhumation processes (Willet et al. 1993). Successive exhumation events of *HP*-rocks (Thomson et al. 1999; Brix et al. 2002; Brichau et al. 2008a; Marsellos et al. 2010) may be correlated with convergence rate changes. Roll-back also provides space that allows for *HP*-rocks to exhume from depth in a very short time (Royden 1993; Jolivet et al. 1994b; Lister et al. 2001). Trench migration relative to the volcanic arc (i.e. Aegean/Hellenic system) and fore-arc (Brun & Faccenna 2008) is one effect of roll-back, but in a curved arc other consequences such as differential roll-back and along-arc stretching (arc-expansion – Ten Veen & Kleinspehn 2002) must also occur (Marsellos et al. 2010). The Cycladic metamorphic basement is part of the overall exhumation of metamorphic rocks by low-angle shear zones (Lister et al. 1984) related to southwards retreat of the Hellenic subduction zone (Royden & Husson 2006), and associated opposite rotations of the west and east wings of the south Aegean "plate" (Kissel & Laj 1988; Walcot & White 1998; Van Hinsbergen et al. 2005). Thinned (20–6 km) continental crust (Tirel et al. 2004 and references therein) underlies the south Aegean Sea, a result of this crustal extension.

Subduction-related magmatism occurred in the south Aegean region during Oligocene–Middle Miocene (Fytikas et al. 1976, 1984), and the present volcanic arc started in the Early Pliocene. Between these two main phases, scattered volumetrically minor volcanism is observed with variable petrogenetic character, and a gap of volcanic activity during Middle Miocene to Pliocene is prominent in the central and south Aegean and this gap is still unexplained.

Several studies have shown that the Cyclades Miocene plutonism was contemporaneous with large-scale crustal extension in the broad Aegean – Western Turkey region (Wijbrans & McDougall 1988; Buick 1991; Lee & Lister 1992; Gautier & Brun 1993-in the references; Brichau et al. 2008b). Metamorphic core complexes may be triggered by plutonic activity during episodes of continental extension, and this can take place when pulses of ductile deformation (Lister & Baldwin 1993) have taken place during short-lived thermal events initiated by the heat input from intruded plutons or dikes.

Plutons related to subduction-generated magmatism may eventually intrude exhumed *HP*-rocks during the progressive migration of the magmatic arc during subduction roll-back. Magmatism may be absent if consumption of continental lithosphere (Brun & Faccenna 2008) and/or slab roll-back interfere with stable conditions of slab dehydration or remove the asthenospheric mantle between the slab and the lithosphere of the overriding plate. Brun & Faccenna (2008) have suggested that in the Calabria–Apennine and Aegean belts, subduction of small continental blocks was the trigger for slab roll-back.

One way to constrain the timing and rates of the roll-back and slab retreat of the African subducting plate, and its relation to exhumation of *HP*-rocks, is to define the timing of the exhumation of *HP*-rocks along a cross section between the volcanic arc and the fore-arc ridge. The volcanic island of Milos has a small exposure of *HP*-rocks, below the Eocene-Pliocene sedimentary rocks and Middle Pliocene to Recent (3 Ma to the present) volcanic rocks (Fytikas et al. 1984), that can provide useful information in this context. Many Cycladic islands host the Cyclades Blueschist Unit (CBU) rocks but on Milos these *HP*-rocks are unique by being the closest exposure to the area of the youngest exhumation of the *HP*-rocks in the Hellenic fore-arc ridge, the Kythera region. Thus they occupy a key position for understanding the long-term progression of exhumation.

Arc-expansion induced by differential roll-back and expressed by arc-parallel extension is responsible for a significant Middle–Late Miocene exhumation event of *HP*-rocks in the southwestern part of the Hellenic fore-arc ridge (Marsellos & Kidd 2008). Cooling ages suggest that there were two distinct events of exhumation accompanied by extensional detachments in the area of the Kythera strait, one prior to 15 Ma and another in the ~13–7 Ma interval (Marsellos & Kidd 2009; Marsellos et al. 2010). The first detachment was characterized by arc-normal extension, essentially parallel with the cross-section Kythera–Milos, while the subsequent (ductile–brittle) event and detachment reflects arc-parallel extension.

In the Hellenic fore-arc, the bulk of the deeply-exhumed rocks below the detachments are quartzites and phyllites. The metamorphic grade of these rocks varies, but they tend to be dominated by blueschist facies metamorphism (*HP/LT*) or lower pressure low-temperature (*LP/LT*) mineral assemblages. In most places there are few datable phases that can be studied to help understand the temporal evolution of exhumation. Detrital zircon is common in the Phyllite Quartzite Unit (PQU) and well as the Cycladic Blueschist Unit (CBU), and fission track dating on these detrital zircons provides one of the few ways that we can approach the thermochronology of these rocks. While detrital zircon is common, and relatively easy to date using the fission track method, there are complexities that are particular to this setting. The main challenge – and opportunity – is that the rocks have been heated to temperatures in the partial annealing zone of typical detrital zircon with radiation damage. Because of the variation in radiation damage, some grains become annealed in this sort of setting, while others do not, and we can use the annealed,

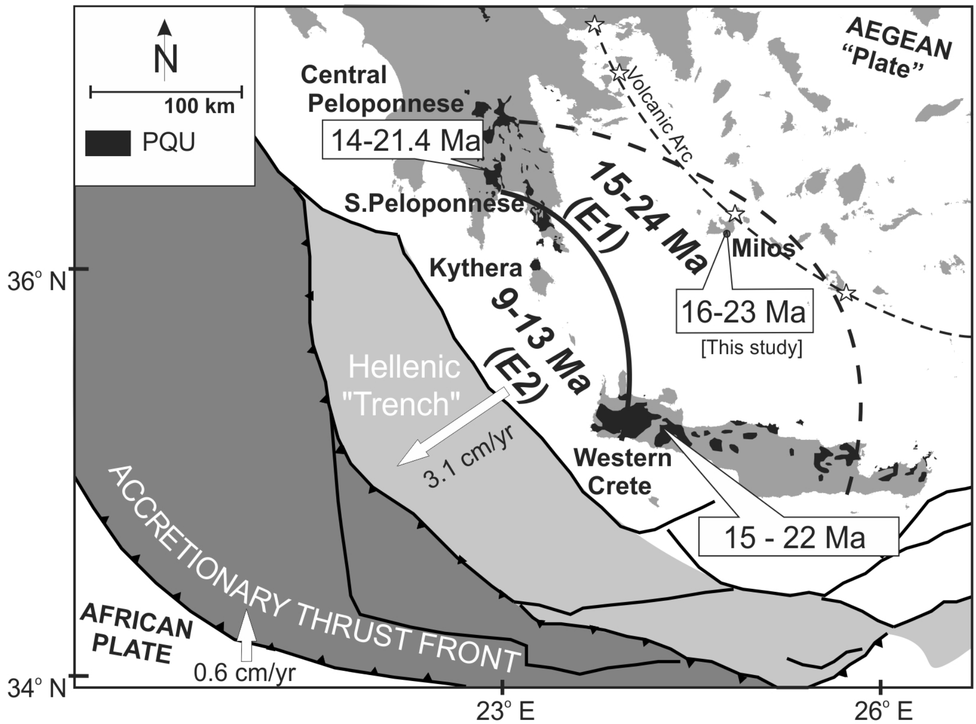


Fig. 1. Tectonic setting of the Hellenic arc. (E1), older exhumation of high pressure-low temperature rocks in the fore-arc and Recent volcanic arc (the white stars represent the active and recent volcanoes); (E2) the youngest exhumation of high pressure-low temperature rocks in the fore-arc region. Present GPS Eurasia-Africa relative velocity and average western Hellenic Arc-Africa relative velocity (derived from the average of five stations in western-central Crete, Kythera, and south Peloponnese) after McClusky et al. (2000). Phyllite-Quartzite Unit (PQU) exposed rocks and outcrop areas are shown black

fully reset radiation-damaged zircons to date exhumation.

This paper provides new cooling ages from detrital zircon from Milos Island. This sample location provides a crucial new understanding of the spatial distribution of exhumation accompanying slab roll back in the Hellenic subduction zone. The comparison of Kythera and Milos exhumation histories has the potential to reveal the roll-back and trench migration rate in a section approximately parallel with the roll-back direction.

## Zircon fission-track dating

Fission-tracks in zircon result from the spontaneous fission of $^{238}U$ and the formation of a track or damage zone in the crystal from these fission events (Garver 2008). At elevated temperatures these tracks anneal, which means they disappear as fast as they form, but at low temperatures all tracks that form are fully retained. There is a temperature range below which tracks are fully retained and above which tracks are immediately lost, which is commonly referred to as the Zircon Partial Annealing Zone (ZPAZ) (see Wagner & van den Haute 1990). Fission-tracks in crystals held in (or slowly traversing) the ZPAZ shorten but do not become completely erased by annealing. For simplicity, especially in areas of rapid exhumation, many workers refer to an effective closure temperature of the fission-track (FT) system instead of using the partial annealing zone (Reiners & Brandon 2006). The zircon FT system closes at about 240 ± 50°C (Brandon et al. 1998), but this temperature is very sensitive to the rate of cooling and radiation damage in the zircon (see Garver et al. 2002, 2005; Rahn et al. 2004). This effective closure temperature really applies to zircon exhumed from depth, the crystals having little to no accumulated radiation damage, and no previously formed tracks.

Heating zircon that has previously resided at near surface temperatures, and therefore contains abundant fission tracks, causes both the fission tracks and the internal radiation damage to anneal. But the annealing of fission tracks and the repair of radiation damage appear to have slightly different mechanisms as they occur over different and discrete temperature bounds (Montario et al. 2008). Practically speaking, what this means is that if these grains are brought to sufficiently high temperatures, track-length reduction and annealing of radiation damage occurs. The temperature required for the annealing of tracks varies dramatically from grain to grain especially if the interval of time at near-surface temperatures is sufficient to change the relative radiation damage from grain to grain. It is widely appreciated that the process of thermal annealing for any particular grain is largely a function of internal radiation damage, which affects its annealing properties (i.e. Kasuya & Naeser 1988).

Low-damage zircon grains are more resistant to annealing (i.e. are more highly-retentive zircons – HRZ) than high-damage zircon grains (which are less-retentive zircons – LRZ) (see discussion in Garver et al. 2005). In other words, zircon grains in any typical detrital sample have a continuum of fully crystalline (no damage), transitional (moderate damage), to metamict (high damage) and different grains have different effective closure temperature as a result (see Garver & Kamp 2002): we refer to this as differential annealing. Most differential annealing occurs in the range from about 200°C (low retentive zircons) to 300°C or higher (high retentive zircons).

Practically speaking, detrital zircon grains in low to moderate-grade metamorphic rocks typically consist of a population of fully reset grains and also grains with a wide range of cooling ages that are either partially reset or unrest (see Garver 2008). Studies of rocks metamorphosed to prehnite-pumpellyite, greenschist, blueschist, and even amphibolite-grade metamorphism show over-dispersion related to differential annealing (see Garver & Kamp 2002; Garver et al. 2005, 2010; Fellin et al. 2006; Meigs et al. 2008; Marsellos et al. 2010).

Many of these samples show over dispersion, which means that that they fail the $\chi^2$ test and do not represent a single statistically coherent population, and the main issue is that the grain-age distribution has an old-side bias. This over dispersion results from the fact that the unreset or partially reset grains usually have a wide spread of ages, all of which are older than the young reset age that is generally of interest. The $\chi^2$ test provides the method for assessing if the distribution is "over-dispersed" relative to the expectation for counting statistics for the fission process (Galbraith 1981). Failure of the $\chi^2$ test is very common even for sample suites containing two or more population ages very close to each other. It is clear that rocks heated only to temperatures between 180° and about 220°C (the lower part of the zircon partial annealing zone) have the potential to record both thermal resetting and original provenance information depending on the range of radiation damage and uranium content in any sample (see discussions in Brandon et al. 1998 and Garver et al. 2005).

## Methods

Zircon fission-track ages are reported here from a detrital zircon suite from a blueschist-grade rock from the Mesozoic metamorphic basement, obtained from the exposure on the southeastern coast of Milos Island. The sample was collected from a locality (Paliochora coast)

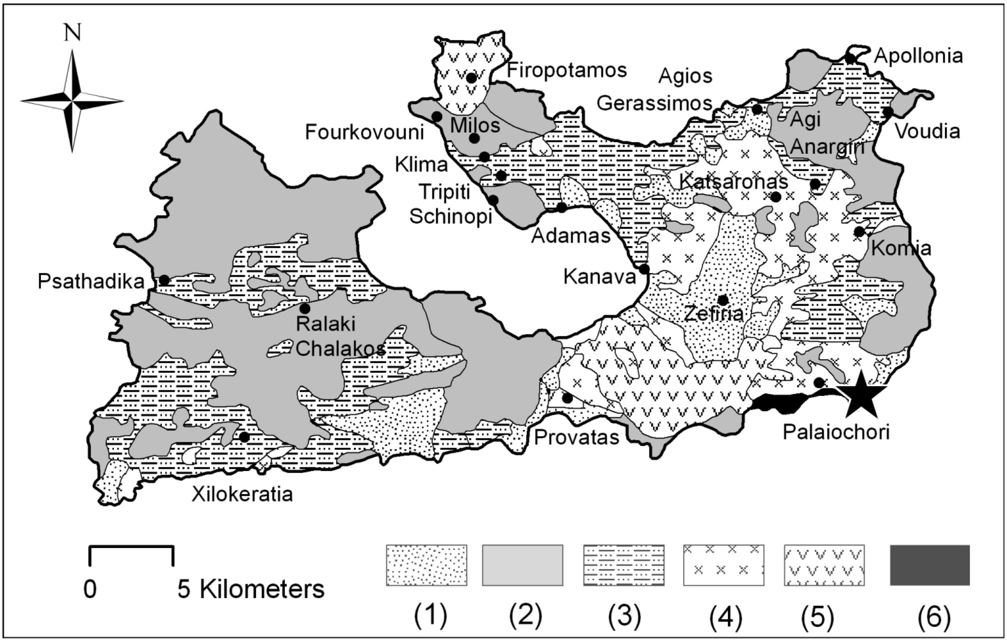


**Fig. 2.** Simplified geological map of the Milos island (modified after Fytikas 1989). (1) Upper Miocene-Pleistocene sediments, (2) domes and lava flows, (3) pyroclastic series, (4) phreatic activity products, (5) rhyolitic complexes, (6) metamorphic basement. Sample location is marked with a black star

close to the contact between the metamorphic PQU and the overlying volcanic rocks. From this locality about 10 kg of suitable material was taken and processed for zircon using conventional techniques, specifically crushing with a disk mill, sieving, separation by Rogers table, heavy liquids, and Frantz magnetic separator (Bernet & Garver 2005). Zircon age mounts for fission-track analyses were prepared following the techniques outlined by Bernet & Garver (2005). Zircons were mounted in Teflon® discs and then polished to expose internal zircon surfaces. The mounted zircons were etched in a KOH:NaOH eutectic melt at 228°C for 25 hr.

Thermal neutron irradiation was performed in the thermal neutron facility at the Oregon State University nuclear reactor, and unknowns were irradiated along with CN glasses and well-calibrated age standards (Fish Canyon Tuff, Buluk Tuff, and Peach Springs Tuff). All samples were dated using the external detector method with a zeta calibration (Naeser 1976; Gleadow 1981; Hurford 1990). The detector mica was etched for 900 s in 49% HF at 20–22°C. All samples were counted at 1250x using a dry 100x objective (10x oculars and 1.25x tube factor) on an Olympus BMAX 60 microscope fitted with an automated stage and a digitizing tablet. Fission-track ages ($\pm 1\sigma$) were calculated using the computer program and equations in Brandon & Vance (1992). Ages were determined for the sample using the zeta method: $\zeta$ values (Hurford & Green 1983). Zeta factor was determined by multiple analyses of zircon standards, using Buluk Member Tuff, Peach Springs Tuff (PST) and Fish Canyon Tuff zircons (see Hurford 1990 for methodology). Errors were calculated using the "conventional analysis" given by Green (1981).

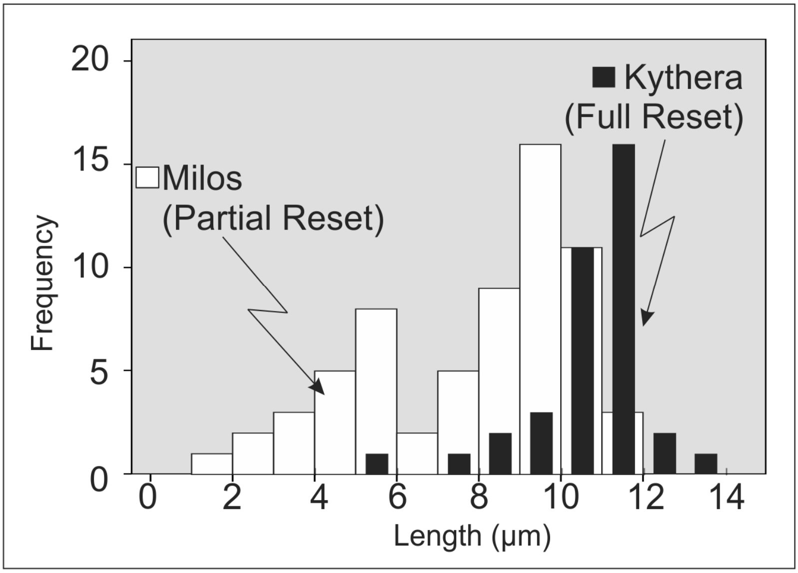


Fig. 3. Length distributions of horizon-tal confined fission-tracks in zircon from Kythera and Milos. Histograms showing the fission-track length distribution of 37 confined tracks from a full reset sample from Kythera (black bars) and the fission-track length distribution of 65 confined tracks from a partial reset sample from Milos (white bars)

Track length measurements are not routine in zircon because track revelation is complicated by the etch response of zircons with different levels of radiation damage (i.e see Bernet & Garver 2005 and Tagami 2005- for discussions). Because this is not a routine measurement for tracks in zircon, we briefly outline this approach. We are mainly interested in whether samples have an abundance of short tracks as would be predicted in a sample that has experienced significant partial annealing. Alternately the sample might have only fully annealed zircons, but the timing of individual grain closure may vary: in this case we would predict that all grains have long tracks with little evidence of shortening and track length reduction. Because we attempt to address this rather simple difference, our method requires no special etch technique and we measure track lengths on samples counted and prepared for normal age analysis. Technically, our measurements of track lengths were restricted to horizontal confined tracks.

We measured track lengths only on grains that were well etched, which means that etch pits generally fell in a range between 0.5 and 1.5 μm. This approach means that we avoid the problem of measuring tracks in under-etched samples that may have only partly revealed confined tracks. We made the measurements using diode-bearing cursor on a digitizing tablet interfaced through a drawing tube on a BX60 Olympus microscope at 1250x (100x dry objective, 1.25 tube factor, and 10x oculars). The length measurements were calibrated by repeated measurements of a calibrated graticule (using FTStage 4.0 software developed by T. Dumitru). Samples from both Kythera and Milos were etched for 24 hr prior to measuring confined fission-tracks and track densities for age determination. We measured horizontal confined tracks in all grains possible in the Teflon mount, including those few grains that were actually used for age determination. Typically these grain mounts have several hundred grains available for this sort of analysis: horizontal confined tracks are uncommon in zircon, certainly in comparison to apatite. Length measurements of horizontal confined fission-tracks from the Fish Canyon Tuff standard were measured for comparison with the Kythera and Milos results (Fig. 3 and Table 1). Results and locations are shown in Figures 1, 2 and 3. These zircons, originally detrital grains, have a typical range of uranium content from 100–1100 ppm, and a mean of 334 ppm (see Garver & Kamp 2002; Bernet & Garver 2005).

Table 1. *Average length measurements of horizontal confined fission-tracks in zircon from the fast-cooled Fish Canyon Tuff age standards and from Milos and Kythera samples*

| Irradiation | Etch Time (hours) | Average Track-Length (μm) |
|---|---|---|
| STD-U30Z-18 | 26 | 10.33 |
| STD-U21Z-2 | 26 | 10.46 |
| STD-U26Z-2 | 27 | 10.53 |
| STD-U26Z-29 | 27 | 10.32 |
| STD-U19Z-2 | 28 | 10.57 |
| MILOS-M1 | 24 | 7.89 |
| KYTHERA-T13C | 24 | 10.69 |

*STD stands for Fish Canyon Tuff Standard

## Interpretation

Here we explore the implications of these data in two separate sections. The first section explores the implications and significance of the resetting of low-retentive zircon and the thermal implications of this result. The second section explores the tectonic implications of this discovery of the cooling ages from Milos. This small isolated island may provide key insight into how slab roll back has affected a large area of rock in the Hellenic fore-arc.

### *Zircon resetting*

The majority of zircon fission track ages from Milos Island cluster around ~16 Ma and there is a secondary population at ~24 Ma. The young population of grain ages has a clear geological significance in that this is the time of cooling of low retentive zircons as they pass through effective closure temperature for these grains. The significance of the second population at ~24 Ma, however, is not straightforward. This second population may correspond to: 1) an earlier cooling age of more retentive zircon; 2) zircons that are partly reset. Note that the difference between these two possibilities is profound because in the former case the age has geological significance, but in the latter case it is geologically meaningless.

A key issue is where the second population of grain ages has geological significance. It may reflect passage through the zircon partial annealing zone (ZPAZ) for more retentive zircon at ~24 Ma and this could be part of a progressive exhumation path with a starting point at ~31 Ma as defined by a K-Ar age on white mica (350–400°C). This differential resetting can be explained by the existence of high-retentive and low-retentive zircons, if the high-retentive zircons closed to annealing (at higher temperature ~280–300°C) at ~24.3±1.3 Ma, while the less-retentive zircons closed to annealing (at a lower temperature range of ~180–220°C) at ~15.9±1.0 Ma. A problem here, however, is that we are uncertain of the exact temperature bounds of this potential resetting. The range of ~6–10 Ma of thermal resetting of the zircons would seem to imply a prolonged residence time in ZPAZ conditions for retentive zircon (~300°C). The preservation of blueschist minerals in the Milos rocks suggests rapid exhumation from high *P/T* conditions into the ZPAZ (i.e. Liakopoulos et al. 1991). The peak metamorphic mineral assemblage in these rocks requires that they were at or above ~400°C prior to 16 Ma, and there-fore it is less likely that old (pre-24 Ma) fission-tracks have been preserved in even the high-retentive zircons (HRZ), rather than the accumulation of newly formed tracks that were then partly annealed during the interval ~24–16 Ma.

We infer the PQU rocks of Kythera and the adjacent southeastern Peloponnese experienced a longer duration at temperatures above those required for total zircon FT annealing, because all of the zircons, including highly retentive grains, are fully annealed (Marsellos et al. 2010). There are two possibilities for this observation: 1) the suite of zircon grains had few if any high-retentive zircons; or 2) they experienced longer exposure to ideal annealing conditions (higher temperatures or a longer duration at peak temperatures). We suspect that these rocks crossed the ZPAZ (Fig. 4) in a short time so that few or no short tracks (Fig. 3) accumulated by partial annealing. In contrast, we suspect that zircons from Milos, western Crete, and the central Peloponnese (Figs. 4, 5) returned slowly through the ZPAZ toward the surface, with full annealing only of

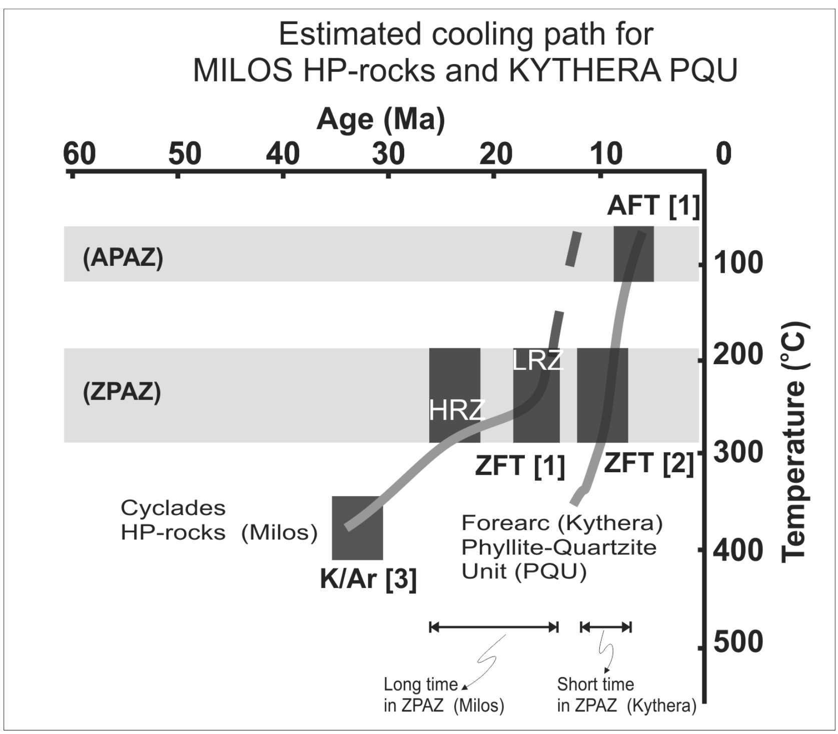


Fig. 4. Temperature-time (T–t) diagram for Milos and Kythera HP-rocks (western part of Hellenic Arc) combining: [1] ZFT (zircon fission-track) data of this study from Milos, [2] ZFT data from Kythera PQU (Marsellos & Kidd 2008; Marsellos et al. 2010), and [3] K-Ar data (white mica) from Milos HP-rocks of Kyriakopoulos (1998). Black boxes and thick grey line are PQU metamorphics of "lower plate" of detachment. (ZPAZ) zircon partial annealing zone; (AFT) apatite fission-track; (APAZ) apatite partial annealing zone; (HRZ) high-retentive zircons; (LRZ) low-retentive zircons

the least retentive zircons, and with shortening by partial annealing of most fission-tracks in more-retentive zircons. We hypothesize that the track lengths provide a clue as to the viability of either option. In the case of the long-annealed grains with low dispersion we would expect a narrow distribution of long track lengths because all cooled at the same time and spent little time in the ZPAZ. On the other hand, samples with significant annealing times in the ZPAZ will have a large proportion of partially annealed fission tracks, and therefore a track-length distribution that shows a significant number of short tracks.

Horizontal confined track lengths based on a suitable number of measurements have been produced from the samples from Kythera and Milos. A mean track length of 10.69 µm (Fig. 3) with a standard deviation of 1.4 µm was obtained from 37 measurements from a Kythera fully reset sample. A mean track length of 7.89 µm with a standard deviation of 2.6 µm was obtained from 65 measurements from the Milos partially reset sample. This short mean track length, as compared to 10.69 µm for full reset sample of Kythera zircons, indicates that the Milos sample did experience annealing and track shortening of some tracks.

A key question is whether igneous activity affected the FT system of zircons on Milos. It is clear that the sample from Milos has a young population of grain ages at ~15 Ma, and that the track length distribution would seem to suggest that the older grains are partly reset and therefore probably not meaningful. Nonetheless, the young population of grain ages is robust and older than that recognized farther to the west in the fore-arc at Kythera. We think that neither Recent volcanism nor Cycladic Miocene plutonism has affected the fission-track system of the zircon grains from the exposed *HP*-rocks of Milos, because volcanism occurred in this part of the volcanic arc only from the Early Pliocene to Holocene (Fytikas et al. 1984). Likewise there are no plutonic rocks or evidence of contact metamor-phism exposed on the surface or deeper (see

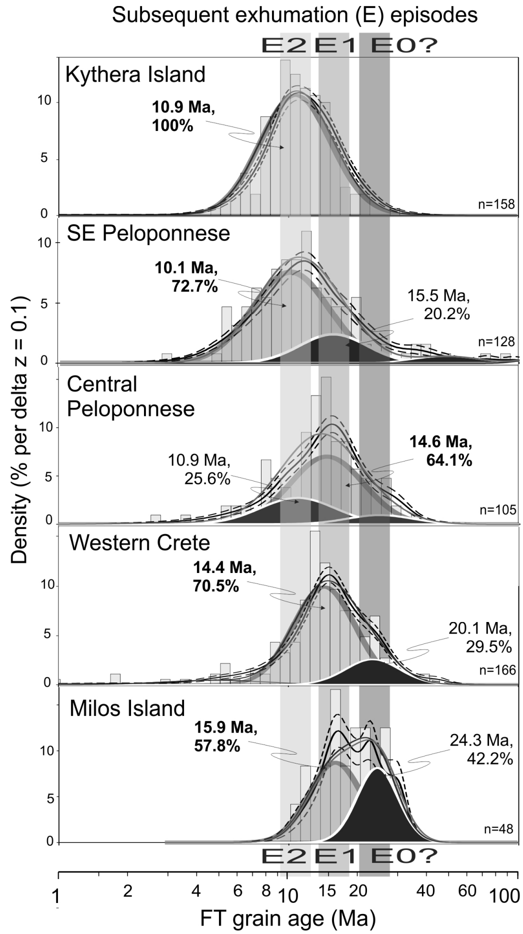


Fig. 5. Results from binomial peak-fitting represented through the probability density plots (Brandon 1996). On these plots, the individual histogram bars represent the grain-age components. Thin solid lines represent successive peaks (population ages) identified in the age distributions. Results for 1st and 2nd populations are discussed in text. Zircon fission-track (ZFT) population grain ages are from a sample from the HP-rocks of Milos (this study), and from the PQU exposed rocks from Kythera (9 samples) (Marsellos et al. 2010), western Crete (6 samples) (Marsellos et al. 2010), central Peloponnese (7 samples) (Marsellos et al. 2010), southeastern Peloponnese (9 samples) (Marsellos et al. 2010). E0, E1, E2 stand for the successive exhumation episodes

borehole data from Liakopoulos et al. 1991), and none of the zircon grains from our sample shows any Pliocene-Pleistocene FT ages, which would be expected if these young volcanics had affected the FT system. The zircon fission-track dating shows a total range for the zircon grain ages from ~11 Ma to 30 Ma implying that zircon grains from the exposed area of metamorphic basement of Milos have not been affected by the Late Pliocene to Recent magmatic activity.

The Milos Island sample provides important insights into the effects of extensive thermal resetting of detrital zircon fission-tracks. This sample shows an age distribution that fails the $\chi^2$ test, with widespread resetting at ~16 Ma, suggesting differential annealing (Fig. 5). The general impression from these fission-track cooling ages is that the zircon grains reached the ZPAZ at ~24 Ma, with the HRZ grains starting to accumulate fission-tracks from this time, and at ~16 Ma the least retentive LRZ grains became cool enough to accumulate fission-tracks. This sample and the thermal history are instructive because it shows that annealing from relatively high temperatures produces a wide range of grain ages caused by heterogeneous annealing of grains having a wide range of radiation damage.

Confined track lengths from zircons have been shown to be a valuable tool in the reconstruction of the thermal history of metamorphic rocks (Gleadow et al. 1983, 1986a,b; Corrigan 1991; Yamada et al. 1995; Yamada et al. 2003; Tagami 2005). The histograms of the horizontal confined fission-tracks length (FTL) measurements from Kythera and from Milos zircons clearly represent two different and distinct thermal histories (Fig. 3). The Milos FTL distribution shows two distinct FTL populations, while the Kythera FTL distribution shows a unimodal distribution. Kythera FTL distribution implies a homogeneous annealing and apparently full resetting of the (previous) fission-tracks in these detrital zircons. In contrast, the Milos FTL distribution shows a bimodal distribution that most likely represents a partially reset sample. The bimodal distribution of the Milos FTL shows that the secondary ZFT population age of 24 Ma might be meaningless. The resulting bimodal distribution, perhaps, is ascribed to the wide range of radiation damage between the HRZ and LRZ that permits partial annealing. As a result part of the zircon grain population will be fully reset, representing the true ZFT age, and part of the grain population will be a pseudo ZFT age. The partially reset zircons that exist in Peloponnese, Crete and Milos, compared to Kythera fully reset zircons, implies a pattern where partially reset samples occur in the E1 region and disappear towards the E2 region (Fig. 1).

*Tectonic implications.*

The zircon FT grain age analysis from Milos *HP*-rocks is similar to those from the exposed PQU rocks of central-south Peloponnese and central-western Crete. Zircon FT population ages from Kythera and southeastern Peloponnese are consistently younger than 13 Ma. In contrast, western Crete PQU, central Peloponnese PQU and Milos *HP*-rocks have ZFT population ages (15–24 Ma) older than those on Kythera (Marsellos et al. 2010). This overall population age contrast shows that Kythera Strait is the youngest exhumed part (Figs. 1, 5) of the *HP/LT* metamorphic rocks of the Hellenic fore-arc ridge and that the ages imply an exhumation that migrated from the Peloponnese, from Crete, and from Milos toward the area of the Kythera Strait.

The Milos ductile detachment occurred before ~16 Ma and detachments in Crete and central Peloponnese also operated before this time. The two successive population ages of ~16 Ma and ~24 Ma are comparable with those of Crete and Peloponnese (Marsellos et al. 2010), which perhaps link the Milos detachment with the Cretan and central Peloponnese detachments. The exposed mylonitized metamorphic basement on Milos represents an older mylonitic front now structurally above the younger mylonitic front of Kythera. The continuing migration of the

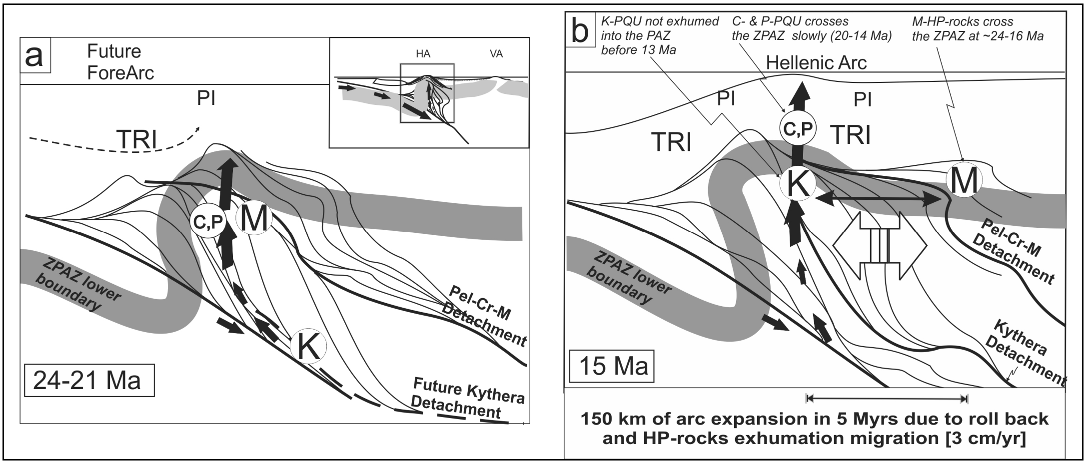


Fig. 6. Exhumation of *HP*-rocks along the cross sec-tion of Kythera–Milos: a) During the earlier activity of the detachment and associated exhumation of Cretan, central Peloponnese and Milos *HP*-rocks (Pel–Cr–M); b) Kythera and southeastern Pelopon-nese PQU rocks (K) were situated at a deeper crustal level after the first (arc-normal extension) stage compared to rocks of Milos *HP*-rocks (M), central Peloponnese PQU and Crete PQU (C, P) which reached the zircon fission-track partial annealing zone (ZPAZ). Localized along-arc stretching caused Kythera and Southeastern Peloponnese rocks to exhume quickly through the zircon fission-track partial annealing zone (ZPAZ) between ~13–9 Ma. (PI) Pindos carbonate unit; (TRI) Tripoli carbonate unit; (HA) Hellenic arc; (VA) volcanic arc

downgoing slab shifted the development of a fore-arc from an older location (current volcanic arc) to the present one (Peloponnese-Cretan ridge). Successive detachments (Fig. 6) associated with at least two exhumation episodes (Fig. 1, 5) of *HP/LT* rocks were active during the interval ~24–10 Ma. Peloponnese, Milos, and Crete show an exhumation activity at ~24–16 Ma, while southeastern Peloponnese and Kythera shows 9–13 Ma. These episodes of rapid exhumation and extension might be a result of variations in roll-back rate, or they might be due to spatially heterogeneous portioning of the extensional strain resulting from a more-or-less steady rate of slab roll-back. Between those two episodes E1-E2 a roll-back of the African plate over ~ 4–6 Myrs may have caused substantial arc-expansion and fore-arc migration for at least 150 km south-westwards at a rate of 37–25 mm/yr (Fig. 7).

## Conclusion

Zircon fission-track age data from the metamorphic rocks of the Hellenic fore-arc and volcanic arc in Milos show at least two successive exhumation episodes of *HP*-rocks. The ZFT age of Milos *HP*-rocks shows strong resetting with a population age at ~16 Ma, recording a late Middle-Miocene cooling episode. The site of exhumation of *HP*-rocks migrated across strike from the future location of the present volcanic arc (Milos) to the current fore-arc (in Kythera) during the interval 15.9±1.0 and 10.9±0.4 Ma. These data provides an estimate of rate and amount of roll-back of the African plate over ~ 4–6 Myrs which caused arc-expansion and fore-arc migration for at least 150 km southwestwards at a rate of 37–25 mm/yr, a rate which is similar to the overall convergence rate today.

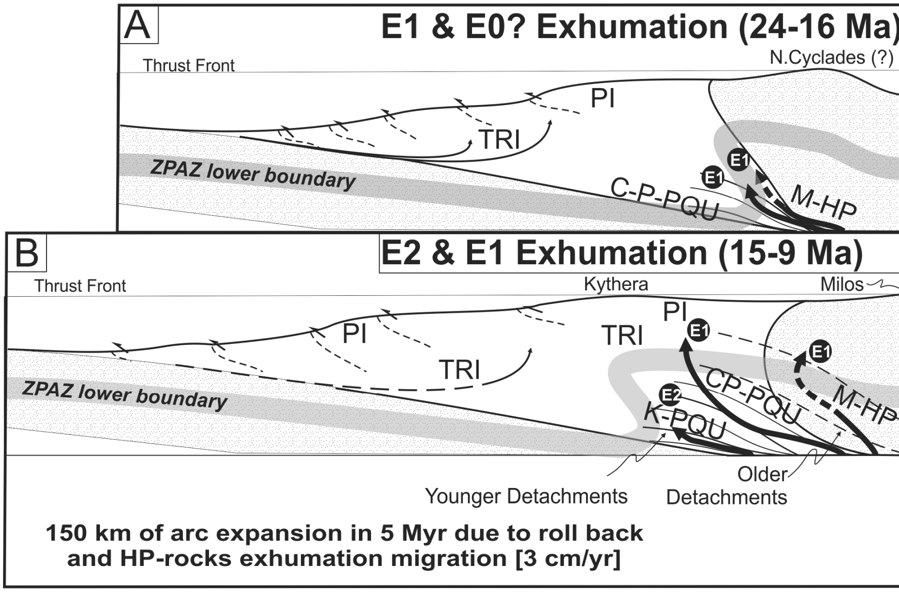


**Fig. 7.** A simplified model of the successive (E0, E1, E2) Miocene detachments and associated exhumation of *HP*-metamorphic PQU rocks of Kythera (K-PQU), Central Peloponnese–Crete (CP-PQU), and *HP*-rocks of Milos (M-HP). (PI) Pindos carbonate unit; (TRI) Tripoli carbonate unit; (ZPAZ) zircon partial annealing zone

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