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EXTENSION AND EXHUMATION OF THE HP/LT ROCKS IN THE HELLENIC FOREARC RIDGE

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ABSTRACT. Localized intensive ductile and ductile-brittle extension of along-the-arc orientation is prominent in Phyllite-Quartzite unit (PQU) rocks in Kythera and the adjacent southeastern Peloponnese but declines in prominence to the north and to the south along the Cretan-Peloponnese ridge. Using zircon and apatite fission track dating we find that this structural characteristic is correlated with the youngest zircon fission track cooling ages of 14 to 9 Ma, and with the highest pressure-temperature condition recorded in the metamorphic rocks below the structural detachment. The cooling ages of the high pressure Phyllite-Quartzite unit (PQU) rocks along the Hellenic forearc ridge show that exhumation migrated from both Crete and from the Peloponnese to the area with the youngest ages, in Kythera and the southeastern Peloponnese. Starting in the Early Miocene, and continuing to the present, trench-rollback and slab retreat expanded the Hellenic arc, and this bending of the arc from an initial more rectilinear geometry increased areas of oblique convergence and we suggest this localized the subsequent arc-parallel extension and local enhanced exhumation of HP-rocks. The Zircon FT exhumation ages from the arc-parallel stretching episode restrict the ductile part of this episode in exposed rocks to between about 14 and 9 Ma. Apatite FT ages suggest brittle along-arc extension continued to about 7 Ma. This episode is proposed to be the result of a temporary higher rate of rollback and slab retreat. Younger normal faults, including those which define the margins of the present Hellenic Arc, show return to arc-normal extension.

INTRODUCTION

Arc-normal extension has been shown to be an important mechanism to bring high-pressure, low-temperature metamorphic rocks to shallow levels in accretionary wedges (for example Platt, 1986). However, oblique convergence and consequent arc-parallel motion, if accompanied by extension and crustal thinning, also may provide a significant mechanism for bringing high-grade metamorphic rocks to the surface of subduction complexes (McCaffrey, 1992).

Examples of fore-arc rocks showing ductile along-arc extensional strain below extensional detachment fault systems are rare, and the only clear example of which we are aware is the Sanbagawa belt of Mesozoic age in Shikoku (Wallis, 1995). Along-arc extension in the brittle regime has been reported for Cretaceous forearc rocks in the San Juan Islands, Washington State (Schermer and others, 2007), and for Neogene arc platform rocks in Attu, Aleutian Ids (Ave Lallement, 1996). Local extensional structures (faults, basins) in forearc platforms below sea level, identified by marine geophysical methods, are reported by Kimura (1986), Geist and others (1988), and Harjono and others (1991). All these various occurrences have been related to along-arc extension caused by oblique subduction, for example McCaffrey (1991, 1992).

Besides extension caused by oblique subduction, expansion of a curved arc during a laterally limited slab rollback event also will cause arc-parallel extension. This second mechanism is the one we think is responsible for a significant mid-late Miocene event of arc-parallel extension and crustal exhumation in the western Hellenic arc, for which we report structural and thermochronological evidence in this paper.

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TECTONIC AND GEOLOGICAL SETTING

Motion of Africa with respect to Europe in the Mediterranean region (Savostin and others, 1986; Rosenbaum and others, 2004, and references therein) shows a progressive deceleration since 35 Ma, and in the eastern Mediterranean decelerated from 35 Ma to 10 Ma to a very low overall convergence rate of a few mm/yr. However, the rollback of the Hellenic part of the subducting African slab began in this interval causing localized more rapid subduction (presently ~35mm/yr in the central part of the arc) and a broad extensional event in the Aegean occurred as a result.

The substantial accretionary prism of the Hellenic subduction zone (fig. 1) has a width of c. 170 km close to Kythera strait and western Crete, and narrows to 60 to 80 km towards the terminations of the approximately 500 km long arc opposite the Peloponnese and eastern Crete. The thickness of about 8 km does not change much over its inner 100 km width to the foot of the Hellenic arc margin, where the crustal thickness increases abruptly to about 30 km in the adjacent Hellenic Arc (Truffert and others, 1993). Miocene turbidites (between 19 and 15 Ma) make up the front of the forearc ridge (Le Pichon and others, 2002) overlain by a thick Messinian evaporite sequence. Close to the front of the forearc ridge and below those sediments there is a "backstop" consisting of pre-Neogene sedimentary rocks, mainly of Tripolis and Gavrovo-Tripolitza units of the Hellenic nappes (Aubouin and others, 1976; Le Pichon and others, 2002). According to Le Pichon and others (2002) the present accretionary complex was initiated in late Middle Miocene (14.8–11.2 Ma).

The south Aegean forearc ridge, the Hellenic Arc, is a prominent horst formed by the Peloponnese-Cretan ridge (fig. 1), and separates the 3000 to 5000 m deep Hellenic "trench" to the southwest from the 1000 to 2000 m deep Cretan Sea basin to the northeast. The Late Miocene-Recent extensional opening of the Cretan sea has been the most recent major event in the construction of the Peloponnese-Cretan ridge which is bounded by major normal faults and scarps on both sides. Measured crustal thickness of 20 to 26 km in the Cretan Sea between Kythera and Crete (Tirel and others, 2004, and references therein) is somewhat less than the adjacent Hellenic Arc (Meier and others, 2004; Snopek and others, 2007) and this thinning is related to the opening of the Cretan Sea. A series of transverse faults cut the Peloponnese-Cretan Ridge. The largest of these (fig. 1) are the North Mani Transverse Fault (NMTF) that has a transcurrent offset of 10 km (Lallemant, 1984; Le Pichon and others, 2002), and the Ierapetra Transverse Fault (ITF) in Crete (Le Pichon and others, 2002). Both were active in the Late Miocene (Le Pichon and others, 2002). The ITF was initiated in Late Serravallian, about 13 Ma, but there is no indication of post-Miocene lateral displacement (Fortuin and Peters, 1984). Lallemant (1984) proposed a Late Serravalian age (12–11 Ma) for both the ITF and NMTF. However, the ITF was later reactivated as a prominent normal fault (Angelier, 1979; Angelier and others, 1982; Veen and Kleinspehn, 2003). In between those faults, there are other smaller transverse faults with strike-slip [for example the North Kythera Transverse Fault (NKTF) (Marsellos and Kidd, 2008)] and/or normal slip that segment the fore-arc ridge.

The large-scale internal structure of the Hellenic forearc ridge developed during the late Eocene-early Miocene collision of the Apulia microcontinent (attached to the African plate) as it was being subducted beneath and accreted against the active European continental margin (the Pelagonian "terrane") (Thomson and others, 1998). The sedimentary cover of Apulia is mostly represented by the rocks of the Phyllite-Quartzite Unit (PQU) and the Tripolitza unit, which are exposed over wide areas on the Peloponnese-Cretan ridge. Upper Carboniferous and Permian stratigraphic sections are dominated by shallow-water marine siliciclastic rocks, while Permian-Triassic up to Oligocene strata comprise the Plattenkalk unit (PKU), mainly carbonates and local evaporitic metasedimentary rocks (Krahl and others, 1983). The

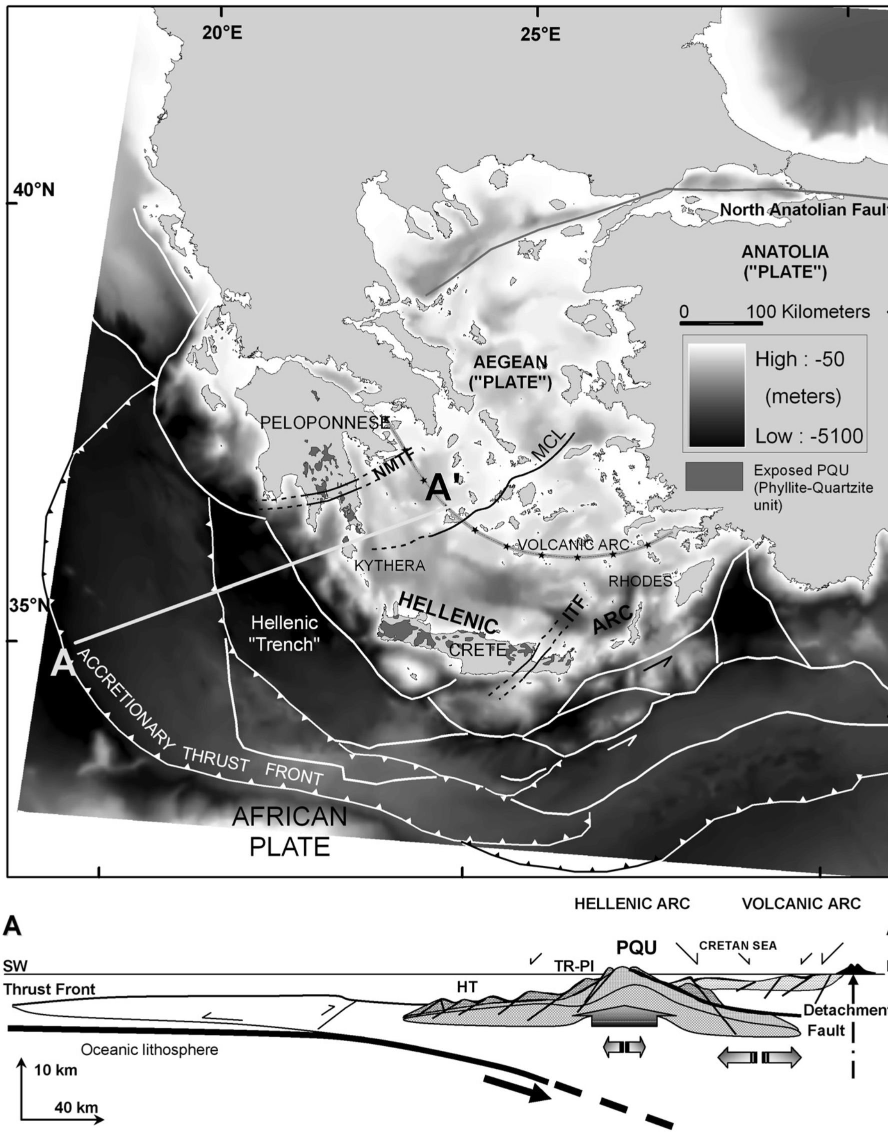

Fig. 1. Tectonic setting of the Hellenic Arc; a representative cross-section line A–A′ shown through Kythera strait. See text for discussion and reference sources. HT—Hellenic "Trench", TR–PI—Tripolis-Pindos nappe units above extensional detachment; PQU—Phyllite-Quartzite Unit below extensional detachment;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

metasedimentary rocks were underthrust and experienced a HP/LT metamorphism in the Oligocene to Early Miocene. In Crete these rocks experienced high pressure/low temperature metamorphism under conditions up to 350° C (in eastern Crete) and 400° C ± 50° C (in western Crete) and 0.8 to 1.2 GPa (Seidel and others, 1982; Theye and others, 1992) between 24 and 19 Ma (Brix and others, 2002). In the Peloponnese these rocks experienced conditions up to 1.5 GPa and 450° C (Seidel and others, 1982; Theye and Seidel, 1991; Theye and others, 1992; Theye and Seidel, 1993). In Kythera

PQU, peak metamorphic assemblages give 1.5 to 1.7 GPa and temperature close to 500° C (Gerolymatos, 1994). Zircon Fission Track (ZFT) data from Crete show only either partial resetting or unreset zircons from PQU rocks, with some ZFT ages of several hundred Ma in eastern Crete (Thomson and others, 1998; Brix and others, 2002). Stratigraphic and geochronologic constraints on the P-T-t path proposed in Thomson and others (1998) imply that near-peak temperatures lasted for a maximum duration of only 4 ± 2 Myr, with the PQU rocks being largely exhumed by oblique buoyant escape from depth within a few million years. During Early to Middle Miocene exhumation, a series of large-displacement extensional detachment faults developed, and these now separate the metamorphic PQU and PKU rocks from their non-metamorphic (mostly Tripolitza) cover (Fassoulas and others, 1994; Kilias and others, 1994; Jolivet and others, 1996; Jolivet and others, 1998; Thomson and others, 1999; Marsellos, ms 2006, 2008; Marsellos and Kidd, 2008; Marsellos and others, 2008a).

In Crete, the post-Oligocene ductile shear zones underlying the extensional detachment faults show mostly arc-perpendicular (S-N) stretching lineation directions (Fassoulas, 1999) with mostly northward transport. Recently, we reported evidence of a significant along-strike arc-parallel transport associated with the later ductile and ductile-brittle transition strain of the detachment fault and shear zone exposed on northern Kythera (adjacent to the southeastern Peloponnese—fig. 1), together with an initial zircon FT cooling age of 11.4 Ma which hinted that this exhumation was younger than the extensional exhumation in Crete (Marsellos and Kidd, 2008). This paper reports new structural data, and extensive zircon and apatite FT cooling age data related to the exhumation of PQU metamorphic rocks in the Hellenic arc of the southern Peloponnese, Kythera, and western Crete, and places the along-strike extensional event in the larger context of the Neogene development of the Hellenic Arc, the southern Aegean, and the Hellenic subduction system.

STRUCTURAL GEOLOGY AND LITHOLOGY OF THE PHYLLITE-QUARTZITE UNIT AND THE ASSOCIATED DETACHMENT SHEAR ZONE

All the occurrences of the upper part of the Phyllite-Quartzite Unit in the area of the Hellenic Arc discussed in this paper are bounded (in different places) either by a detachment fault and ductile shear zone of extensional type, or by younger steeply-dipping normal faults that cut the detachment. The metamorphic rocks of the PQU are almost entirely either phyllites, quartzites and meta-arenites (psammites), or less abundant marbles and calc-silicate rocks. Strain within the rocks is variable and heterogeneous, and can significantly change the outcrop appearance of rocks of initially similar composition. Additionally, phyllite-dominated sections are commonly not well-exposed; furthermore, highly-strained phyllites and phyllonitic rocks even where well-exposed may not necessarily be easily identified as particularly distinctive, nor do they characteristically show easily identifiable ductile stretching lineation fabrics. Most of the ductile stretching lineation and shear sense indicators we have observed and report here (fig. 2) come from the quartzite/psammite, and marble lithologies, which more consistently develop these features. In the Peloponnese, pelitic rock types dominate the northwestern and western exposures of the PQU (fig. 2), in contrast to the southeastern Peloponnese, and on Kythera, where quartzites and psammites are more abundant; for this reason, it is harder to find shear sense and stretching lineation information in the western/northwestern Peloponnese, although it is obtainable if persistent search is made.

The sense of movement in the detachment fault of Kythera, and in those faults exposed in central-south Peloponnese and western Crete bounding the Phyllite-Quartzite Unit (PQU) and/or Plattenkalk (PLK-marbles) unit, was determined by shear sense kinematic indicators in outcrops and in hand-samples using methods described by Simpson and Schmid (1983), Hanmer (1986), Goldstein (1988), Mawer

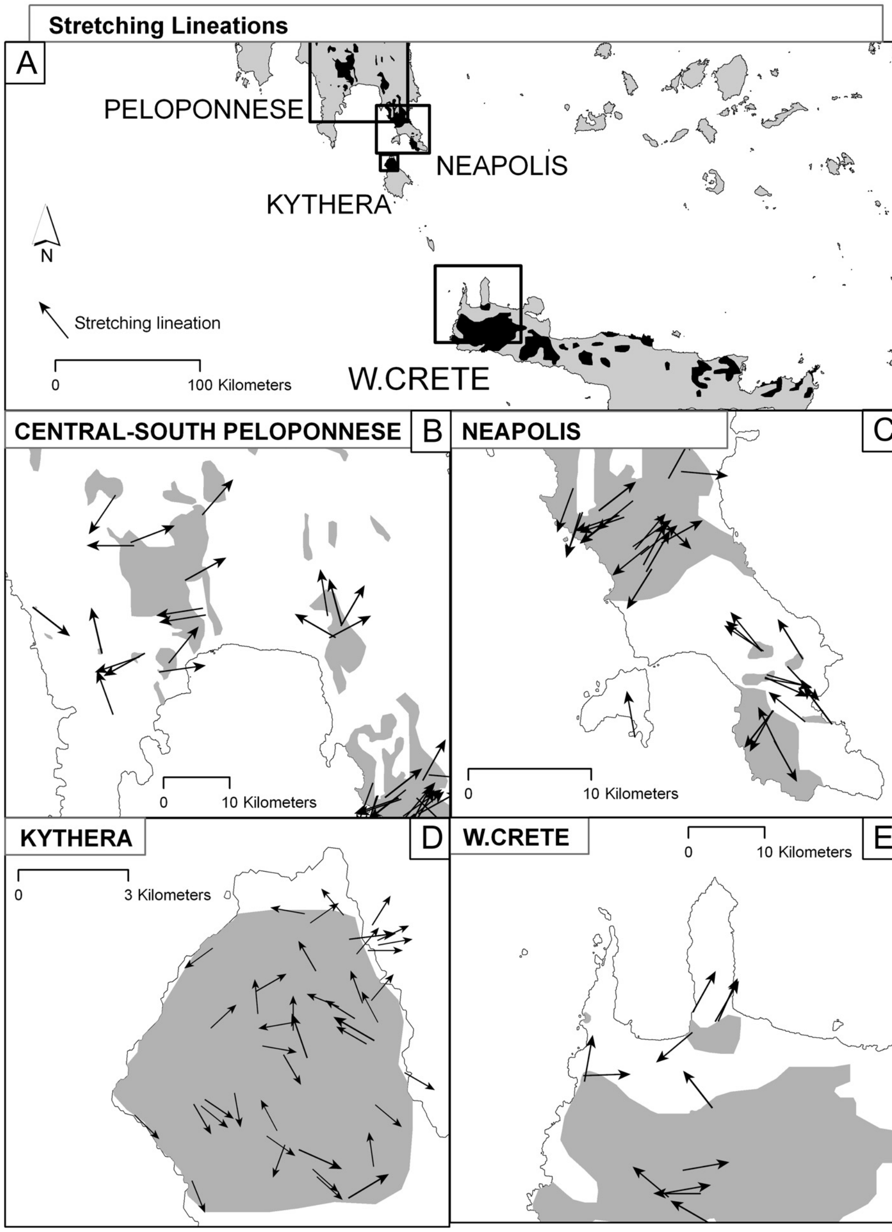

Fig. 2. Distribution of stretching lineations in the PQU of Peloponnese, Kythera, and western Crete. (A) Index map (PQU shown black). (B) central-south Peloponnese; (C) Neapolis, southeastern Peloponnese; (D) northern Kythera; (E) western Crete; PQU exposures shown gray in detailed maps.

(1989), Smith (1995, 1996), and Passchier and Trouw (2005). These ductile shear sense indicators include oblique foliation orientation, shear bands and cleavage, mantled porphyroclasts, white mica fish; ductile to brittle shear sense indicators such as tension gash sets and extensional shear boudins with recognized displaced markers, as well as brittle shear sense indicators, especially tension gas arrays, riedel shears and slickenfibers. Highly strained rocks of the PQU associated with the extensional detachment(s) in the SE Peloponnese-Kythera area show a substantial change in extension direction during their ductile strain history, which we have previously documented for the Kythera detachment (Marsellos, ms, 2006; Marsellos and Kidd, 2008). Relative to the local trend (fig. 1) of the Hellenic Arc (not that of the volcanic arc), this change from arc-perpendicular to younger arc-parallel extension correlates with the change in the quartzose lithologies from earlier planar mylonite/ultramylonite fabrics to S/C-type mylonites and C/C′ shear band ductile fabrics in the region showing the change in stretching lineation orientation and extension direction. The shear sense indicators have been correspondingly separated into an early ductile set, and a late ductile to early brittle set, and these are shown in map form on figures 3 and 4. The early ductile structures show mainly arc-perpendicular (and mostly top to N/NE) shear displacement (fig. 3), mostly from delta- and sigma-type porphyroclasts in the mylonites. In areas with arc-parallel stretching lineation, later ductile shear sense indicators are mostly of asymmetrical oblique foliation, either S/C or C/C′ shear bands, and shear boudins, and these give mainly top to SE sense of shear in the SE Peloponnese-Kythera area (fig. 4). There appear to be relict zones preserving an older shear sense and direction, of oblique to across-arc direction, among rocks showing ductile strain related to the later stages of the detachment shear zone, which show along-arc extension in the SE Peloponnese-Kythera region. In westernmost Crete, locally developed top to W/NW indicators were seen, mostly of slightly rotated shearband boudins. Elsewhere in western Crete, and in the central-south Peloponnese, ductile-to-brittle displacements mostly show normal top-NE and top-N shear sense and direction, approximately perpendicular to the arc.

In areas showing arc-parallel extension, some brittle structures, mainly tension gash arrays and some riedel shear fracture sets and feather fractures, show that arc-parallel extension continued through the transition into brittle conditions, and demonstrate that significant exhumation and cooling must have accompanied this episode of extension. In some places in southern Peloponnese and northern Kythera, rotated tension gashes occur as overturned sets, and in places are boudinaged. These show strong ductile shear subsequent to the initial shear fractures. Mylonitized Y-Riedel shear zones cut the rotated tension gashes, and later unrotated top-to-SE tension gashes cut the mylonitized layers. Cataclastic rocks of fault gouge and breccia are particularly well developed in southern Peloponnese and Kythera at and above the detachment fault surfaces, corresponding to the areas which show along-arc ductile shear.

Younger brittle structures, as on Kythera (Marsellos and Kidd, 2008), all show a return to arc-perpendicular extension, dominated by steep normal faults striking along the arc. These are accompanied locally by faults and vein arrays at a high angle to, and segmenting the arc, and which have moderate to small displacements, in different places, of either strike-slip or normal sense.

zircon fission track ages

Zircon fission track data have been obtained from 33 samples, all detrital zircon suites mostly from quartzites, and micaceous quartzites, of inferred Carboniferous-Permian and perhaps Triassic depositional age. The samples are from the Phyllite-Quartzite Unit (PQU) in the Peloponnese, Kythera and western Crete, as well as one sandstone sample from the upper plate above the detachment fault(s) confining the PQU metamorphics. Samples were collected from localities close to the detachment contact between the metamorphic PQU and the overlying unmetamorphosed units, and locations are shown in figure 6 and listed in table 1. These zircons, originally detrital grains from quartzites, have a typical range for uranium content of 100 to 350

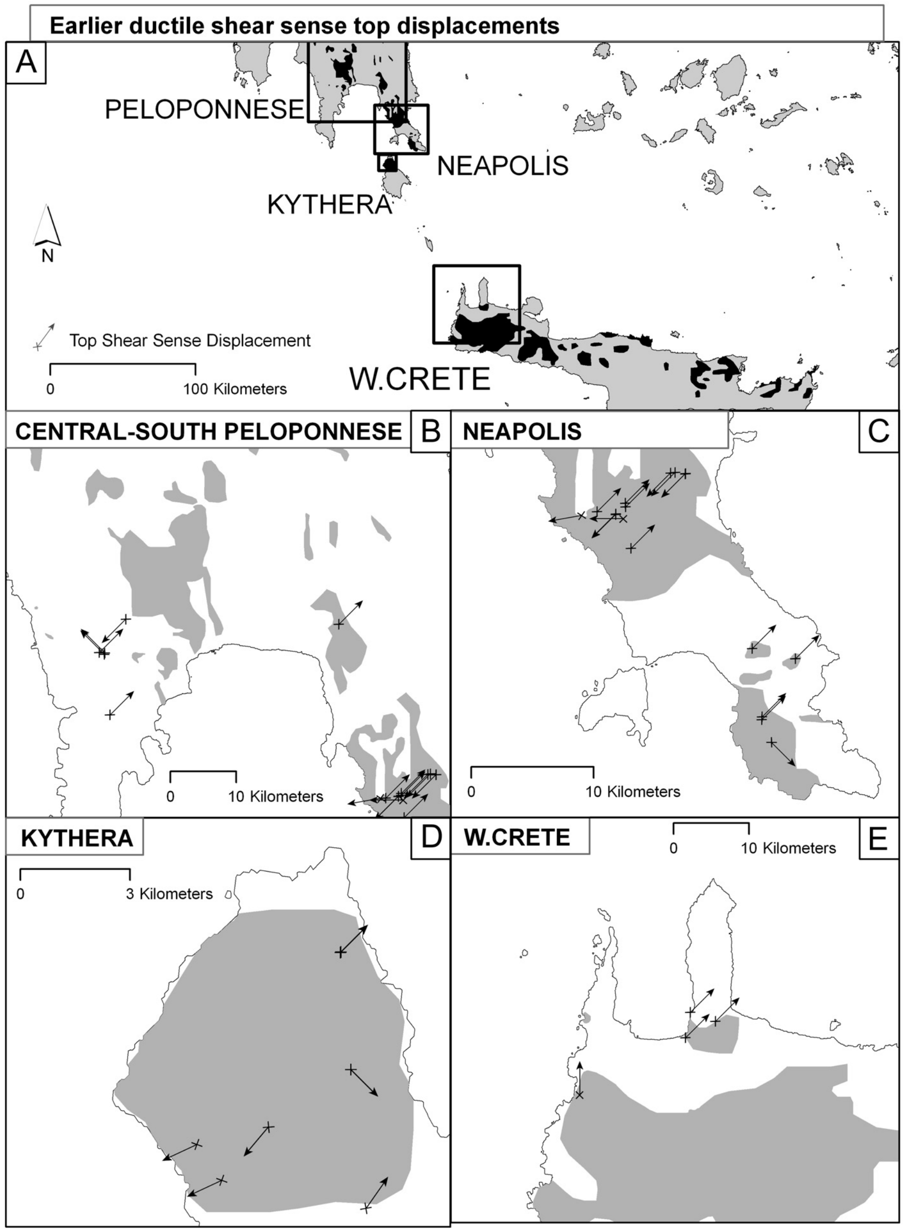

Fig. 3. Distribution of earlier ductile shear sense top displacement in the PQU of Peloponnese, Kythera, and western Crete. (A) Index map (PQU shown black). (B) central-south Peloponnese; (C) Neapolis, southeastern Peloponnese; (D) northern Kythera; (E) western Crete; PQU exposures shown gray in detailed maps.

ppm with a few exceptional higher values. Details of the sample preparation and analytical methods are given in Appendix 1.

Fission track analyses of zircons from PQU rocks along the forearc ridge reveal a significant variation in time of exhumation of HP rocks along the ridge. In Kythera,

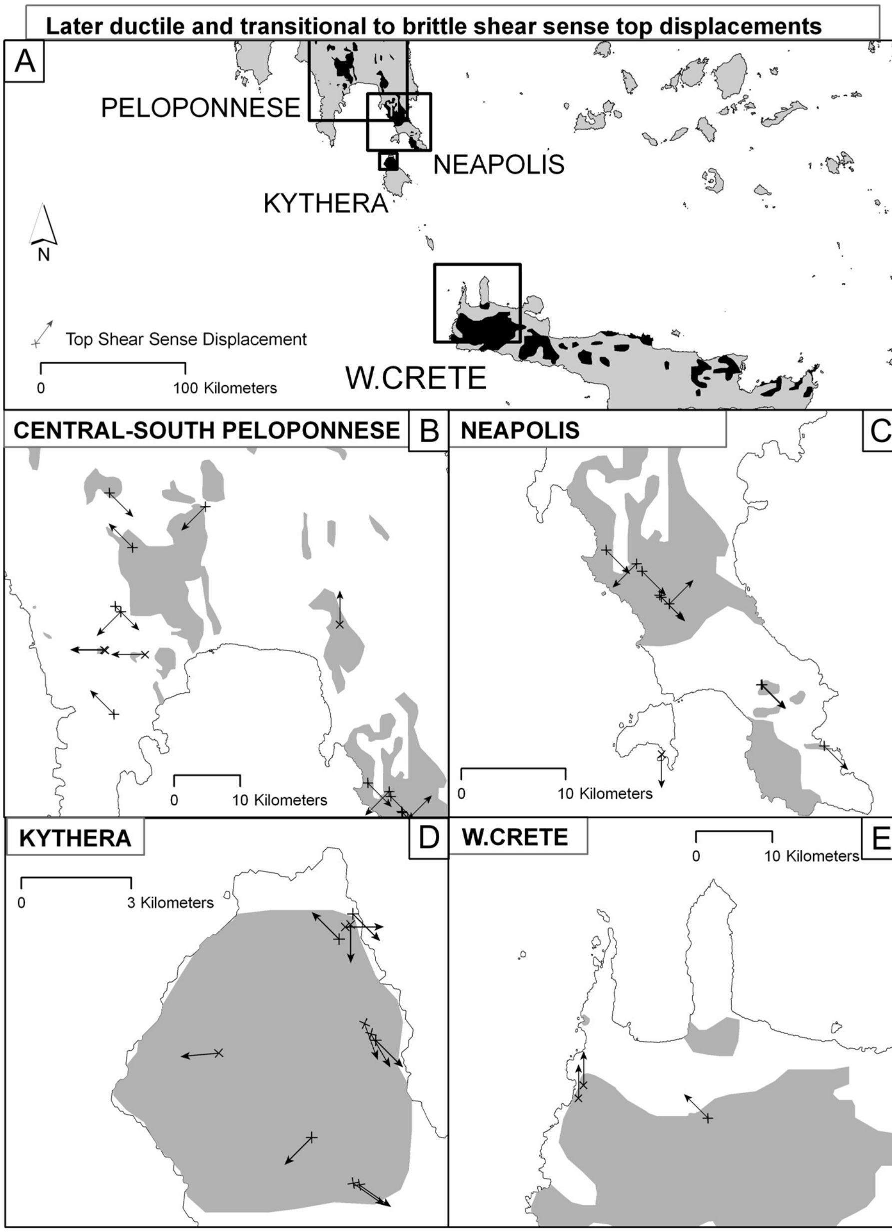

Fig. 4. Distribution of later ductile and transitional to brittle shear sense top displacement in the PQU of Peloponnese, Kythera, and western Crete. (A) Index map (PQU shown black). (B) central-south Peloponnese; (C) Neapolis, southeastern Peloponnese; (D) northern Kythera; (E) western Crete; PQU exposures shown gray in detailed maps.

zircon FT ages range from 9.1 ± 0.8 Ma to 12.9 ± 1.2 Ma (pooled ages) with very low age dispersion, in most samples of less than 1 percent, and a few other samples are all less than 15 percent. In the adjacent Neapolis region of the southeastern Peloponnese ZFT ages range from 9.2 Ma to 12.8 Ma, while in the central Peloponnese ZFT ages

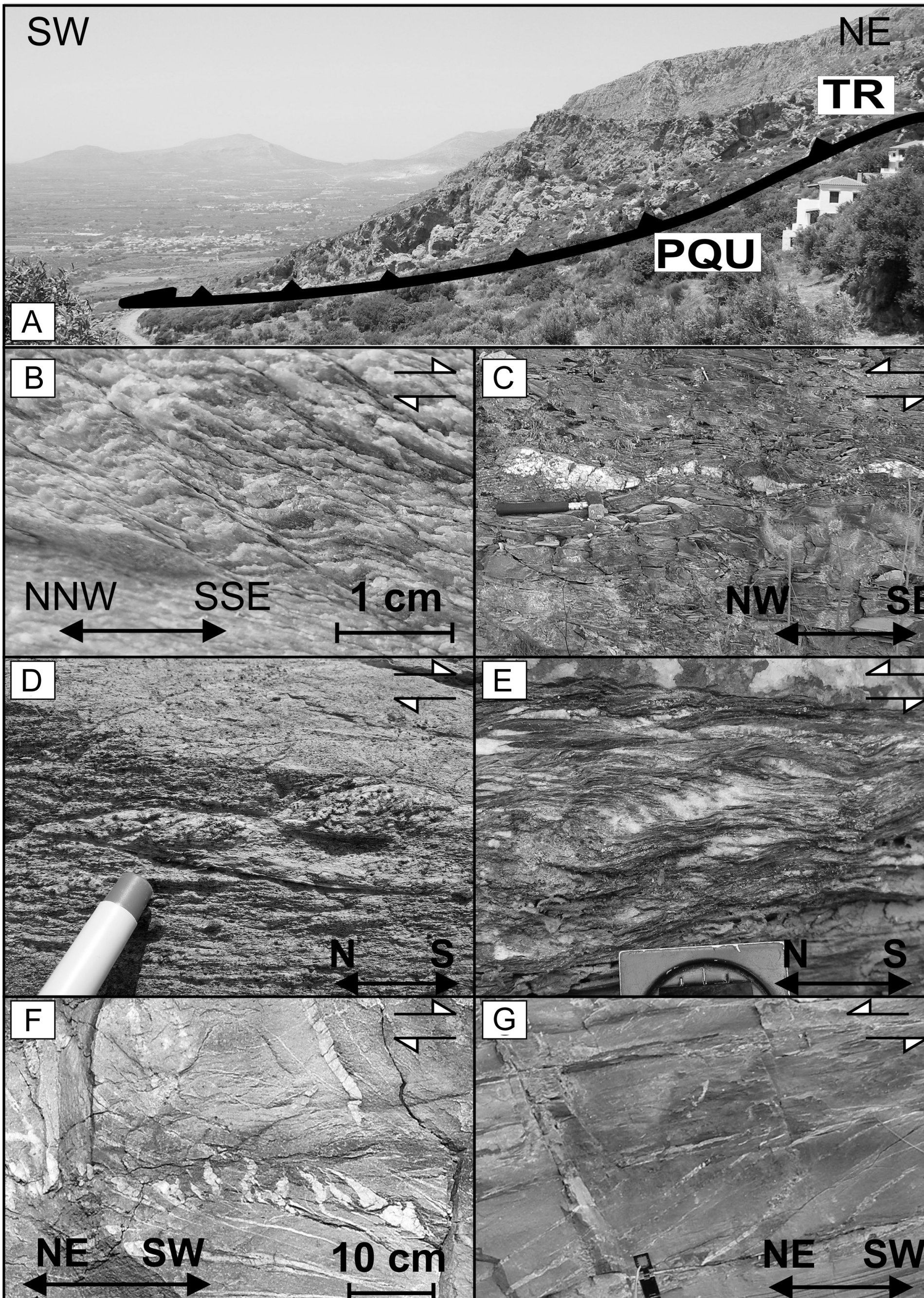

Fig. 5. (A) Detachment fault near Neapolis (Southern Peloponnese) placing limestones (Tripolis unit—TR) over the metamorphic Phyllite-Quartzite rocks (PQU)—view along the transport direction, top moved towards viewpoint; (B-G) Shear sense kinematic indicators from the PQU rocks near the detachment fault (shear sense shown by half-arrows at the top right corners) exposed (B) in northern Kythera (C, E, G) in western Crete, and (D, F) in southeastern Peloponnese. S/C asymmetric foliations (B, E); C/C′ shear bands/shear boudins (C, D); tension gash arrays (F, G).

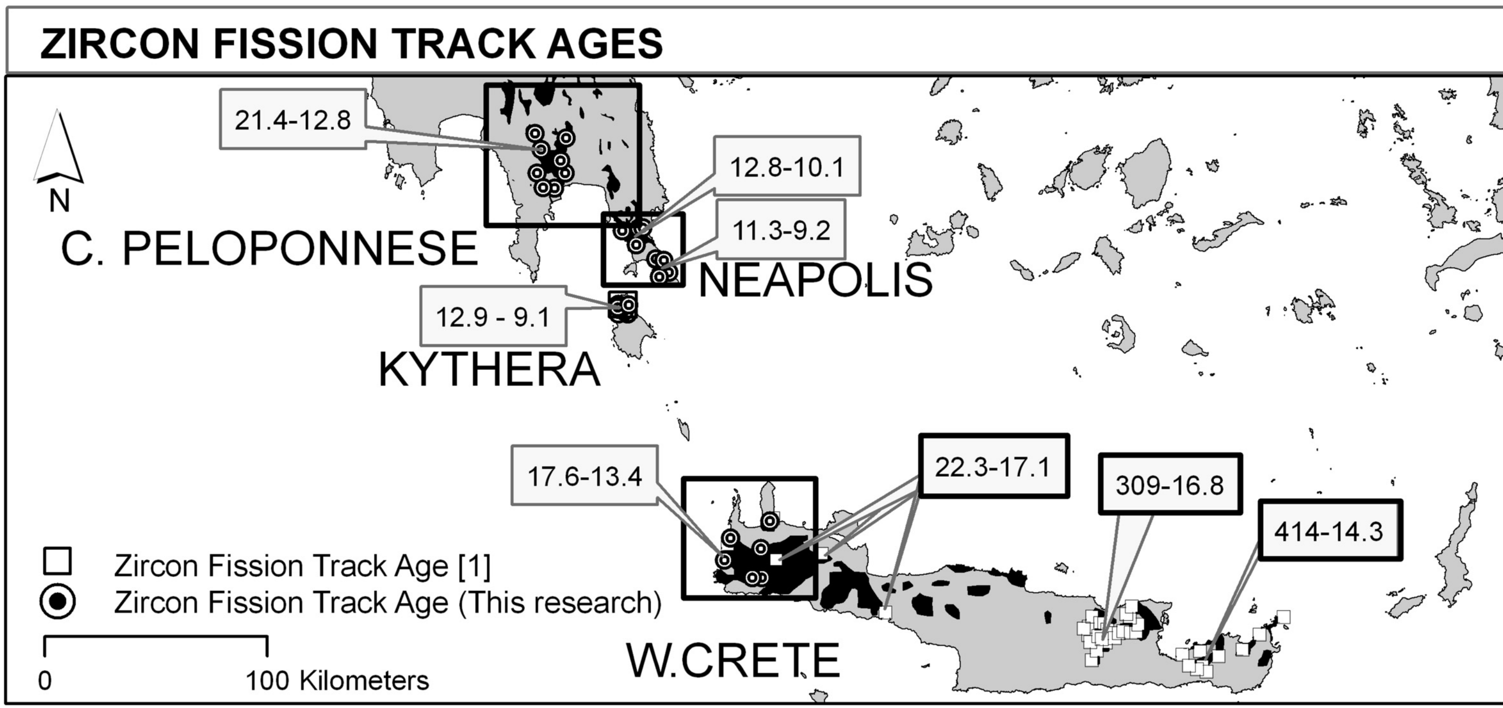

Fig. 6. (A) Distribution of zircon fission track ages in the Phyllite-Quartzite Unit of Peloponnese, Kythera, and western Crete, and index map of the following (B, C, D, E) detailed maps of ZFT ages from this research. Sample localities are shown by circles, while ZFT age ranges in bold-outline boxes from eastern Crete and some from western Crete are from [1] Brix and others (2002), and are shown by open squares in the index map. The black areas in the index map indicate the exposures of the PQU.

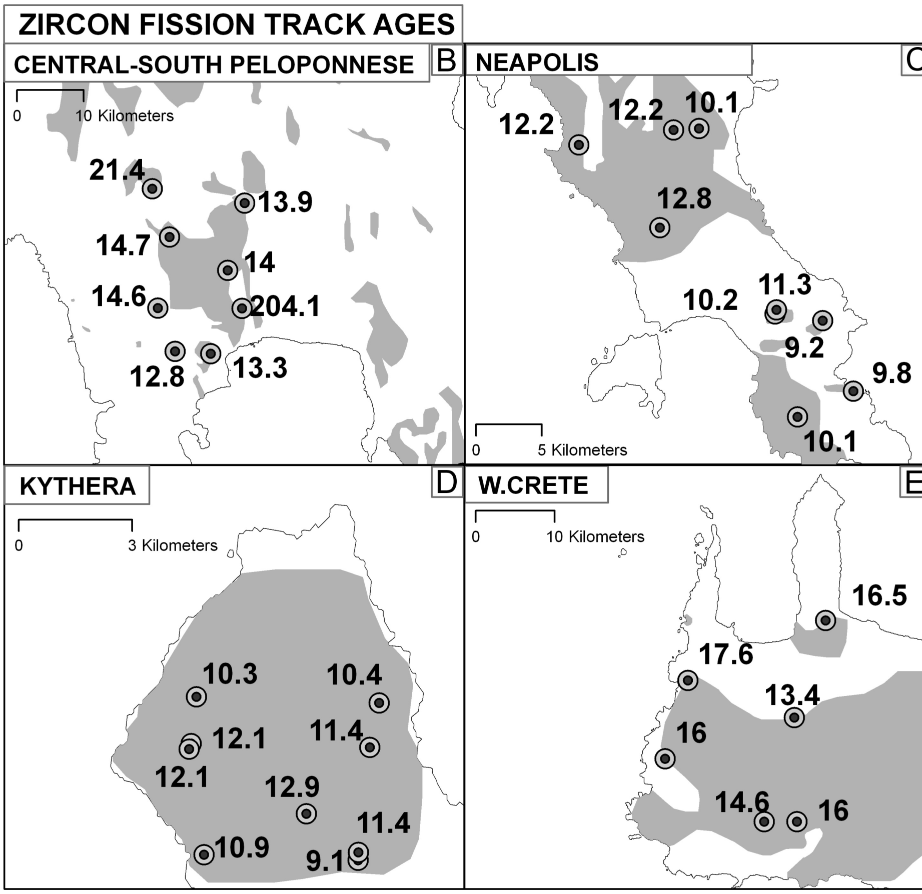

Fig. 6. (B-E): Zircon fission track ages determined in this research from the Phyllite-Quartzite Unit of Peloponnese, Kythera, and western Crete. ZFT age sample locations are shown by circles; (B) central Peloponnese; (C) southern Peloponnese; (D) northern Kythera; (E) western Crete; PQU outcrop areas shown gray. Age data, error limits, and location data are given in table 1.

range from 12.8 Ma to 21.4 Ma. In western Crete ZFT ages determined in this study range between 13.4 Ma to 17.6 Ma. High age dispersion and more than a single-component population are apparent in most of the older ZFT ages (table 1), specifically in samples from Crete and the Peloponnese, implying the presence of both fully reset and partially reset individual zircons in samples with ages older than 13 Ma. It is important to note that these samples have a component of young grains, which are likely fully reset and give tectonically meaningful ages. They also have a few older grains that span some 100 Myr or more in their age range. The population of young grains is likely comprised of non-retentive zircon (less resistant to annealing), while the older population are likely to be retentive zircons (more resistant to annealing), in the sense of Garver and others (2005). We refer to samples with this grain age pattern as “mixed-reset” as opposed to partially annealed because they appear to have some fully reset grains, and likely also have partially reset grains. Here we use the term “annealed” and “reset” interchangeably and both refer to the full removal of older tracks by thermal processes. The existence of some partially reset grains in rocks which have, from peak metamorphic data, been subjected to temperatures exceeding the nominal

TABLE 1

Summary of zircon fission-track data from the Hellenic Fore-Arc ridge

			ZETA Age program													Binomfit Program	
Sample	Elev	Mineral	ρs	Ns	ρi	Ni	ρd	Nd	n	χ^2	Age	-1σ	+1σ	U+/-2se	Age Dispersion (%)	*Primary Age (Ma)*	*Secondary Age (Ma)*
Peloponnese																	
AAP4	348	Zircon	1.12E+07	123	4.29E+07	471	2803	2.349E+05	15	3.7%	14.6	-3	+6.2	146.4 ± 14.2	33.8	*14.6*	*5.7*
PAA-1	487	Zircon	1.08E+07	79	4.79E+07	407	2801	2.358E+05	3	16.7%	8.8	-1	+1.2	937.4 ± 97.1	2.5	*8.7*	
PAA-2	480	Zircon	1.96E+07	207	8.08E+07	851	2798	2.375E+05	15	1.3%	14.7	-1.1	+1.3	275.7 ± 20.5	28.8	*14.7*	*8.1*
D01	109	Zircon	1.91E+07	183	7.75E+07	737	2765	2.571 E+05	15	37.1%	12.2	-1	+1.1	228.2 ± 18	8.3	*11.3*	*20.9*
D03	222	Zircon	2.50E+07	264	9.68E+07	1020	2762	2.588E+05	15	8.9%	12.8	-0.9	+1	303.3 ± 20.8	17.3	*11.0*	*16.2*
D08	365	Zircon	1.98E+07	210	8.20E+07	857	2759	2.605E+05	15	20.4%	12.2	-1	+1.1	252.1 ± 18.6	11.7	*12.2*	
D09	223	Zircon	1.61E+07	177	7.97E+07	868	2756	2.622E+05	15	48.9%	10.2	-0.9	+0.9	237 ± 17.5	1.2	*10.2*	
D10	288	Zircon	1.82E+07	192	8.11E+07	856	2753	2.639E+05	15	40.9%	11.3	-0.9	+1	249.6 ± 18.6	12.6	*12.4*	*8.6*
D13	151	Zircon	5.81E+07	622	6.75E+07	741	2750	2.656E+05	24	0.0%	9.2	-2.6	+2.8	131.7 ± 10.4	94.4	*9.2*	*84.4*
D18	15	Zircon	1.73E+07	182	9.01E+07	951	2747	2.673E+05	15	88.7%	9.8	-0.8	+0.9	277.2 ± 19.9	0.2	*9.8*	
D20	75	Zircon	2.56E+07	266	1.34E+08	1358	2744	2.690E+05	28	61.9%	10.1	-0.7	+0.8	209.2 ± 13.1	1.8	*10.1*	
D24	112	Zircon	1.33E+07	146	6.93E+07	747	2741	2.707E+05	14	15.7%	10.1	-0.9	+1	218.7 ± 17.4	15.1	*9.3*	*16.0*
D25	48	Zircon	2.14E+07	226	8.38E+07	883	2738	2.724E+05	15	65.0%	13.3	-1	+1.1	249.4 ± 18.6	26.3	*13.3*	
D26	157	Zircon	2.02E+07	224	8.20E+07	919	2735	2.741 E+05	15	61.3%	12.8	-1	+1.1	243.8 ± 18	4.7	*12.8*	
D28	153	Zircon	1.66E+08	1477	4.21E+07	375	2733	2.758E+05	15	0.0%	204.1	-13	+13.9	119 ± 12.9	56.4	*215.4*	*39.4*
D29	270	Zircon	1.69E+07	178	6.42E+07	677	2730	2.775E+05	15	55.0%	14	-1.2	+1.3	187.7 ± 15.8	0.3	*14.0*	
D30	105	Zircon	1.73E+07	*157*	6.44E+07	*602*	2727	2.792E+05	15	57.5%	13.9	-1.3	+1.4	187.8 ± 16.7	1.1	*13.9*	
D32	677	Zircon	2.96E+07	289	7.33E+07	726	2724	2.809E+05	15	36.3%	21.4	-1.6	+1.7	211.2 ± 17.4	8.9	*21.3*	
Kythera																	
D43	77	Zircon	2.97E+07	310	1.55E+08	1614	2720	2.826E+05	28	87.0%	10.4	-0.7	+0.8	241.2 ± 14.9	0.4	*10.4*	
T04	123	Zircon	2.43E+07	304	5.36E+07	696	1938	1.303E+05	18	81.7%	10.9	-0.8	+0.9	259 ± 21.6	0.2	*10.9*	
T06	341	Zircon	2.70E+07	291	7.15E+07	787	1922	1.292E+05	15	94.9%	9.1	-0.7	+0.8	475.7 ± 37.9	0.1	*9.1*	
T07	345	Zircon	2.61E+07	307	5.66E+07	662	1906	1.281 E+05	15	47.2%	11.4	-0.8	+0.9	366.8 ± 31.5	0.4	*11.4*	
T13	366	Zircon	1.83E+07	223	3.34E+07	420	1890	1.270E+05	15	45.8%	12.9	-1.1	+1.2	214.3 ± 22.4	9.7	*12.9*	
T14	298	Zircon	1.87E+07	191	4.17E+07	437	1850	1.243E+05	15	40.9%	10.4	-0.9	+1	274.6 ± 28.6	14.8	*10.4*	
T15	353	Zircon	1.37E+07	152	2.69E+07	295	1834	1.232E+05	15	45.1%	12.1	-1.2	+1.4	178.1 ± 22.1	12.9	*12.1*	
T18	298	Zircon	1.84E+07	230	3.53E+07	443	1818	1.222E+05	17	84.1%	12.1	-1	+1.1	206.3 ± 21.6	0.9	*12.1*	
QZ12	155	Zircon	1.68E+07	160	6.16E+07	580	2313	2.167E+05	20	81.8%	11.4	-1	+1.1	176.5 ± 16.1	0.2	*11.4*	
Crete																	
CR01	51	Zircon	1.71E+07	172	4.64E+07	481	2792	2.409E+05	15	24.5%	16.5	-1.5	+1.6	148.7 ±14.2	12.7	*18*	10.3
CR07	246	Zircon	2.26E+07	278	5.92E+07	733	2788	2.434E+05	15	72.4%	17.6	-1.3	+1.4	186.6 ±14.7	0.7	*17.1*	
CR09	521	Zircon	6.33E+07	756	1.78E+08	2064	2785	2.443E+05	36	16.7%	16	-0.8	+0.9	241.8 ±12.6	15.6	*15.7*	21.3
CR11	561	Zircon	6.30E+07	649	2.01E+08	2076	2776	2.494E+05	35	0.3%	13.4	-1.1	+1.3	276 ±14.2	24.2	*12.5*	20.2
CR14	867	Zircon	9.96E+07	1126	2.99E+08	3394	2772	2.519E+05	44	28.3%	16.1	-0.7	+0.8	313.9 ±13.8	9.9	*15.1*	21.7
CR15	305	Zircon	3.12E+07	341	1.05E+08	1135	2768	2.545E+05	21	25.2%	14.6	-1	+1.1	250.4 ±16.4	17.6	*12.5*	19.6

Elevations are given in meters, ρs is the density (cm^2) of spontaneous tracks and Ns is the number of spontaneous tracks counted; ρi is the density (cm^2) of induced tracks; and ρd is the density (cm^2) of tracks on the fluence monitor (CN5); n is the number of grains counted; and χ^2 is the Chi-squared probability (%). Fission track ages (± 1σ) were determined using the Zeta method, and ages were calculated using the computer program and equations in Brandon (1992). All ages with $\chi^2 > 5\%$ are reported as pooled ages. A Zeta factor for zircon of 382.20 ± 11.00 (± 1 se) is based on 11 determinations from both the Fish Canyon Tuff and the Buluk tuff. Glass monitors (CN5 for zircon), placed at the top and bottom of the irradiation package were used to determine the fluence gradient. All samples were counted at 1250× using a dry 100× objective (10× oculars and 1.25× tube factor) on an Olympus BMAX 60 microscope fitted with an automated stage and a digitizing tablet.

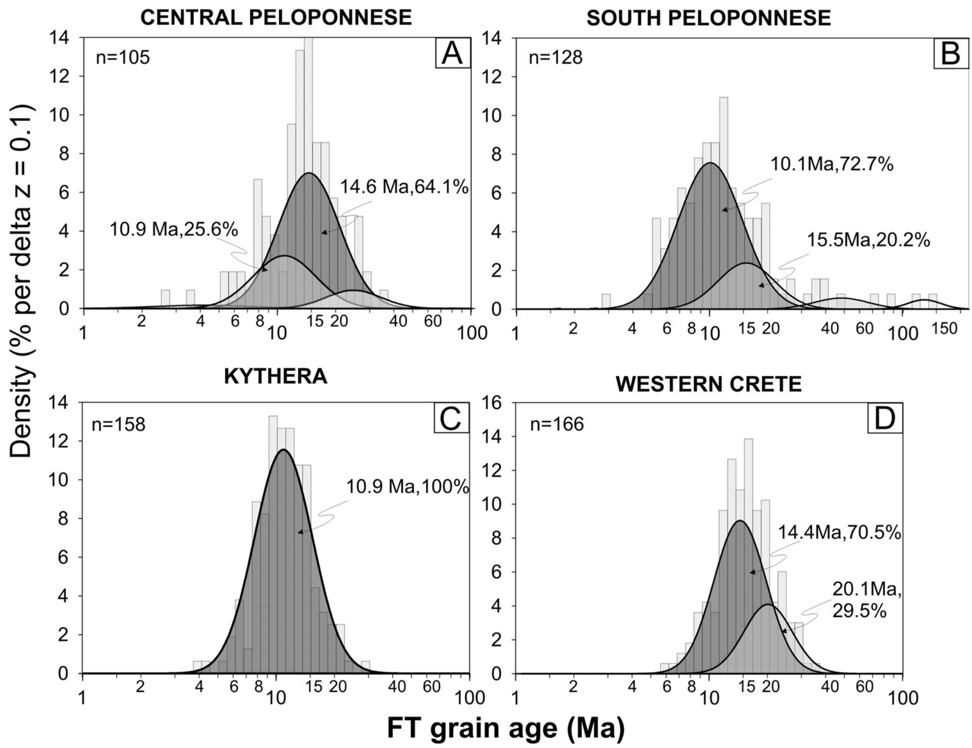

Fig. 7. Results from binomial peak-fitting (Brandon, 1996) represented through the probability density plots. On these plots, the individual histogram bars (gray) represent the grain-age components. Thin solid lines represent successive peaks identified in the age distributions. Results for first and second peaks are listed in table 3. ZFT grain ages are from the exposed PQU rocks (lower plate): (A) seven samples from the PQU of central Peloponnese. (B) nine samples from the PQU of southern Peloponnese. (C) nine samples from the PQU of Kythera. (D) six samples from PQU of western Crete.

annealing temperature for zircon fission tracks, is ostensibly a paradox. However, for zircons there appears to be a considerable range of temperatures and resistance to annealing, which we are currently attempting to constrain by experiments (Marsellos, ms, 2008; Marsellos and others, 2008b; Marsellos and Garver, 2009).

All the collected zircons of the PQU in the Kythera-Neapolis segment of the Cretan-Peloponnese ridge appear to have been fully annealed, showing ZFT age patterns of a distinctive fully reset character. In Crete and the other parts of Peloponnese, a change to mixed-reset ZFT age patterns is found. Rocks from Kythera-Neapolis PQU segment apparently were heated to temperatures sufficient to anneal even retentive grains and then, upon exhumation (fig. 7), were carried up through the PAZ (Partial Annealing Zone) quickly enough that no significant accumulation occurred of partly annealed tracks. In contrast PQU rocks of the central Peloponnese and western Crete entered the PAZ by exhumation and cooling in the interval ~20 to 15 Ma and remained there long enough for partial annealing of "new" tracks in all grains, and of "older" tracks in more retentive grains. This is consistent with the concept that stability of fission tracks in zircons is a function of single-grain radiation damage, and in samples with grain-to-grain variability in radiation damage, resetting results in variable resetting and multiple age populations (Garver and others, 2005).

SECONDARY PEAK ZFT AGES

Wide age dispersion in many ZFT samples also may provide evidence for more than one thermal event in these rocks (fig. 7 and table 2). Parameters for best-fit peaks, generated from the Binomfit program (Brandon, 1992) show the primary peak ages (P1) summarized above, as well as secondary peak ages that make up smaller fraction (table 1). The older secondary peak ages are likely related to more retentive zircons that are more resistant to track annealing and one possibility is that they represent an earlier thermal event (or events, as discussed for the northern Peru radiation-damaged zircons by Garver and others, 2005). Many of these grains show secondary peak ages close to the primary peak ages of other western-central Crete ZFT samples, in the range of 17 to 21 Ma. The young secondary age component close to the Kythera ZFT age range of 9 to 13 Ma likely comes from less retentive grains.

Application of the Binomfit program to all the samples (fig. 7 and table 2) in each of the four different areas shows peak ages at 14.4 Ma (70.5%) and 20.1 Ma (29.5%) for the suite of all the western Crete samples, and 14.1 Ma (42.3%) and 10.0 Ma (51%) for all the Peloponnese samples. A common peak age of 14 Ma exists in both western Crete and Peloponnese PQU rocks. An older secondary peak age of 20 Ma exists in Crete PQU rocks, and a younger 10 Ma secondary peak age in Peloponnese PQU rocks.

The contrast of primary peak ZFT ages between Kythera and the adjacent areas of Peloponnese and western Crete shows that the cooling event (9-13 Ma) recorded in the fully reset zircons in the Kythera PQU has also affected the less retentive zircons in the PQU rocks of Peloponnese and western Crete. In particular, western Crete zircons show the cooling ages terminating at 14.4 Ma while zircons from Kythera and Peloponnese show termination at about 10 Ma. This age pattern may imply an exhumation polarity of the HP rocks in this event from Crete towards Peloponnese, as exhumation migrated from the area of arc-normal extension to the area of arc-parallel extension.

APATITE FISSION TRACK AGES

Forty two samples from along the Hellenic forearc ridge were selected for apatite fission track analysis: four of Tripolis flysch, from the upper plate of Kythera; eleven of quartzites, and micaceous quartzites from the lower plate of Potamos Detachment fault on Kythera; six of quartzites from the western Crete PQU; twenty of quartzites and phyllites from the central and southern Peloponnese PQU; as well as one of sandstone above the Peloponnese detachment. Of these, 14 contained apatite but only 6 with sufficiently high and consistent uranium content to be suitable for fission track analysis. The sample locations are shown on figure 8 and figure 9 and listed in table 3. The analytical details and methods used are the same as those given by Hurford (1990).

AFT ages from the PQU metamorphic rocks below the detachment on Kythera are 6.5 ± 1.1 Ma (gneiss; mean uranium concentration of 44 ppm) and 7.0 ± 1.8 Ma (mica-schist; mean uranium content of 23 ppm), while an AFT age of 6.8 ± 3.8 Ma (mica-schist; mean uranium content of 25 ppm) was obtained from the southern Peloponnese. Many apatites from metamorphic rocks sampled in Kythera and the Peloponnese have very low uranium concentrations of less than 1 ppm, and these samples have disparate scattered ages that we deem unreliable.

Apatites from sandstones from the upper plate above the extensional detachment were collected from the Upper Eocene Tripolis flysch. AFT ages (fig. 9, and table 3) above the Potamos detachment on Kythera range from 14.8 ± 4.5 Ma to 23.4 ± 2.8 Ma. In these rocks apatite grains vary in uranium content from 100 to 1 ppm. The AFT age of 23.4 Ma has a very high dispersion due to several apatite grains with old AFT ages (grains with greater than 100 ppm uranium content), which show a contrasting age to the rest of the apatite grain age population. Binomfit reveals two peak ages for this

TABLE 2

Summary of Zircon Fission Track first and second peak ages using Binomfit program (Brandon, 1996)

	First Peak				Second Peak				
All Samples from	Peak (Ma)	68% CI		Frac. %	Peak (Ma)	68% CI		Frac. %	grains
S. & C. Peloponnese	10.0	-0.8	+0.8	51.0%	14.1	-1.3	+1.4	42.3%	276
South Peloponnese only	10.1	-0.7	+0.7	72.7%	15.5	-2.9	+3.5	20.2%	121
Central Peloponnese only	14.6	-1.5	+1.6	64.1%	10.9	-1.9	+2.3	25.6%	105
Kythera	10.9	-0.4	+0.5	100.0%					157
W.Crete	14.4	-0.8	+0.8	70.5%	20.1	-1.9	+2.2	29.5%	163

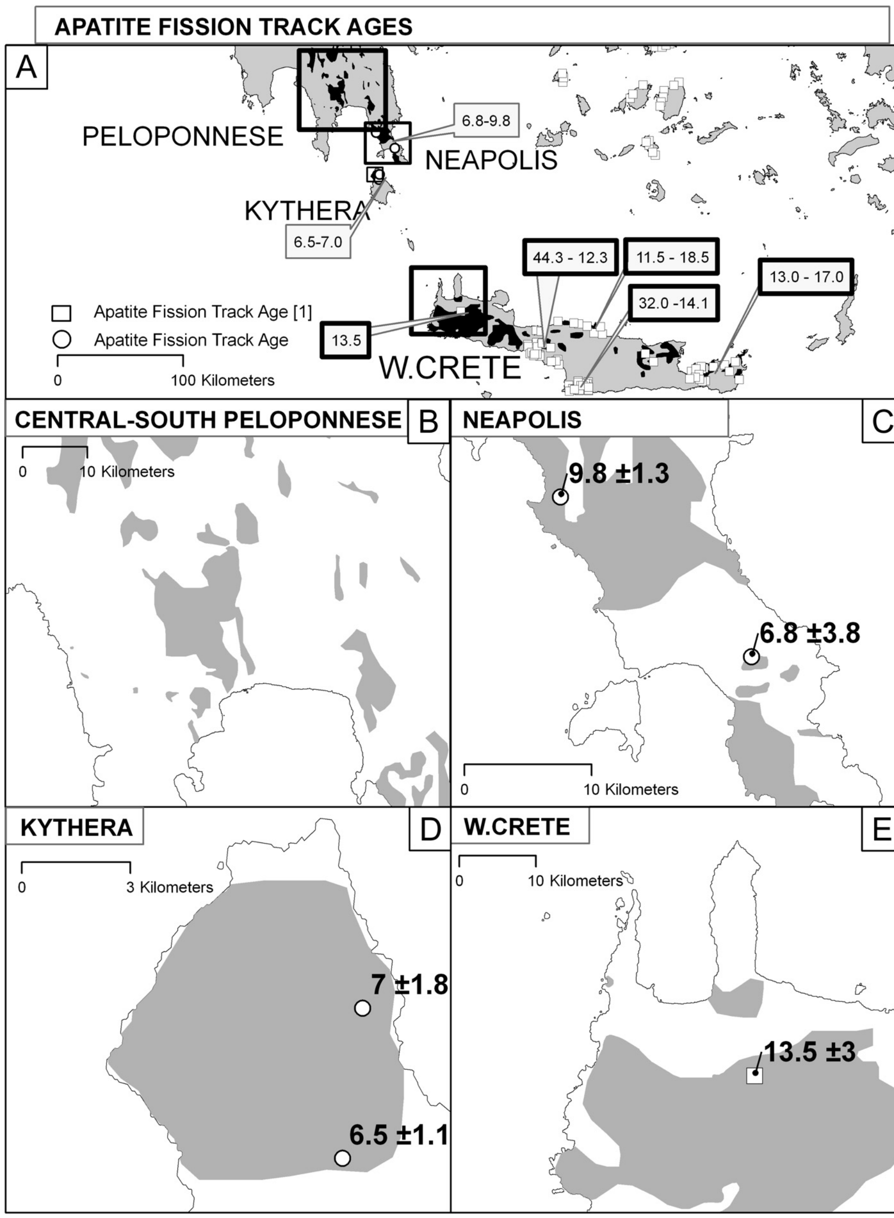

Fig. 8. Distribution of apatite fission track ages in the Phyllite-Quartzite Unit of Peloponnese, Kythera, and western Crete. (A) Index map. The black areas indicate the outcrops of the PQU; (B) central Peloponnese; (C) southern Peloponnese; (D) northern Kythera; (E) western Crete. The AFT ranges shown with bold outline boxes in (A), and the age (square) shown in Crete (E) are from [1] Thomson and others (1998). Age data, errors and locations are given in table 2.

sample. The first is ~10 Ma, which is identical to the young peak age of many other Peloponnese ZFT samples. The second is ~102 Ma which may reflect a primary age of grains in the sandstone. Removal of those three grains from the apatite population gives an apparent age of 10.1 Ma, which is similar to ZFT ages of the metamorphic PQU in Kythera and near Neapolis.

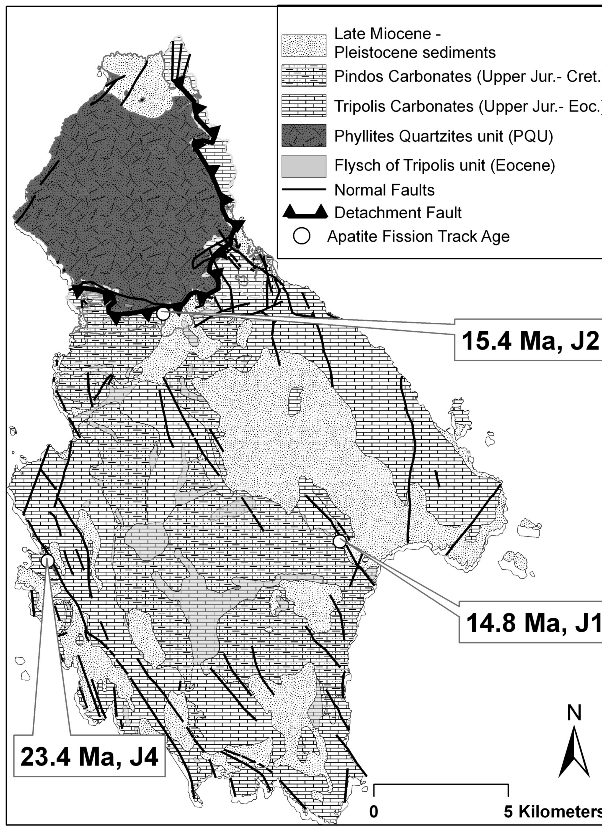

Fig. 9. Sample locations of AFT ages from upper plate (Tripolis flysch) on Kythera Island. Simplified geological map of Kythera after Petrocheilos (1966) and our observations. Age data, errors, and locations are given in table 2.

Track lengths in apatite were not routinely measured because, due to the very low uranium content and young cooling ages, each grain contains only a small number of tracks. However, some individual measurements of the track lengths gave a range of 8 to 13 μm in the metamorphic samples from Kythera PQU and the two samples of the Peloponnese PQU, and much shorter tracks, mostly about 6 to 8 μm with few around 10 μm from the Tripolis flysch from above the Potamos Detachment of Kythera. These observations are consistent with rapid exhumation of the PQU, and much slower exhumation of the overlying Tripolis flysch, through the apatite PAZ.

DISCUSSION AND IMPLICATIONS

Arc-Parallel Lineation Versus ZFT Ages

In Kythera and the southeastern Peloponnese, the youngest ZFT ages show a consistent correlation with areas of development of the ductile extension (or stretching) lineation of arc-parallel NW-SE orientation. Arc-parallel extension lineation (fig. 2) occurs mostly where the samples giving ZFT ages of 9.2 to 10.2 Ma occur in the southeastern Peloponnese (fig. 6C), and the 9.1 to 10.4 Ma ages from Kythera (fig. 6D). The arc-parallel lineation becomes less prominent and is replaced by an arc-perpendicular lineation farther to the northwest in the Peloponnese from the Kythera-

TABLE 3

Summary of apatite fission-track data from the Hellenic Fore-Arc ridge

Sample	Elev.	Mineral	ρs	Ns	ρi	Ni	ρd	Nd	n	χ^2	Age	-1σ	+1σ	U+/-2se
Peloponnese														
D01	109	Apatite	2.28E+06	77	3.81 E+07	1341	2689	3.513E+06	16	38.3%	9.8	-1.2	+1.4	24.9 ± 1.5
D10	288	Apatite	7.34E+04	5	2.42E+06	133	2718	3.652E+06	27	69.1%	6.8	-3.1	+4.4	0.7 ± 0.1
Kythera (Upper Plate)														
J1	89	Apatite	6.00E+05	15	6.07E+06	152	2597	3.085E+06	7	71.7%	14.8	-4.0	+5.0	11.7 ± 1.9
J2	314	Apatite	1.70E+06	43	1.44E+07	370	2603	3.111E+06	9	66.7%	15.4	-2.7	+3.0	20.6 ± 2.3
J4	61	Apatite	2.22E+06	106	1.69E+07	690	2614	3.161 E+06	15	0.0%	23.4	-2.6	+3.0	14.7 ± 1.2
Kythera (Lower Plate)														
D43	77	Apatite	7.76E+05	20	1.58E+07	486	2684	3.488E+06	9	64.3%	7.0	-1.6	+1.9	22.5 ± 2.1
T06	341	Apatite	2.65E+06	48	6.20E+07	1187	2649	3.325E+06	14	78.2%	6.5	-1.0	+1.1	44.1 ± 2.9

Elevations are given in meters, ρs is the density (cm^2) of spontaneous tracks and Ns is the number of spontaneous tracks counted; ρi is the density (cm^2) of induced tracks; and ρd is the density (cm^2) of tracks on the fluence monitor (CN5); n is the number of grains counted; and χ^2 is the Chi-squared probability (%). Fission track ages (± 1σ) were determined using the Zeta method, and ages were calculated using the computer program and equations in Brandon (1992). All ages with χ^2 >5% are reported as pooled ages. A Zeta factor for zircon of 382.20 ± 11.00 (± 1 se) is based on 11 determinations from both the Fish Canyon Tuff and the Buluk tuff. Glass monitors (CN5 for zircon), placed at the top and bottom of the irradiation package were used to determine the fluence gradient. All samples were counted at 1250× using a dry 100× objective (10× oculars and 1.25× tube factor) on an Olympus BMAX 60 microscope fitted with an automated stage and a digitizing tablet.

Neapolis area. In western Crete along-arc lineations occur in a few places but are not strongly developed; the stretching lineation in this area is mostly oblique to or normal to the arc. Zircons with older ZFT ages occur in samples from areas showing arc-normal stretching lineation.

We have used the combination of the stretching lineation orientation and the character of the associated later ductile fabrics near the detachment fault to segregate two groups of samples on which ZFT ages were determined. One set represents the arc-normal extension that occurred in the earlier ductile phase, while the other set corresponds to the arc-parallel extension that occurred in the late ductile to ductile-brittle transition conditions, and that overprints the previous earlier ductile structures. A plot of the ZFT ages versus the associated stretching lineation orientations from the same outcrops (fig. 10), shows that there is a prominent change of the ductile extension of the southwest segment of the forearc ridge at 13 to 12 Ma, from arc-normal extension to arc-parallel extension.

Within the south-central Peloponnese, although there is a large area of across-strike lineation with respect to the local trend of the Hellenic Arc (fig. 2), there are also areas of along-the-arc lineation that have associated young ZFT ages (fig. 6B). In western Crete, this association is not so prominent, but it can be seen from secondary ZFT peak ages in mixed-reset zircons (fig. 7). The youngest western Crete samples have zircon FT ages of 13.4 Ma and 14.6 Ma (fig. 6E). The same samples also show a secondary peak age of 12.5 Ma (fig. 7) and these rocks have a weak development of (here E-W) arc-parallel stretching lineation (fig. 2). The samples from western Crete having zircon FT ages that mainly range from 16 to 18 Ma and are from rocks that have a weak N-S arc-normal stretching lineation or no visible lineation at all.

An episode of expansion of the arc expressed by the localized (ductile to transitional ductile-brittle) extension directed along the fore-arc ridge can be constrained from these age data to have occurred later than 15 Ma and prior to 9 Ma.

The rocks with arc-perpendicular lineation may be in areas where along-strike arc-parallel extensional deformation did not occur. Those across-strike lineations could be all old, or some of them could possibly represent some late-stage across-strike extension. The distribution of ZFT cooling ages points to an older exhumation event associated with the arc-normal lineation, and a younger exhumation event associated with the area where arc-parallel (NW-trending) lineation occurs.

Shear Sense Displacement Pattern

Ductile structures near the detachment faults consistently show top-to-NE shear displacement in the PQU and PLK units along the southern-Peloponnese-western-Crete ridge. Ductile to brittle structures in the southeastern-Peloponnese-Kythera ridge segment show mostly top-SE (arc-parallel) and few top-SW shear displacement; and in westernmost Crete, top-NW (approximately arc-parallel) and top-N both occur. The initiation of the PQU exhumation was undoubtedly activated through a ductile detachment of NE-SW extension direction in the Kythera area (Marsellos, ms, 2006; Marsellos and Kidd, 2006; Marsellos and Kidd, 2008). This same event in Crete has a N-S extension direction because of the arc curvature. Near the end of this early ductile extension as the PQU approached the ductile-brittle transition a subsequent ductile-brittle event of NW-SE extension with an associated detachment overprinted the early structures along part of the Peloponnese-Cretan ridge in the Kythera Strait-southeastern Peloponnese. Brittle structures, including significant normal faults that define continuous features in the inland and submarine topography, cut rocks both above and below the PQU-PLK detachment. Along the Peloponnese-Cretan ridge, these are the controlling structures defining this structural high, and are integral to the development of the present forearc ridge. These latest structures, formed by extension perpendicular to the arc, overprint all the previous ductile and ductile-

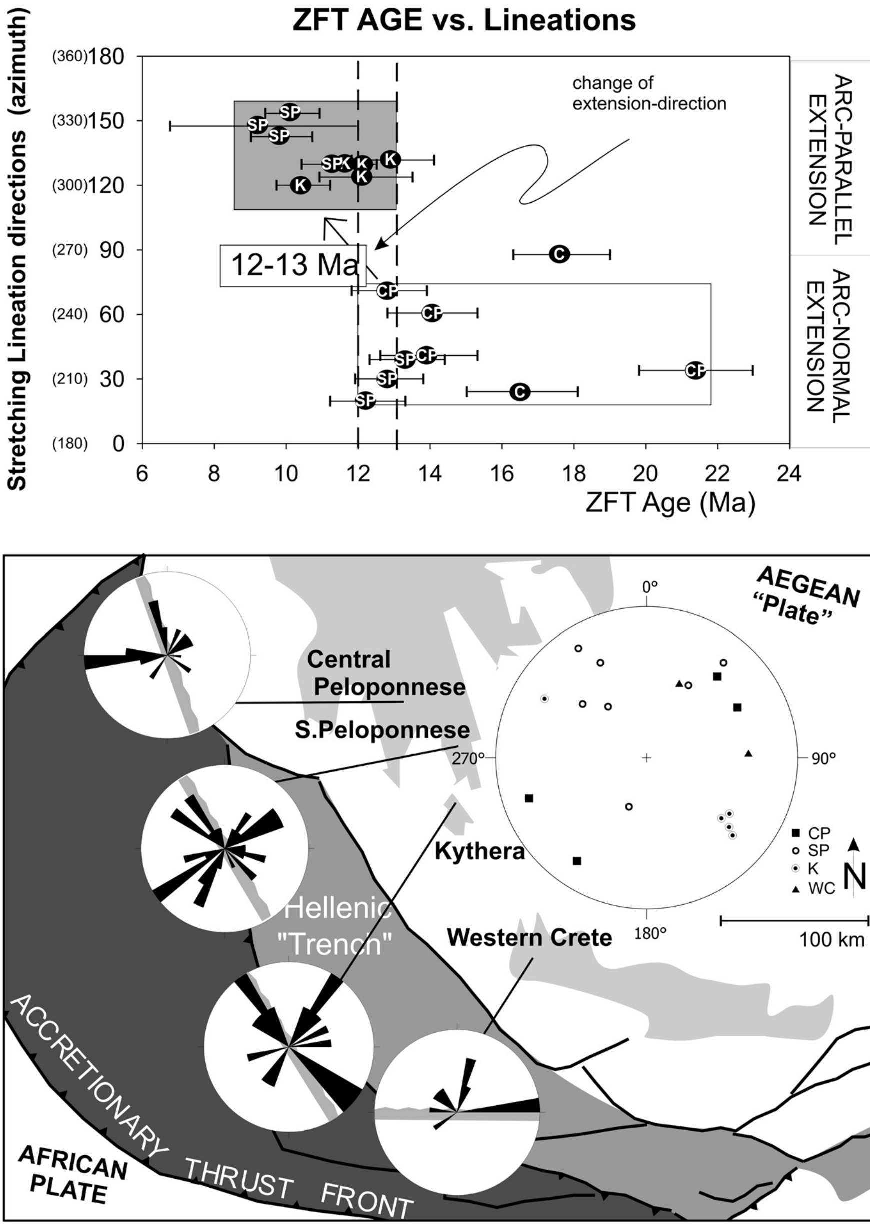

Fig. 10. Orientation of stretching lineations observed in the areas of PQU rocks of the western Hellenic Arc investigated for this study. Rose diagrams show lineation trend data for each of four areas with the local strike of the Hellenic Arc indicated by the gray bar. The stereonet (lower hemisphere projection) shows the lineation orientation for each outcrop where a Zircon FT age was obtained. The Zircon FT ages are plotted together with the associated outcrop lineation direction in the plot above the map. The gray shaded box in this plot contains the ZFT ages of PQU rocks having a strong arc-parallel extensional stretching lineation. C—western Crete; K—Kythera; SP—southeastern Peloponnese; CP—central Peloponnese.

brittle structures. The three extensional stages of exhumation of the PQU/PLK in the western Hellenic forearc ridge are consistent with those previously documented locally for the Kythera PQU (Marsellos, ms, 2006; Marsellos and Kidd, 2008).

Displacement Slip Rate

Slip rates on extensional faults can range from less than 1km/Myr up to greater than 20 km/Myr (for example Lister and others, 1984; Baldwin and Lister, 1994). A common problem in estimating the displacement rate on faults is that the total displacement is difficult to quantify. However, in the Hellenic Arc, a broad estimation (Ring and others, 2001a; Ring and others, 2001b) gives a displacement of >100 km and a very fast slip rate of >25 km/Myr for the Cretan detachment. Thomson and others (1998) showed that more than 80 percent of the exhumation in Crete was achieved by normal faulting, on a detachment with arc-normal extension. In Peloponnese-Kythera segment of the Hellenic Arc the ZFT ages reported in this paper can be used to constrain displacement slip rates, but associated with the arc-parallel extension. There is a systematic gradient in these ZFT ages in an Hellenic Arc-parallel direction from the south-central Peloponnese to Kythera (fig. 6), and over a distance of ~100 km between south-central Peloponnese and northern Kythera the ZFT cooling ages have an overall range of ~21 to 9 Ma. Assuming that this age gradient resulted from uniform movement on a single detachment, projection of the ages onto a Hellenic Arc-parallel section line gives a minimum overall slip rate of about 16 km/Myr. The southern Peloponnese ZFT ages are constrained by the available outcrop in two separated areas (figs. 6A, 6B), which might not have been affected by the same detachment fault. If separate slip rate estimates for these two areas are made using the same simple assumptions, the age pattern (fig. 6) suggests the earlier along-arc displacement slip rate, in central-south Peloponnese near Sparti (minimum ~ 4 km/Ma; 6 Myr over 25 km), was slower than the later movement in the southeast area around Neapolis (minimum ~ 12 km/Ma; 2 Myr over 25 km).

Progressive Exhumation of HP-Rocks in the Forearc

Zircon FT ages from Kythera are consistently younger than 13 Ma. In contrast, western Crete has ZFT ages (15–18 Ma) mostly older than those on Kythera, and ZFT ages increase eastwards to around ~20 Ma in central Crete (Brix and others, 2002). In the southeastern Peloponnese we have found young ZFT ages similar to nearby Kythera, while ages increase up to 21 Ma or more to the northwest. This overall age pattern shows that Kythera Strait is the youngest exhumed part of the HP/LT metamorphic rocks of the Hellenic forearc ridge and the ages imply a progressive younger exhumation that migrated from the Peloponnese, and from Crete, toward the Kythera Strait. As discussed above, arc-normal extension (dominantly recorded in Peloponnese and Crete) is the older ductile fabric and more localized arc-parallel extension (observed near and in the Kythera strait) is the younger ductile fabric.

All the Kythera and some southeastern Peloponnese FT zircon ages have very low age dispersion and are fully reset and show evidence of a single and rapid cooling event, unlike the FT zircon ages from most sites in Crete or central Peloponnese. These fully reset PQU zircons have probably experienced a very rapid exhumation in the interval of the zircon FT closure temperature (about 240° C; Brandon and others, 1998). This temperature falls slightly below the 300° C ductile-brittle transition for quartz-bearing rocks, and therefore these ages (for rapid exhumation) will be only slightly younger than the passage from ductile to brittle-ductile conditions, for which structural evidence is seen in Kythera and elsewhere in PQU rocks near the extensional detachment faults (Marsellos and Kidd, 2008). The PQU rocks of Kythera and some of the southeastern Peloponnese have experienced a longer duration at temperatures above those required for total zircon FT annealing, annealing all of the retentive

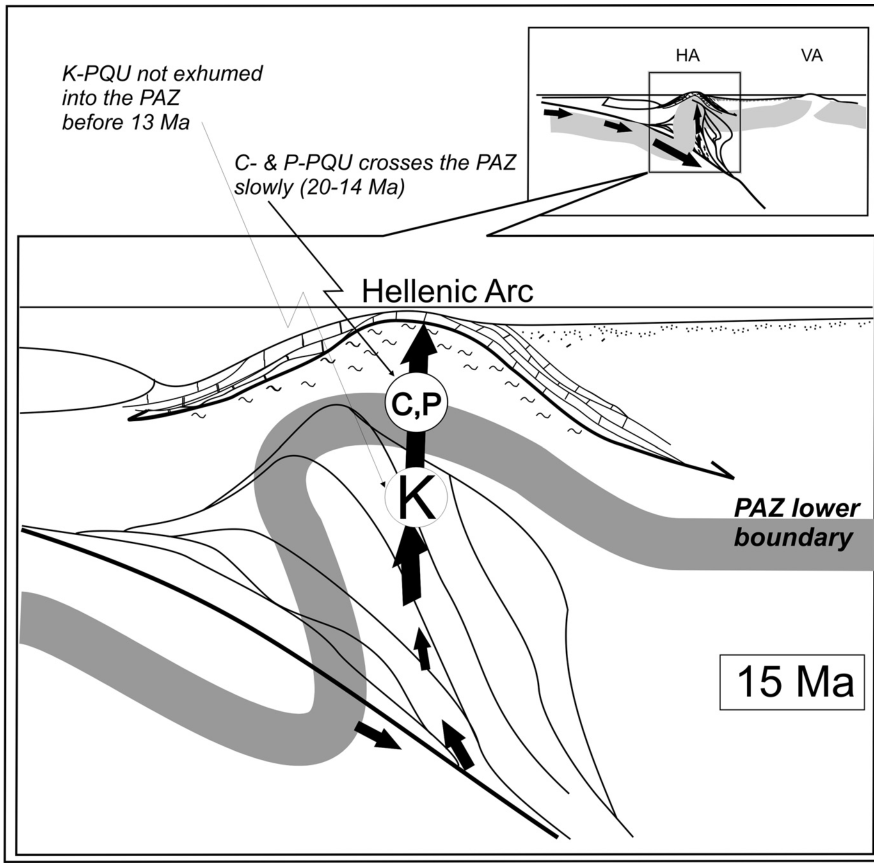

Fig. 11. Kythera and southeastern Peloponnese PQU rocks (K) were situated at a lower crustal level after the first (arc-normal extension) stage compared to rocks of central Peloponnese PQU and Crete PQU (C, P) which reached the zircon FT PAZ. Localized along-arc stretching caused Kythera and Southeastern Peloponnese rocks to exhume quickly through the zircon FT PAZ between ~13–9 Ma; HA-Hellenic Arc; VA-Volcanic Arc.

zircons, while afterwards they crossed the PAZ in a short time so that few or no short tracks accumulated by partial annealing (fig. 11). In contrast, western Crete and central Peloponnese zircons returned to the surface from HP/LT conditions more slowly through the PAZ with full annealing only of the least retentive zircons, with shortening by partial annealing of most fission tracks in more-retentive zircons (fig. 7).

Cooling Rates

Average cooling rates using both zircon and apatite FT data can be estimated over the temperature intervals between ZFT and AFT closure, and exhumation to the present surface. The rocks from Kythera and southeastern Peloponnese (fig. 12) cooled from ZFT to AFT closure (c. 240° C and 120° C) between ~11 Ma and ~7 Ma, an interval whose range from the FT ages is 1 to 5.8 Myr (including the ZFT errors), which gives a minimum average cooling rate of 30 to 50° C/m.y. Using apatite FT to the present surface, the rocks in Kythera cooled from 120° C to surface temperature in a maximum duration of 5 to 9 Myr and in the Peloponnese in a maximum of 4 to 11 Myr giving a minimum average cooling rate of 10° C/Myr and a wide potential range up to 30° C/Myr.

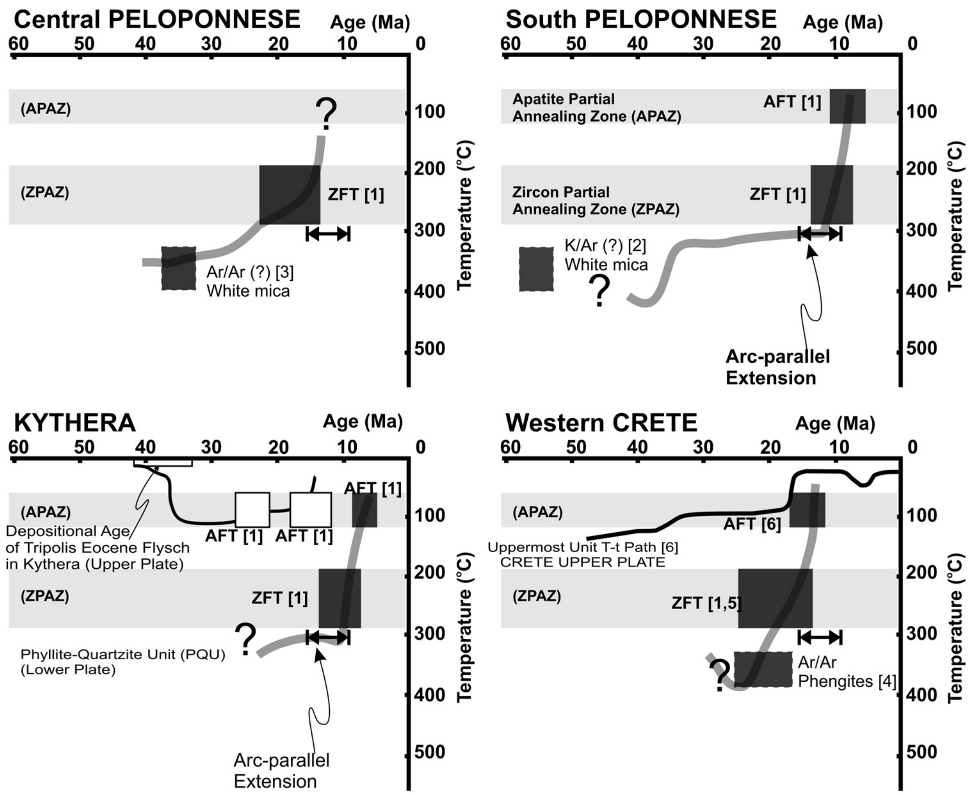

Fig. 12. Temperature-time (T-t) diagram for selected parts of the western Hellenic Arc combining: [1] apatite and zircon fission-track data and Ar-Ar data of this study, [2] K-Ar data of Seidel and others (1982); [3] Ar-Ar data of Panagos and others (1979), [4] Ar-Ar data of Jolivet and others (1996), [5] ZFT data of Brix and others (2002), and [6] AFT data of Thomson and others (1998). T-t history of Uppermost unit of Crete taken from Thomson and others (1998). T-t history of central and south Peloponnese, Kythera and lower plate of westernmost Crete from data obtained in this research. Dark gray boxes and thick gray line are PQU metamorphics of "lower plate" of detachment; white boxes and thin black line are from "upper plate" of detachment.

The time these samples first reached near surface temperatures is uncertain, but the cooling ages suggest that there has been overall slower exhumation after ~7 Ma for the PQU on Kythera and southern Peloponnese (fig. 12). If the mica $^{40}Ar/^{39}Ar$ ages of about 34 Ma from the southern Peloponnese (muscovite—Panagos and others, 1979) are meaningful, cooling from ~350° C to 240° C was much slower than the 240° C to 120° C interval for the PQU rocks of Kythera and vicinity. Consequently, the only rapid exhumation interval for these PQU rocks of the Kythera area occurs between ~11 to 7 Ma, which we think is mostly or entirely in the episode of arc-parallel extension.

A comparison with the better constrained history of the PQU in central-western Crete (Thomson and others, 1998; Brix and others, 2002), and consideration of the peak metamorphic assemblage temperatures on Kythera of about 500° C (Gerolymatos, 1994) together with the likely similar tectonic history to the same rocks in Crete, also suggests that cooling for the Kythera area rocks prior to 13 Ma was most probably slower than in the interval of 13 to 10 Ma, and was very rapid after 10 Ma.

AFT from Upper and Lower Plate in Kythera and Peloponnese

AFT ages reported in this work from the upper plate rocks on Kythera have a narrow range of ~15 to 23 Ma, while upper plate rocks on Crete have a wider range of AFT ages of 11 to 45 Ma (Thomson and others, 1998; Thomson and others, 1999; see fig. 12). The stratigraphic transition up from limestone to flysch is observed on Kythera in the Tripolis unit (Petrocheilos, 1966; Danamos, ms, 1992) and occurs about the mid-Late Eocene boundary (Petrocheilos, 1966; Fleury, 1980; Thiebault, 1982), which implies proximity to the subduction trench at this time (~37-34 Ma). 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° 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. 9), apatites from the Tripolis flysch (sandstone) cooled through the apatite PAZ at ~15 Ma with some evidence of partial resetting at ~23.4 Ma. Because the Tripolis flysch has not experienced high-pressure metamorphism, then most likely the Tripolis unit escaped the subduction trajectory in the interval 23 to 15 Ma.

AFT ages of ~7 Ma from rocks in the sub-detachment PQU unit of Kythera and the southeastern Peloponnese are here inferred to 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.

Time of Transition from Arc-Parallel to Younger Arc-Normal Extension

The question remains as to when transition occurred from the arc-parallel extension to the younger arc-normal extension. ZFT cooling ages of rocks showing arc-parallel extension lineation have ZFT ages of 13 to 9 Ma (corresponding to ~240° C ± 50° C) implying the presence of ductile arc-parallel extension just before that time if accompanying exhumation was rapid, which is consistent with the slip and cooling rates discussed above. Kythera and southeast Peloponnese PQU rocks were also rapidly exhumed, based on the ZFT-AFT age differences, from 240° C to 120° C (a temperature range which requires brittle conditions), during ~11 to 7 Ma. While we do not have (despite trying to find) slickenside information from outcrops of the detachment surface on Kythera and in the southeast Peloponnese to confirm this, we think that it is most plausible that the along-arc extension shown by the ductile to ductile/brittle transition structures continued for exhumation under brittle conditions through the AFT closure temperature. If an approximately 90 degree change in extension direction occurred during a rolling hinge-type detachment event, then subsequent motion on the active inclined brittle fault segment would become strike-slip, or highly oblique slip, and exhumation and cooling rates should have dropped significantly on the existing active fault(s). However, cooling and slip rates we have inferred from the ZFT and AFT data remained high at least through AFT closure at ~7 Ma. For this reason, we think it is unlikely that arc-normal extension on young faults activated in this area until this time. In other words, the arc-parallel to arc-normal transition probably took place at the earliest about 7 Ma. The oldest sediments in the area of Kythera-SE. Peloponnese, which are affected only by the younger arc-normal extension faults, including those of the central graben of the southern half of Kythera (fig. 9) are latest Miocene (late Tortonian, ~7 Ma) according to Meulenkamp and others (1977), which is consistent with this interpretation.

Papanikolau and Royden (2007) show only arc-normal extension (expressed by arc-parallel normal faults) on the detachment(s) in the northern Peloponnese, and point out (page 13 of their paper) that the age of activity of these structures is not well determined. Our apatite FT ages from the PQU in the southern Peloponnese and

Kythera range down to about 7 Ma, which we think approximately constrains the lower age limit of significant brittle displacement on the PQU detachment(s) in the southern Peloponnese. On Kythera, latest Miocene-Pliocene sediments (from ~7Ma) are mildly tilted and cut by young normal faults expressing arc-normal extension (Marsellos and Kidd, 2008), and these small-displacement faults must cut the exposed PQU detachment(s) of Kythera and the southern Peloponnese. The latest Miocene and younger normal faults in the area we have investigated might express motion on a younger detachment (or detachments), but that structure would have to be unexposed (still at depth), and cannot be directly connected with the exposed PQU detachment(s). We suggest that the same may be the case in the northern Peloponnese, where cooling ages have yet to be determined.

The distribution of ZFT ages in the southern Peloponnese and Kythera (fig. 6) by itself might be interpreted to show evidence of cooling related to arc-normal extension from west to east between about 14 and 9 Ma. We think this would be a mistaken interpretation, however, as the ages from 14 to 9 Ma are so clearly associated with arc-parallel extension and sense-of-shear (fig. 10). The spatial distribution of cooling ages that we have obtained, however, obviously needs improvement, particularly for apatite ages, in order to better understand the activity of detachments throughout the Peloponnese.

Van Hinsbergen and Meulenkamp (2006) give a comprehensive synthesis of the sedimentation related to brittle extension on Crete in the Neogene, and claim that progressive abandonment of extensional klippen occurred from south to north over the mid-late Miocene. Zircon FT cooling ages from western Crete, including those determined in this research (fig. 6) suggest that currently exposed PQU rocks there had entered the brittle regime at the latest by 14 Ma and, together with the minimum apatite FT cooling ages of ~12 Ma throughout Crete (fig. 8), make it difficult to argue that the currently exposed detachment fault(s) was still an active extensional feature much later than this age. We suggest that the brittle extensional faults documented by the evidence of Van Hinsbergen and Meulenkamp (2006) affecting sedimentation down to ~7 Ma may have been rooted to another, younger detachment, deeper than, and cutting the detachment currently exposed at the margins of the PQU and PKU outcrop areas.

Age of Arc-Transverse Faults and Their Role in Arc-Parallel Extension and Segmentation

Transverse, arc-perpendicular cross faults (NMTF, NKTF and ITF) may have initiated as normal faults in mid-Miocene, because many other parallel mid-Miocene normal faults were formed in this area (LePichon and others, 2002). The normal displacement on these faults reflects arc-parallel extension, during the late Serravallian (13–11 Ma), the early part of the same interval we have identified as having arc-parallel extension from the ZFT exhumation ages. Some of these faults have clearly had significant strike slip displacements, which we connect to differential movement of segments of the curved forearc in response to slab rollback and upper-plate extension. The Aegean arc convergence history (Savostin and others, 1986) shows an increase of the subduction rate at 10 Ma ago, which would require increased rollback that would drive significant extension in the Aegean and differential expansion of the forearc.

Bending of the Hellenic Arc and Subducting Slab, and Differential Slab Rollback

Motion of Africa with respect to Europe in the eastern Mediterranean area decelerated to a very low convergence rate of a few mm/yr by about 10 Ma ago (Savostin and others, 1986; Rosenbaum and others, 2004, and references therein). Large differential rotations (fig. 13) have been identified from paleomagnetic data (Kissel and Laj, 1988; Morris, 1995; Morris and Anderson, 1996; Walcott and White, 1998; Duermeijer and others, 1998) causing the progressively more prominent curva-

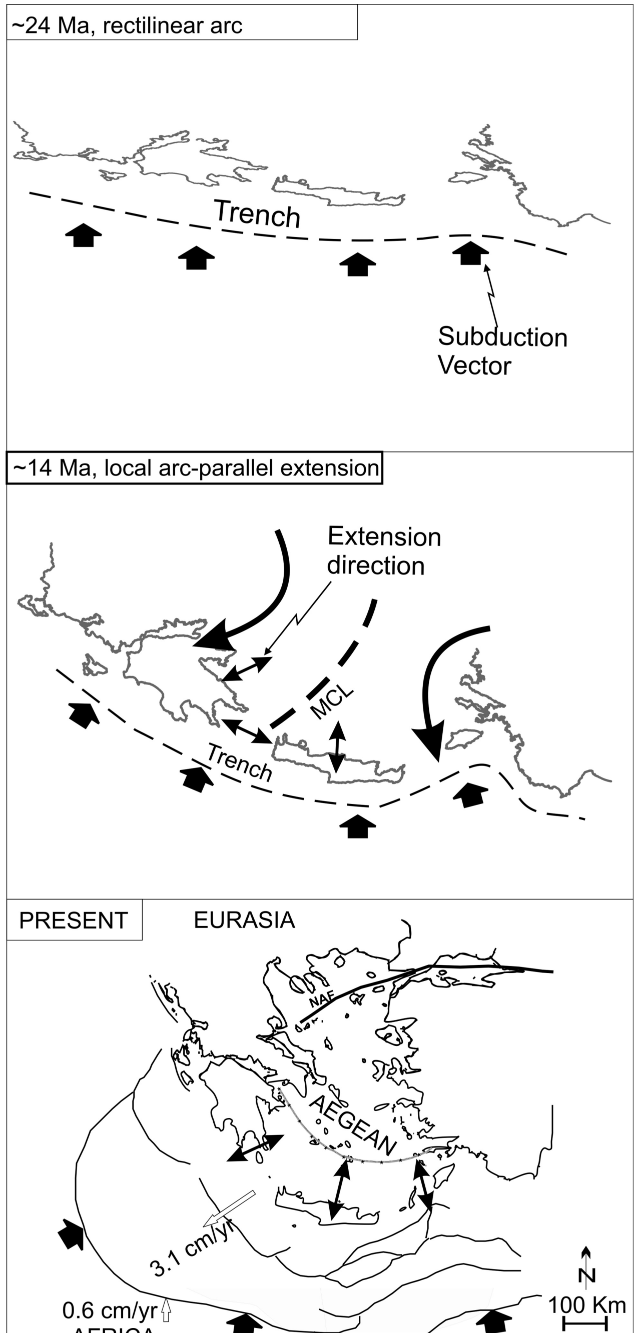

Fig. 13. Tectonic development of the Aegean subduction system; illustrating the expansion and rotation of the western and eastern parts since 24 Ma. Reconstructions at 14 and 24 Ma based on Kissel and Laj (1988) and Walcott and White (1998). See discussion in text. GPS Eurasia-Africa velocity and along the western Hellenic Arc average Hellenic Arc-Africa velocity (derived from an average of five stations LEON, KYRA, OMAL, XRIS and ROML) after McClusky and others (2000).

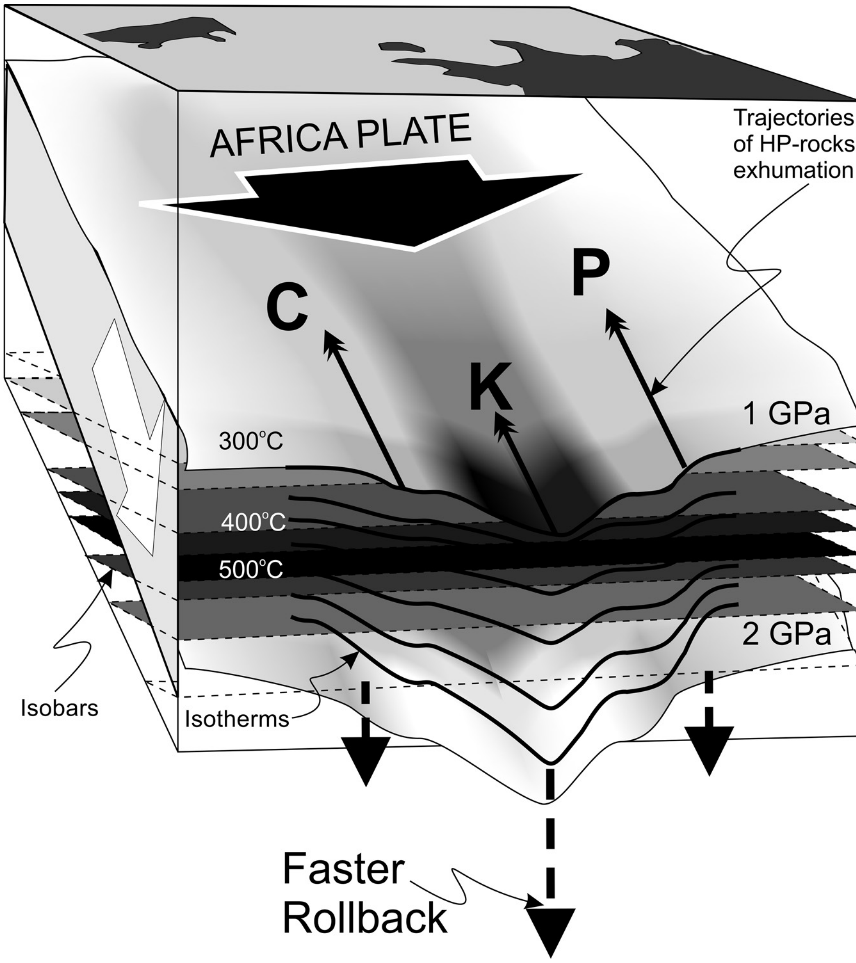

Fig. 14. Depiction of the bending of isotherms during the bending of the subducting slab below the western part of the Hellenic forearc induced by differential slab rollback at a curved subduction zone; C—Crete; K—Kythera; P—Peloponnese.

ture and expansion of the originally rectilinear Hellenic Arc since about 24 Ma. The data compiled by Walcott and White (1998, their table 1) suggest that the differential rotation was rapid in the interval around 12 Ma. The prominent localized arc-parallel extension we have found between 14 to 7 Ma reflects this expansion of the arc. The curving and expansion of the arc requires differential rollback (or slab retreat) of the African oceanic lithosphere, with local rates of convergence between Africa and the Hellenic forearc ridge (as seen now from GPS measurements—fig. 13) much faster than overall Africa-Eurasia motion. This process will also produce a bend and structural low in the downgoing slab (fig. 14), and might have contributed to the occurrence of higher PT metamorphic assemblages now seen in the subsequently exhumed PQU rocks of the southeast Peloponnese-Kythera segment of the Arc. The accretionary prism (Aubouin and others, 1976; Le Pichon and others, 2002) in front of the Kythera-strait-western Crete zone of the Hellenic Arc is the wider part of the accretionary prism (fig. 1), and it narrows in front of eastern-central Crete and central

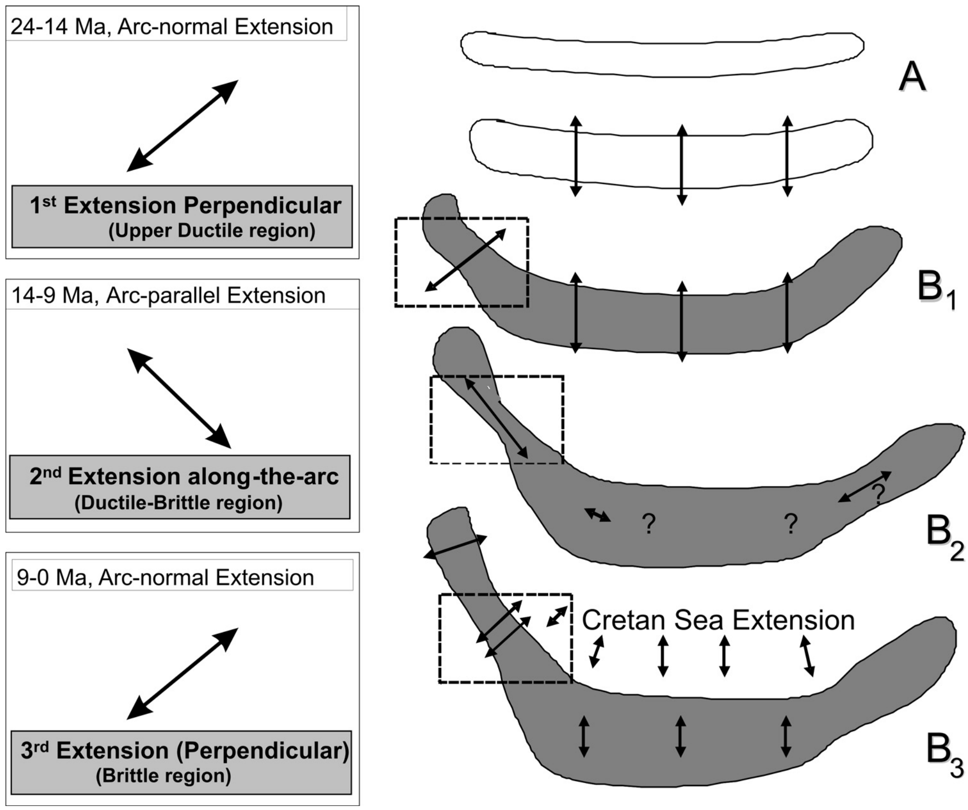

Fig. 15. Extensional episodes of the southwest part of the Hellenic forearc ridge (Marsellos, ms, 2006; Marsellos and Kidd, 2006). Boxed area represents the region including Kythera and the southeastern Peloponnese.

Peloponnese, a feature that could also be related to differential rollback and consequent accretion rates.

Tectonic Evolution of the Hellenic Forearc

Oblique subduction and consequent arc-parallel extension, accompanied by crustal thinning, provides a cause for exhumation of HP rocks with arc-parallel fabrics in the forearc ridge. Exhumation appears to have started with early arc-normal extension affecting all parts of the arc where detachment faults have been found, and either continues or perhaps resumes later in the local region of the southwestern part of the arc through the transitional ductile-brittle stage of exhumation under arc-parallel extension (fig. 15).

We do not know the original morphology of the forearc with any confidence, because late faulting has affected topography and bathymetry. The present forearc narrows towards Kythera and Antikythera from the Peloponnese and Crete; perhaps this might reflect localized extension of the arc in between the southern Peloponnese and western Crete during the latest exhumation of the Kythera PQU rocks. Lyberis and others (1982) suggested that the submersion of the Kythera-Antikythera strait is a consequence of extension related to normal faulting, with the extension rate being faster than in the adjacent segments of the forearc. Slab rollback must have caused increasing curvature and expansion of the Hellenic arc, and the extension caused by this process likely affected the arc geometry primarily by extending and thinning parts of the arc where oblique convergence occurred. This pattern of narrow oblique segments resembles a boudinaged shape (fig. 15). A necked and boudinaged forearc morphology, with progressive exhumation of HP/LT rocks along this forearc, is consistent with localized rapid ductile arc-parallel extension. Differential exhumation moving southward towards Kythera from the central Peloponnese, and from western Crete northwards towards Kythera, is also consistent with this mechanism. It might perhaps also have occurred, with less strain and exhumation, east of Crete in the Karpathos strait.

The topography shows a pattern where PQU rocks occur at lower elevation of exposures in the Kythera strait (maximum of 350 m) compared to Crete and the central Peloponnese (up to more than 1100 m). The pattern (fig. 16) implies that differential amounts of erosion or tectonic denudation are not by themselves responsible for the occurrence of younger exhumation ages and the rapid exhumation through the zircon partial annealing zone (PAZ) shown by our data in the Kythera and southeastern Peloponnese area. The zircon and apatite ages from the PQU rocks in the Cretan-Peloponnese ridge show that there is a roughly uniform exhumation rate of the HP rocks from 230 to 260° C to 100 to 120° C (ductile-brittle to brittle regime), even though the Kythera-southeastern-Peloponnese PQU has a younger age of exhumation than other regions. A change from more uniform extension to localized high-strain regions and back to more uniform strain could also be explained in the context of a short-lived localized boudin-like necking in the obliquely convergent parts of the arc.

The detachment is the primary observable feature on the surface that permitted exhumation of HP-rocks; and it is the primary structure responsible for the ZFT cooling ages. Structural data indicate extension direction or/and top-shear displacement, and the thermochronological data establish them in a temporal order. In the entire Hellenic forearc, the preserved ductile structures and the ages point to one regional exhumation event of arc-normal extension and top-to-backarc displacement, while younger ages associated with structures of arc-parallel extension and mostly top-SE displacement, which overprint the ductile arc-normal structures, require a subsequent exhumation event focused on the southeastern Peloponnese-Kythera strait. Kythera and southeastern Peloponnese PQU rocks have been affected by the earlier arc-normal ductile extension but they were left below the PAZ by this event. When the rocks with older cooling ages now exposed in the central Peloponnese and Crete PQU were crossing the ZPAZ, the rocks with younger cooling ages (southeastern Peloponnese and Kythera PQU) were still at a deeper level, below the PAZ.

There are two alternative hypotheses (fig. 17); in both models, Kythera PQU rocks are left at a lower crustal level after the first (arc-normal extension) stage but in model B the detachment is not held at greater depth for the Kythera arc segment. In model A, PQU rocks exhume through the PAZ while they stretch normal to the arc. The ductile detachment is curved down to explain the younger (and rapid) exhumation observed later for the Kythera segment PQU compared to central Peloponnese and Crete. At 12 Ma, when high topography starts to be created in Crete and Peloponnese (recorded in Middle to Upper Miocene strata on Crete; Fassoulas, 1999; Van Hinsbergen and Meulenkamp, 2006), uplift takes place, while localized arc-parallel stretching of the Kythera strait brings the HP-rocks up in that area without creating high topography. A problem with model A is that there is no reason to localize the younger stretching and exhumation event. It also requires special preparation of this area leaving the early detachment at depth. This is unlikely as it would require very large and implausible changes in the structural level of the detachment along the arc during the early extension. If underthrusting of some unusually buoyant segment caused a large imbrication in the base of the accretionary prism in the Kythera strait arc-segment, this

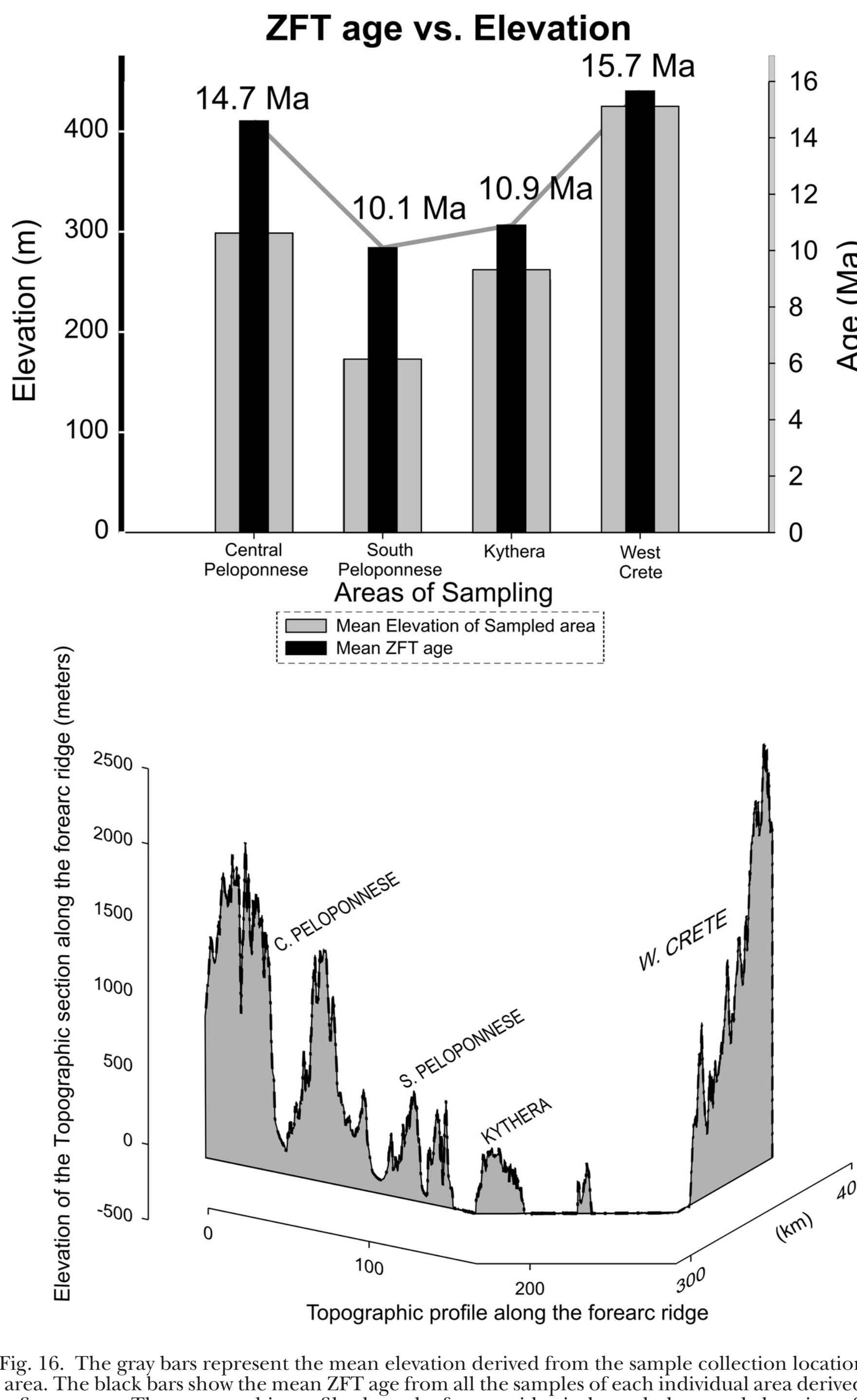

Fig. 16. The gray bars represent the mean elevation derived from the sample collection locations from each area. The black bars show the mean ZFT age from all the samples of each individual area derived by the Binomfit program. The topographic profile along the forearc ridge is through the sample locations. See text for discussion.

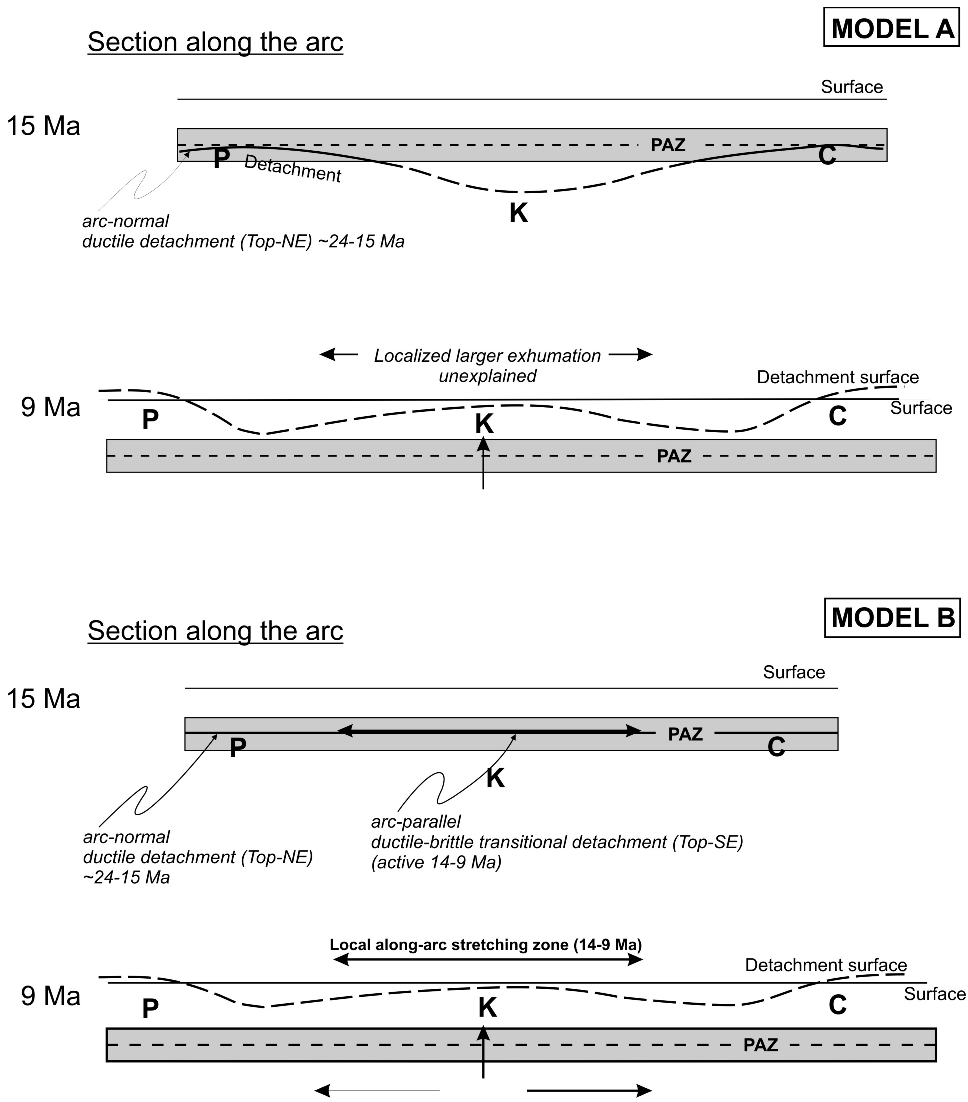

Fig. 17. Two alternative hypotheses for the ZFT exhumation age pattern are shown in models A and B. In both models, Kythera PQU rocks are left at a lower crustal level after the first (arc-normal extension) stage at 15 Ma but in model B the Kythera detachment is not held at anomalous depth at 15 Ma. The rocks with older exhumation ages (central Peloponnese PQU and Crete PQU; marked as P, C) entered the zircon PAZ (Partial Annealing Zone) at or prior to 15 Ma, while the rocks with younger exhumation ages (southeastern Peloponnese and Kythera PQU; marked as K) were deeper, below the PAZ. Between 14 to 9 Ma the Kythera-Neapolis rocks were rapidly exhumed, crossing the zircon PAZ entirely in this interval.

could create local "excess" exhumation of the forearc ridge rocks, but we know of no evidence for this.

Model B is more plausible (fig. 17), where all the HP-rocks along the arc experienced the older ductile detachment, but later a restricted segment experienced local arc-parallel extension. This localized thinning of the upper plate and localized extension and thinning of the PQU then brought the Kythera PQU up to the detachment. The localized extension through an along-the-arc detachment focuses the latest part of the exhumation of HP-rocks in the southeastern Peloponnese-Kythera arc-segment. Peloponnese and Crete have thicker crust and higher topography compared to Kythera and the Kythera strait which is also consistent with this second model, and it is also consistent with the occurrence of the P-T maximum of the exposed relict HP-rocks along this segment of the Hellenic arc.

CONCLUSIONS

Lineations and shear sense kinematic indicators from the sub-detachment rocks of the southwestern Hellenic Arc show that some belong to an old set of arc-normal ductile extension and some to a younger set of arc-parallel ductile to transitional ductile/brittle extension. Cooling ages indicate that there were two detachment events, one prior to 15 Ma and another starting at ~14 Ma. The first detachment was characterized by arc-normal extension and top-NE displacement, while the younger ductile and ductile-brittle transitional detachment overprinted earlier structures with arc-parallel extension and mainly top-SE displacement in the exposures of Kythera and southeastern Peloponnese. NE-trending normal faults are inferred to have initiated the younger exhumation of the exposed metamorphic complex in the western Cretan-Peloponnese ridge. Some of those faults have been converted to transverse strike-slip faults after extension returned to arc-normal direction during the latest (late Miocene-Recent) episode of brittle deformation.

ZFT cooling age gradients mark two opposed exhumation polarities of HP-rocks in the forearc ridge, from Crete towards Kythera, and from Peloponnese to Kythera. The Kythera and southeastern Peloponnese PQU are the areas of youngest exhumation of HP-rocks, and were affected by an arc-parallel extensional tectonic event between about 14 and 7 Ma ago. ZFT cooling ages from the PQU suggest that this younger exhumation of HP-rocks was progressive along the western Hellenic forearc ridge, and age gradients of the ZFT ages imply extension rates in the range 4 to 12 km/Ma. However, the rate of the exhumation in different places, as far as constrained by the ZFT to AFT age interval, does not show large differences. Zircons from HP rocks of eastern Crete and central Peloponnese did not get fully reset and probably were never exposed to higher temperatures than the limit of the zircon PAZ. In contrast, zircons from the HP rocks in the Kythera and southern Peloponnese show mixed-reset ages to full resetting, and have been subjected to temperatures above the zircon PAZ. Apatite FT ages of ~7 Ma from the PQU of Kythera and nearby SE Peloponnese reflect late Miocene exhumation, probably the brittle stage of the arc-parallel extension event, and which was followed by a return to arc-normal extension. The young exhumation of the Kythera PQU is likely a product of very intense expansion of the Aegean arc caused by rollback of the African oceanic subducted plate, and was probably localized by a strain partitioning response to the increasingly oblique plate convergence vector on the western "wing" of the Hellenic Arc.

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Appendix 1

fission track age analytical methods

Zircon Fission Track Analyses

Zircon fission track data have been obtained from 33 samples, all being detrital zircon suites, mostly from quartzites and micaceous quartzites of the Phyllite-Quartzite Unit (PQU) in the Peloponnese, Kythera and western Crete. Samples were collected from localities close to the detachment contact between the metamorphic PQU and the overlying unmetamorphosed units. At each locality about 7 to 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 in them (Naeser, 1976). Zircons from samples with pyrite were hand-separated using two adjacent glass slides (surfaces) with different elevations located in a dish filled with ethanol. After the ethanol dried, the slide having the separated zircons without pyrite was removed and the zircons collected.

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 to 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 9h to 38h depending on the sample. Samples from Kythera, as well as those from the Neapolis area needed more than 30h to etch, as compared to samples from the Peloponnese and Crete, which in some cases needed less than 10h.

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 (that is Fish Canyon Tuff, Buluk Tuff, and Peach Springs Tuff; see Hurford, 1990). All samples were dated using the external detector method (Naeser, 1976; Gleadow, 1981). The detector mica was etched for 18min in 49 percent HF at room temperature. All samples were counted at 1250× using a dry 100× objective (10× oculars and 1.25× tube factor) on an Olympus BMAX 60 microscope fitted with an automated stage and a digitizing tablet. All ages with χ^2>5 percent are reported as pooled ages. Fission track ages ($\pm 1\sigma$) were determined using the Zeta method, and ages were calculated using the computer program and equations in Brandon (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, that is 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.

Apatite Fission Track Analyses

Forty two samples from along the Hellenic forearc ridge were selected for apatite fission track analysis. Of these, 14 contained apatite but only 6 with sufficiently high and consistent uranium contents to be suitable for fission track analysis. The analytical details and methods used are the same as those given by Hurford (1990).

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