Bulletin of the Geological Society of Greece

Vol. 43, 2010

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https://doi.org/10.12681/bgsg.11183

Δελτίο της Ελληνικής Γεωλογικής Εταιρίας, 2010
Πρακτικά 12ου Διεθνούς Συνεδρίου
Πάτρα, Μάιος 2010

Bulletin of the Geological Society of Greece, 2010
Proceedings of the 12th International Congress
Patras, May, 2010

EXHUMATION OF THE HELLENIC ACCRETIONARY PRISM – EVIDENCE FROM FISSION-TRACK THERMOCHRONOLOGY

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Abstract

Below the Potamos extensional detachment fault exposed in northern Kythera, the phyllite-quartzite unit (PQU) shows very consistent zircon FT cooling ages of c.11 Ma reflecting the time just after the rapid exhumation through the brittle-ductile transition. In contrast, a wide range of Mesozoic and some Paleozoic zircon FT cooling ages from Eocene-Oligocene Tripolis and Pindos flysch sandstones from above the detachment reflect sedimentary source ages. Early Miocene apatite fission-track cooling ages characterize the flysch sandstones, and show that early Miocene exhumation affected rocks above the detachment.

The thermotectonic evolution of the flysch of Tripolis and Pindos units within the rocks above the Potamos detachment on Kythera is reconstructed using zircon and apatite fission-track (FT) thermochronology. The apatite FT data provide evidence for a burial depth of at least 6km for the samples, which were reset. Burial was not deeper than 11km, since the zircon fission-track system in the same rocks was not reset. The exposed rocks of Tripolis and Pindos flysch on Kythera represent part of an accretionary wedge with a burial shortly after deposition in or near the subduction trench, and a cooling history due to exhumation of the flysch in the early Miocene. The subsequent Mid-Late Miocene exhumation of the PQU unit follows from beneath the (mostly carbonate) Tripolis and Pindos sedimentary rocks.

Key words: *Tripolis and Pindos units flysch, accretionary prism, fission-track thermochronology, Potamos detachment fault, Hellenic forearc.*

1. Introduction

Extensional detachment faulting under both ductile and brittle conditions has been shown to be an important mechanism to bring high-pressure/low-temperature metamorphic rocks to the surface (Platt, 1987). This is common in subduction systems where they experience rollback and slab retreat, such as the Hellenic subduction zone where exhumation of HP-rocks has been confirmed by thermochronology to have been active through detachment faulting from Early to Late Miocene (Thomson et al., 1999; Ring et al., 2001; Brix et al., 2002; Marsellos, 2008; Marsellos et al., 2010). In this setting, some accretionary wedge rocks now in the upper plate of the detachment did not follow the same subducting trajectory as the exhumed HP-rocks. Thermochronological data show that flysch

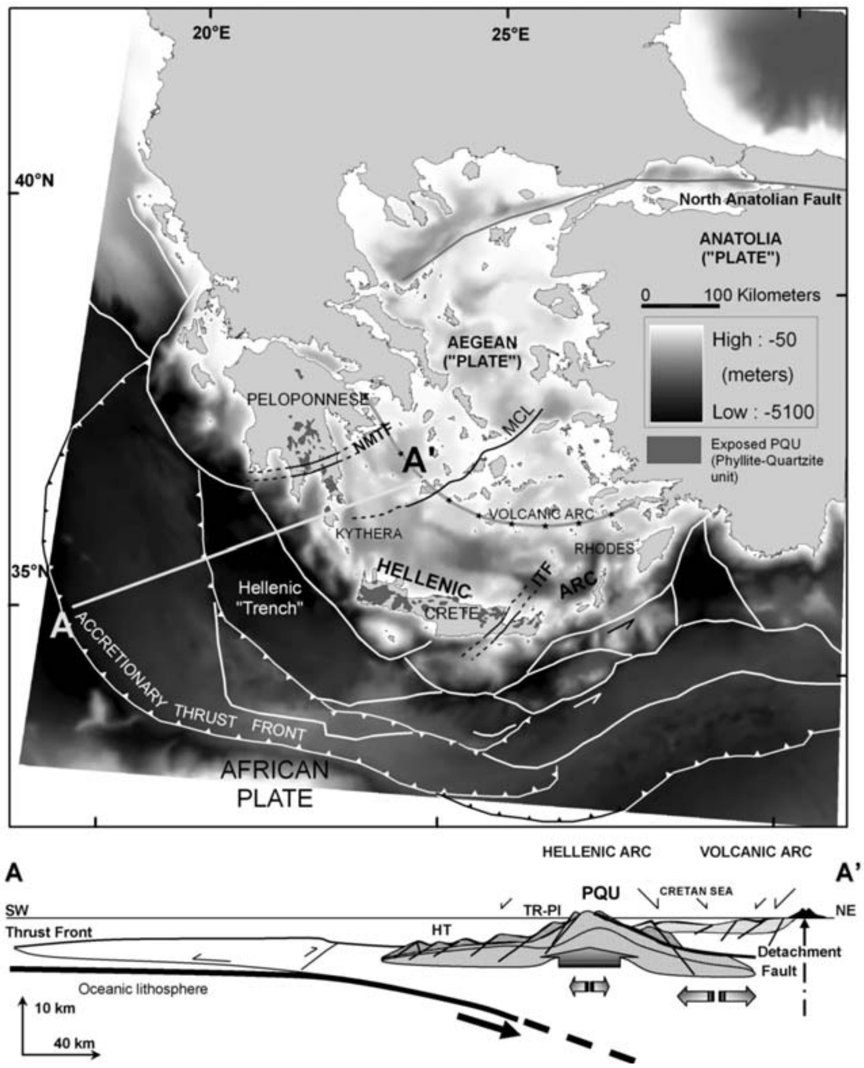

Fig. 1: Tectonic setting of the Hellenic Arc; a representative cross-section line A-A´ shown through Kythera strait. See text for discussion and Marsellos et al., (2010) for reference sources. HT - Hellenic "Trench", TR-PI - Tripolis-Pindos nappe units above extensional detachment; PQU - Phyllite-Quartzite Unit below extensional detachment; NMTF - North Mani Transverse Fault; ITF - Ierapetra Transverse Fault; MCL - Mid-Cycladic Lineament.

turbidites in the Tripolis and Pindos units of Kythera did not become deeply subducted with the HP rocks, but instead they escaped the subduction trajectory in the interval 23 to 15 Ma (Marsellos et al., 2010).

In this paper we attempt to reconstruct the thermotectonic evolution of the flysch of Tripolis and Pindos units within the rocks above the Potamos detachment on Kythera (Marsellos, 2006; Marsellos & Kidd, 2006; 2008) using apatite (Marsellos et al., 2010) and zircon fission-track (FT) thermochronology. We use the thermochronological data to constrain the deformation paths of the Neogene Hellenic orogenic wedge, and discuss possible implications of the rollback and slab retreat which affect the exhumation of HP-rocks and the evolution of the Hellenic orogenic wedge.

2. Tectonic and geological setting

The Hellenic forearc ridge contains substantial exposures of the accretionary wedge of the subduction system uplifted and exposed above sea level (Fig. 1). The pre-Neogene thrust nappes exposed in the Hellenic forearc ridge overlie the young metamorphosed basement of HP rocks. The forearc ridge became emergent in connection with rapid exhumation and uplift of the underlying HP-rocks beginning in Early Miocene in Crete (Fassoulas et al., 1994; Jolivet et al., 1996; Thomson et al., 1999, Brix et al., 2002), in central Peloponnese (Marsellos et al., 2010), and since Middle-Late Miocene in Kythera (Marsellos & Kidd, 2008, Marsellos et al., 2010).

The rocks of the pre-Neogene nappes of the External Hellenides that occur on Kythera Island resulted from northward subduction and late Eocene collision between Apulia and the Pelagonian microcontinent (Mountrakis 1986; Robertson et al., 1991; Doutsos et al., 1993). There are three lithotectonic units exposed in Kythera. The structurally lower metamorphic unit mainly consists of phyllite and quartzites, some mylonitic, with uncommon intercalations of marbles, and blueschists (Lekkas, 1986; Gerolymatos, 1994; Marsellos, 2006), as well as rare, small occurrences of metagranite and gneiss. The protolith of the metamorphic Phyllite-Quartzite unit has been suggested to have formed as a mid-Carboniferous to Triassic rift clastic sequence (Krahl et al. 1983) resulting from the opening of a southern branch of the Neotethyan ocean (Pe-Piper 1982; Seidel et al., 1982; Robertson and Dixon, 1984). The Phyllite-Quartzite unit (PQU) formed from a detrital sequence of Upper Carboniferous to Mid Triassic age (Krahl et al., 1983) with some basement units exposed in eastern Crete and Kithira that provided early Mesozoic, some Paleozoic, and few Precambrian ages (Romano et al., 2004; Xypolias et al., 2006; Zulauf et al., 2007). The Pindos and Tripolis units form the overlying unmetamorphosed lithotectonic units.

The contact of the flysch of the Tripolis and Pindos units with the underlying carbonate rocks of the same units in Kythera has been observed to be mostly tectonic (Theodoropoulos, 1973; Danamos, 1992). The depositional age of Tripolis flysch is mostly Late Eocene-Oligocene, while Pindos flysch is Paleocene (Danamos, 1992). There are a variety of observations concerning whether the flysch in Kythera belongs only to Tripolis unit (Petrocheilos, 1966) or/and to Pindos unit (Theodoropoulos, 1973; Danamos, 1992) or to both of them (Christodoulou, 1967). Apatite fission-track data (Marsellos et al., 2010) show that the flysch rocks from Pindos and Tripolis units left the apatite partial annealing zone (APAZ; c. 120^{o} C) and exhumed at the same time at around 15 Ma. In this paper, we investigate if those rocks approached the zircon partial annealing zone (ZPAZ; c. 240^{o} C ± 50^{o} C) during their subduction or whether they escaped the subduction trajectory before reaching this zone.

2.1 Kythera Detachment Faults

On Kythera Island, a major extensional detachment fault that was active during Middle-Late Miocene (Marsellos, 2006; Marsellos & Kidd, 2006; 2008) separates the metamorphic PQU and the overlying unmetamorphosed units, defining the surface of the domed structure of the metamorphic core complex Zircon fission-track cooling ages indicate that there were two detachment events, one prior to 15 Ma and another starting at ~14 Ma (Marsellos et al., 2010). The first detachment was characterized by arc-normal extension, while the younger ductile and ductile-brittle transitional detachment overprinted earlier structures with arc-parallel extension. Slab retreat and trench rollback, which must have caused the expansion of the Hellenic forearc ridge, may have resulted in the series of detachment faulting and associated sequential exhumation of PQU rocks under arc-normal and subsequent arc-parallel extension (Marsellos et al., 2010).

The Tripolis unit underwent thrust imbrication associated with collision and experienced negligible, very low-pressure and low-temperature metamorphism (average metamorphic temperature of about 260° C according to Rahl and others, 2005). Tripolis flysch was underthrust beneath the Pindos imbricated folded carbonates in the same thrust-imbrication event. These thrust events must predate activity on the extensional detachment now separating the Tripolis and Pindos units from the metamorphic PQU unit.

3. Zircon Fission-Track Ages

3.1 Method

Zircon fission-track data have been obtained from two detrital zircon samples from sandstones above the detachment. The samples are from the flysch of Tripolis unit and Pindos unit in Kythera. Samples were collected from localities close to and farther from the detachment contact between the metamorphic PQU and the overlying unmetamorphosed units. Results and locations are shown in Figure 2 and 3. These zircons, originally detrital grains in sandstones, have a typical range of uranium from 100-300 ppm.

At each locality about 7-10 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, Frantz magnetic separator, and final hand-picking from some samples that had pyrite (Naeser, 1976).

Zircon age mounts for fission track analyses were prepared following the techniques outlined by Bernet and Garver (2005). Zircons were mounted in Teflon discs and then polished to expose internal zircon surfaces. The mounted zircons were incrementally etched in a KOH:NaOH eutectic melt at 228° C, between 4-10 hours, until the majority of grains were fully etched. Additionally, multiple mounts from many samples were etched for different times, the total etch time ranging from 9 hr to 24 hr depending on the sample.

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) (Hurford, 1990). All samples were dated using the external detector method (Naeser, 1976; Gleadow, 1981). The detector mica was etched for 15 min in 49% HF at room temperature. 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. All ages with χ^2>5% are reported as pooled ages. Fission track ages (±1σ) were determined using the Zeta method, and ages were calculated using the computer program and equations in Brandon and Vance (1992). Ages were determined for each sample using the zeta method: ζ values (Hurford and Green, 1983) are listed in table 1. Zeta factor was determined by multiple analyses of zircon standards, using Buluk Member Tuff, Peach Springs Tuff (PST) and Fish Canyon Tuff zircons (Hurford, 1990). Errors were calculated using the "conventional analysis" given by Green (1981). The χ^2 analysis (Galbraith, 1981; Green, 1981) was employed to test the assumption that all analyzed grains are derived from a single population and have a common age with only Poissonian variation.

3.2 Results

Fission track analyses of zircons from rocks above the detachment reveal a significant succession of thermal episodes. Parameters for best-ft peaks, generated from Binomfit program (Brandon, 1996)

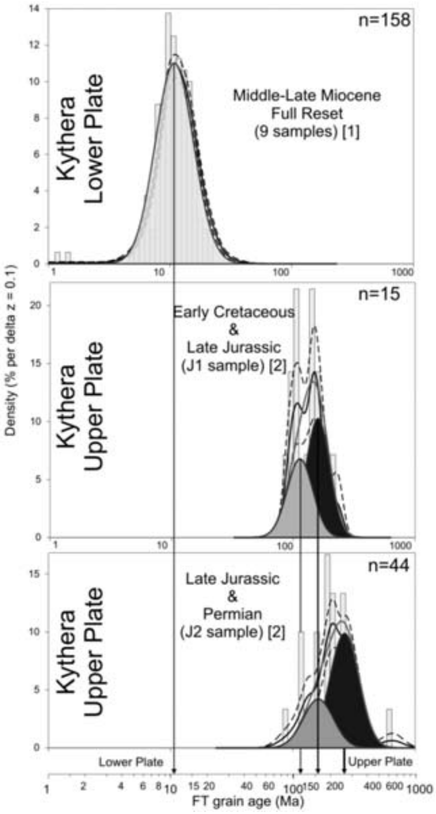

Fig. 2: Results from binomial peak-fitting (Brandon, 1996) represented through the probability density plots. On these plots, the individual histogram bars represent the grain-age components. Thin solid lines represent successive populations identified in the age distributions. Results for first and second population are discussed in text. Zircon fission-track (ZFT) grain ages are from 9 samples from the exposed PQU rocks (lower plate) of [1] Marsellos et al. (2010), and 2 samples from the upper plate ([2] this study).

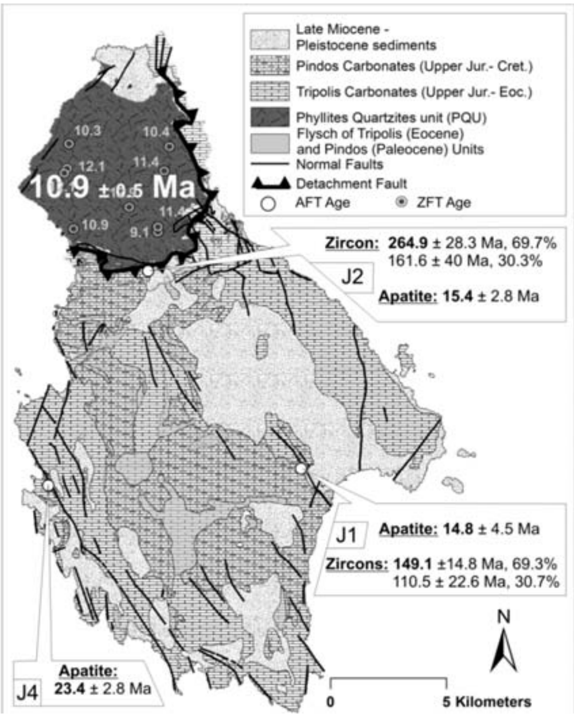

Fig. 3: Sample locations of zircon fission-track (ZFT) and apatite fission-track (AFT) cooling ages from above the detachment (upper plate, Tripolis/Pindos flysch) on Kythera Island (western part of Hellenic forearc). ZFT data from upper plate are reported in this study, ZFT from below the detachment (lower plate, PQ unit) and AFT from upper plate are data first reported in Marsellos et al. (2010). Simplified geological map of Kythera after Petrocheilos (1966) and our observations.

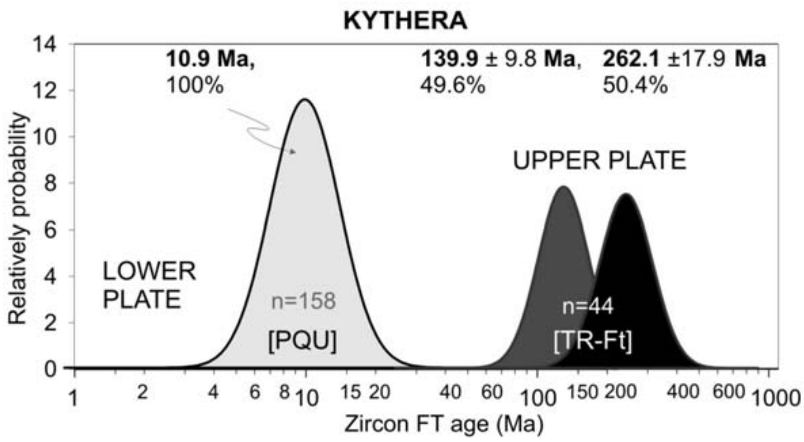

Fig. 4: Results from binomial peak-fitting from Binomfit program (Brandon, 1996) represented through the probability density plots. ZFT grain ages are from nine samples from the exposed PQU rocks (lower plate) from Marsellos et al., (2010), and 2 samples (data of this research) from the flysch of Tripolis and Pindos units (upper plate).

shows for the sample J2 from Pindos flysch a primary population of 149.1 ± 14.8 Ma (69.3% fraction of grains) and a secondary population of 110.5 ± 22.6 Ma (30.7%). Sample J1 from Tripolis flysch shows a primary population of 264.9 ± 28.3 Ma (69.7%) and a secondary population of 161.6 ± 40 Ma (30.3%). Application of Binomfit program to both the flysch samples from above the detachment in Kythera (Fig. 4) gives two distinct population ages of 139.9 ± 9.8 Ma (49.6%) and 262.1 ± 17.9 Ma (50.4%).

4. Discussion

The stratigraphic transition upwards from limestone to flysch is observed on Kythera in the Tripolis unit and Pindos unit (Danamos, 1992; Petrocheilos, 1966) and occurs about the mid-Late Eocene boundary (Petrocheilos, 1966; Fluery, 1980; Thiebault, 1982), which implies proximity to the subduction trench at this time (~37-34 Ma). The Tripolis flysch and underlying carbonates underwent thrust-imbrication associated with collision and experienced negligible, very low-pressure and low-temperature metamorphism (average metamorphic temperature of about 260^{o}C according to Rahl and others, 2005). Tripolis flysch was underthrust beneath the Pindos imbricated folded carbonates in the same thrust-imbrication event. In Kythera (Fig. 3), apatites from the Tripolis flysch (sandstone) cooled through the apatite PAZ at ~15 Ma with evidence of partial resetting at ~23.4 Ma (Marsellos, 2008; Marsellos et al., 2010). Because the Tripolis flysch has not experienced high-pressure metamorphism, then most likely the Tripolis unit escaped the subduction trajectory in the interval 23-15 Ma.

The visual contrast of zircon fission-tracks and associated ages from the detrital grains between the upper plate and lower plate of the detachment in Kythera is very prominent (Fig. 4, 5). Ductile structures are also present in the PQU associated with the exhumation of those HP-rocks (Xypolias & Koukouvelas, 2001; Xypolias & Kokkalas, 2001; Xypolias et al., 2008; Marsellos, 2006; Marsellos & Kidd, 2008; Xypolias et al., 2008; Marsellos et al, 2010) but are missing from the upper plate. The cooling event (9-13 Ma) associated with the detachment activity has been recorded in the fully reset zircons in the Kythera PQU while rocks in the upper plate did not cross the ZPAZ. These data are not compatible with a hypothesis of an overthrusting event placing Tripolis unit above the PQU metamorphics.

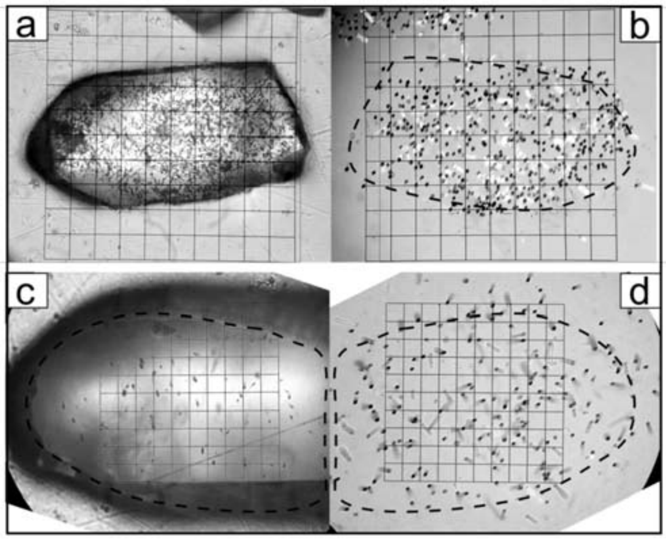

Fig. 5: Photomicrograph of etched zircon grains from (a) upper plate and (c) lower plate under plane transmitted light (100x objective, 1250x total magnification); (b, d) mica print of the zircon after irradiation showing the induced fission tracks in the mica.

Apatite fission track (AFT) ages from the upper plate Tripolis and Pindos flysch older than those from the lower plate PQU also rule this out. AFT ages of ~7 Ma from rocks in the sub-detachment PQU unit of Kythera and the southeastern Peloponnese (Marsellos et al., 2010) represent the time when the Kythera PQU left the apatite PAZ (by exhumation and related cooling) and were tectonically juxtaposed with the Tripolis and Pindos carbonate units. The sub-detachment PQU zircons show cooling ages starting at 12.9 Ma with a peak at 10.9 Ma, while apatites from the rocks above the detachment show cooling below the apatite PAZ at 23.4 Ma and at ca. 15 Ma. The HP-LT rocks below the detachment in Kythera were rapidly exhumed in the interval 13-7 Ma, and while this may have caused local recrystallization in some limestones adjacent to the detachment, our data show that there was no major thermal perturbation caused in the upper plate rocks of the Tripolis unit by this event.

Average cooling rates using both zircon and apatite FT data from Kythera lower plate have been estimated (Marsellos et al., 2010) over the temperature intervals between ZFT and AFT closure, and exhumation to the present surface. The rocks from Kythera (Fig. 6) cooled from ZFT to AFT closure (c. 240^o C and 120^o C) between ~11 Ma and ~7 Ma, an interval whose range from the FT ages is 1-5.8 Ma (including the ZFT errors), which gives a minimum average cooling rate of 30-50^o C/Myr Using apatite FT to the present surface, the rocks in Kythera cooled from 120^o C to surface temperature in a maximum duration of 5-9 Myr giving a minimum average cooling rate of 10^o C /Myr and a wide potential range up to 30^o C/Myr. The time these samples first reached near surface temperatures is uncertain, but cooling ages suggest that there has been overall slower exhumation after ~7 Ma for the PQU on Kythera and southern Peloponnese. This later interval of slower exhumation includes activity on normal faults parallel with the Hellenic Arc some of which cut the detachment and now locally separate the PQU from the unmetamorphosed Tripolis and Pindos units.

Exhumation and cooling, required by the FT ages reported here, can occur either by erosion or by tectonic extension (or a combination of these). Given the temperature constraints on the zircon FT system, with the partial annealing zone maximum temperature not above 280^o C, the cooling observed must be largely or entirely from events when the rocks were in the continental crust, and do not, for the metamorphic PQU rocks, necessarily record anything about earlier oblique buoyant exhumation (Thomson et al, 1999) from greater depths in the subduction channel. While the flysch,

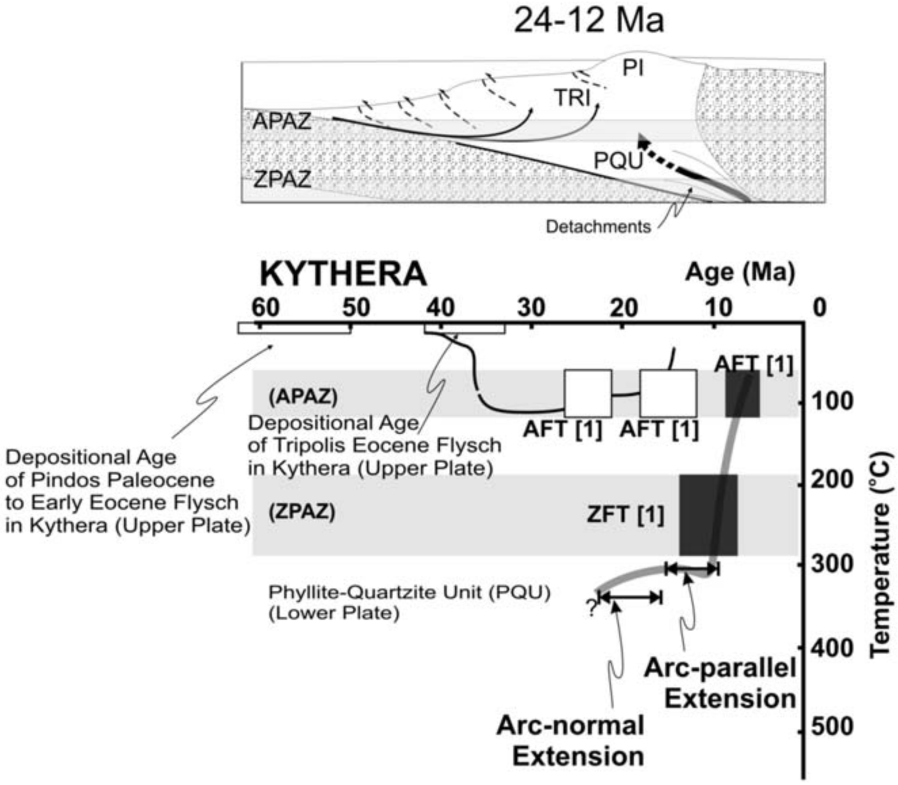

Fig. 6: Temperature-time (T-t) diagram for Kythera (western part of Hellenic Arc) combining: [1] zircon fission-track data of this study, [2] apatite fission-track, and zircon fission-track, of Marsellos et al. (2010). Dark grey boxes and thick grey line are PQU metamorphics of "lower plate" of detachment; white boxes and thin black line are from "upper plate" of detachment. APAZ - Apatite Partial Annealing Zone; ZPAZ - Zircon Partial Annealing Zone.

after incorporation into the thrust accretionary complex, may have been exhumed in significant part by erosion, it is clear from the geological relationships and structures near the detachment fault that exhumation of the PQU in the mid-upper crust through the ZPAZ must have been dominated by tectonic extension. The rapid rates of cooling estimated from the zircon and apatite FT ages in the PQU are consistent with tectonic extension being the dominant exhumation process for these rocks.

In central Peloponnese, we have obtained older zircon FT cooling ages (~21 Ma) from PQU metamorphics compared with those of Kythera, but we have been so far unsuccessful in obtaining apatite FT coling ages from the Tripolis flysch of the Peloponnese. More FT data from the flysch of Tripolis unit and exposed PQU rocks from central or northern Peloponnese are required to extend this study.

Valuable provenance information is retained in these cooling ages. Late Permian to Early Triassic ZFT cooling ages, and Late Jurassic-Early Cretaceous age in the zircons from the Kythera Tripolis and Pindos flysch show the ages of the sediment source rock, which could have been itself sedimentary. The Pindos unit clastic formations of Triassic and Early Cretaceous age correspond to this sedimentary source of Tripolis Unit as Danamos (1992) has independently inferred for the sedimentary source of the Tripolis flysch. Accretion and overthrusting of the Pindos unit to provide a source for the flysch in the late Eocene-Oligocene is plausible in the context of the Apulian-Pelagonian collision.

5. Conclusion

Zircon fission-track ages from Kythera record three thermal episodes. Zircons from the lower plate have Neogene cooling ages associated with the latest exhumation of the HP-LT rocks; the thermal history of these rocks reset and erased sedimentary provenance ages in these zircons. In contrast, zircon grains from the upper plate show Mesozoic and latest Paleozoic zircon fission-track ages that reflect the cooling ages of zircons and thermal evolution in the source region.

Early Miocene apatite cooling ages from above the detachment show when the Tripolis and Pindos units now present on Kythera were exhumed, and perhaps are linked to the earliest activity of the extensional detachment. Apatite FT ages in the PQU metamorphics on Kythera show the-Late Miocene extensional exhumation event of the PQU from beneath the Tripolis (and Pindos) sedimentary rocks.

6. Acknowledgments

Partial funding for field mapping, sample collection, and sample preparation for thermochronology was received from the Geological Society of America (grant to Marsellos). Additional partial funding for sample analysis was provided by the American Chemical Society – Petroleum Research Fund (grant ACS-PRF-47191 to Garver). Neutron irradiation was facilitated by Steve Binney at the Oregon State nuclear reactor as part of the US DOE Reactor Use Sharing Program.

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