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Fast extension but little exhumation: the Vari detachment in the Cyclades, Greece

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Abstract – Markedly different cooling histories for the hanging- and footwall of the Vari detachment on Syros and Tinos islands, Greece, are revealed by zircon and apatite fission-track data. The Vari/Akrotiri unit in the hangingwall cooled slowly at rates of 5–15 °C Myr^{-1} since Late Cretaceous times. Samples from the Cycladic blueschist unit in the footwall of the detachment on Tinos Island have a mean zircon fission-track age of 10.0 ± 1.0 Ma, which together with a published mean apatite fission-track age of 9.4 ± 0.5 Ma indicates rapid cooling at rates of at least ~ 60 °C Myr^{-1}. We derive a minimum slip rate of ~ 6.5 km Myr^{-1} and a displacement of $> \sim 20$ km and propose that the development of the detachment in the thermally softened magmatic arc aided fast displacement. Intra-arc extension accomplished the final ~ 6–9 km of exhumation of the Cycladic blueschists from ~ 60 km depth. The fast-slipping intra-arc detachments did not cause much exhumation, but were important for regional-scale extension and the formation of the Aegean Sea.

Keywords: Detachment faults, fission-track dating, exhumation, Cyclades, Greece.

1. Introduction

In extending orogens like the Basin and Range province of the western United States, the Alboran Sea in the western Mediterranean and the Aegean Sea in the eastern Mediterranean, knowledge of rates of tectonic processes are important for understanding which process is primarily extending the crust. Platt *et al.* (1998) proposed that homogeneous stretching of the lithosphere (vertical ductile thinning associated with a subhorizontal foliation) at rates of 4–5 km Myr^{-1} is the dominant process that formed the Alboran Sea. The Aegean Sea is well known for its low-angle normal faults (detachments) (Lister, Banga & Feenstra, 1984; Lister & Forster, 1996), suggesting that detachment faulting may have been the primary agent achieving $\sim > 250$ km (McKenzie, 1978) of extension since Miocene times.

The Aegean detachments on the Cycladic islands occur in the current back-arc of the southward-retreating Hellenic subduction zone (Fig. 1). The time of movement along the detachments, their relationship to the southward-migrating magmatic arc (Fytikas *et al.* 1984), and the role the late-stage detachments played in the exhumation of the Cycladic blueschist unit and in the formation of the Aegean Sea are poorly known (Lister & Forster, 1996). In regions heated by syn-extensional magmatism, shallow-dipping detachments commonly root at ~ 10–15 km depths (Gans, 1987). A characteristic feature of the footwalls of such detachments is that they cool rapidly as they are dragged towards the surface (Foster & John, 1999). Hence, low-temperature thermochronology is a powerful tool for establishing cooling and slip rates and the time of movement of these detachments.

We report Late Miocene zircon fission-track ages from an ophiolitic mélange in the footwall of the Vari detachment on Syros and Tinos islands, which together with apatite fission-track ages from the Tinos granite (Hejl, Riedl & Weingartner, 2002) indicate rapid cooling of the footwall at 9–12 Ma. Rocks in the hangingwall of the Vari detachment cooled much slower than those in the footwall. Our data provide evidence for fast-slipping detachments in the Cyclades. These detachments did not cause much exhumation but achieved considerable extension indicating that low-angle normal faulting was the dominant tectonic process that formed the Aegean Sea.

2. Setting

Previous research has distinguished several tectonic zones in the Hellenides characterized by rock type, stratigraphy, tectonometamorphic history and pre-orogenic palaeogeography (Robertson *et al.* 1991). The Cycladic zone is fringed to the north by the oceanic Vardar–Izmir–Ankara suture zone, and the continental Lycian/Pelagonian zone (Fig. 1). The dominant tectonic unit of the Cycladic zone is the Cycladic blueschist unit, which comprises an ophiolitic mélange at the top

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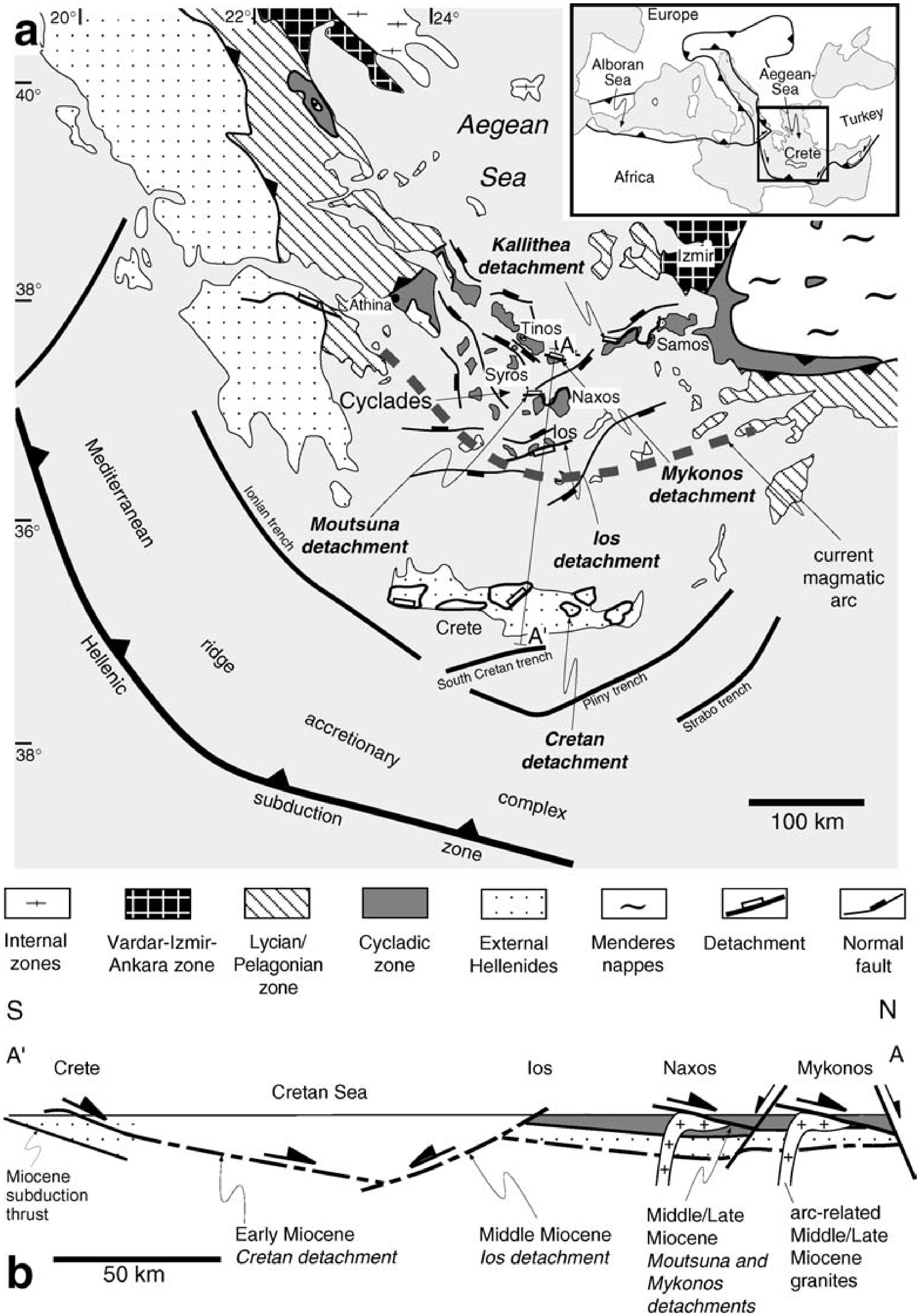

Figure 1. For legend see facing page.

and an underlying Carboniferous basement with a post-Carboniferous cover sequence (Dürr *et al*. 1978; Ring, Laws & Bernet, 1999). The Cycladic blueschist unit is overlain on some islands by the Upper unit, which on the islands of Syros and Tinos is in turn overlain by the Vari/Akrotiri unit. In some windows in the Cycladic zone, the Basal unit, a part of the External Hellenides, crops out below the Cycladic blueschist unit (Avigad & Garfunkel, 1989).

The metamorphic evolution of the Cycladic blueschist unit includes an Early Tertiary high-pressure event (15–20 kbar and 450–550 °C) at ~55–(?)78 Ma followed by a greenschist-facies overprint (4–7 kbar and 400 ± 50 °C on most islands) at ~16–21 Ma (Altherr *et al*. 1982; Wijbrans, Schliestedt & York, 1990; Bröcker *et al*. 1993; Ring & Layer, 2003). The Miocene greenschist-facies metamorphism also affected the Upper unit on Tinos Island at ~21 Ma (Bröcker & Franz, 1998). The Vari/Akrotiri unit experienced lower amphibolite-facies metamorphism (6.5–7.5 kbar and 530–610 °C) at 66–77 Ma (Maluski, Bonneau & Kienast, 1987; Patzak, Okrusch & Kreuzer, 1994). High-pressure metamorphism in the Basal unit on Evia and Samos islands is dated at 21–24 Ma (Ring, Layer & Reischmann, 2001; Ring & Reischmann, 2002).

In Middle to Late Miocene times, the Cyclades became part of the magmatic arc of the southward-retreating Hellenic subduction zone as evidenced by arc-related volcanic rocks ranging from ~5–12 Ma (Fytikas *et al*. 1984; Weidmann *et al*. 1984) and granites spanning an age range from ~10–14 Ma (S. Keay, unpub. Ph.D. thesis, Australian National Univ., 1998). The granites on Mykonos and Naxos islands are syn-tectonic to major detachments (Lee & Lister, 1992; Lister & Forster, 1996). The 14–17 Ma Tinos granite (Altherr *et al*. 1982) has a well-developed contact aureole that formed at ~14 Ma (Bröcker & Franz, 2000). Bröcker & Franz (2000) reported Rb–Sr biotite ages of 8–10 Ma from the contact aureole, which might be related to post-intrusion deformation at the margin of the granite.

3. The Vari detachment

The detachment is exposed on Syros Island, where it separates the Vari gneiss from underlying mica schist, quartzite, marble, metabasite and ophiolitic rocks of the Cycladic blueschist unit and from phyllite of the Upper unit (Fig. 2). The Vari gneiss is only exposed in southeast Syros. However, judging from the general field relations it is realistic to assume that the Vari detachment once occupied the entire island (Bröcker & Enders, 1999). Detailed research has shown that the Vari detachment reappears in the southeast of Tinos Island, where it separates the Akrotiri gneiss from the Upper unit (Fig. 2). This conclusion is based on the similar geology and metamorphic conditions in the foot- and hangingwall of the detachment on both islands (Patzak, Okrusch & Kreuzer, 1994; Maluski, Bonneau & Kienast, 1987) and geometric considerations (Fig. 2c). Between Syros and Tinos islands the Vari detachments has been offset by two high-angle normal faults (Doutsos & Kokkalas, 2001), which caused ~3 km of post-detachment horizontal extension.

The fault zone of the Vari detachment is made up of brecciated cataclasite in which rocks from the hanging- and footwall are intermixed. The rocks immediately above and below the Vari detachment are strongly retrograded and cataclastically reworked. A stretching lineation associated with brittle shear-sense indicators testifies top-to-the-NE tectonic transport for the detachment. Shear-sense indicators and microstructures in the fault zone are equivalent on both islands.

The Upper unit constitutes the footwall immediate to the Vari detachment (Fig. 3) and is separated from the underlying Cycladic blueschist unit by a greenschist-facies mylonite zone interpreted to be an extensional shear zone (Avigad & Garfunkel, 1989). Rb–Sr white mica dating showed that this mylonite formed at ~21 Ma and was cut by 14–17 Ma Tinos granite (Bröcker & Franz, 1998; S. Keay, unpub. Ph.D. thesis, Australian National Univ. 1998). Ophiolitic rocks directly below the Upper unit are suitable for zircon fission-track dating in the Kampos section of northern Syros and near Kionia in southern Tinos. Because these two outcrops occupy different geographic positions parallel to the top-to-the-NE tectonic transport direction of the Vari detachment, potentially different cooling ages should yield a time-averaged displacement rate for the detachment. This statement demands that there is one single detachment, which is in accord with the geological, metamorphic and structural arguments given above. Furthermore, we will argue below that the detachment caused 6–9 km of exhumation, which demands a fairly large lateral extent of the detachment and makes two single detachments unlikely.

4. Fission-track data

Fission-track analysis on zircon and apatite was carried out at Ruhr-Universität, Bochum, and our results are

Figure 1. (a) Generalized tectonic map of Hellenides showing major tectonic zones, islands of Syros and Tinos and major detachments, which represent latest generation of shallow-dipping, penetrative extensional structures; note that pattern of detachments is simplified. Insert: Miocene to Recent thrust fronts in Mediterranean region and location of main map. (b) NNE–SSW cross-section showing nappe pile and major Miocene detachments in southern Aegean; Cretan detachment operated above Early Miocene subduction thrust; Moutsuna and Mykonos detachments are syn-tectonic to arc-related Middle/Late Miocene granites.

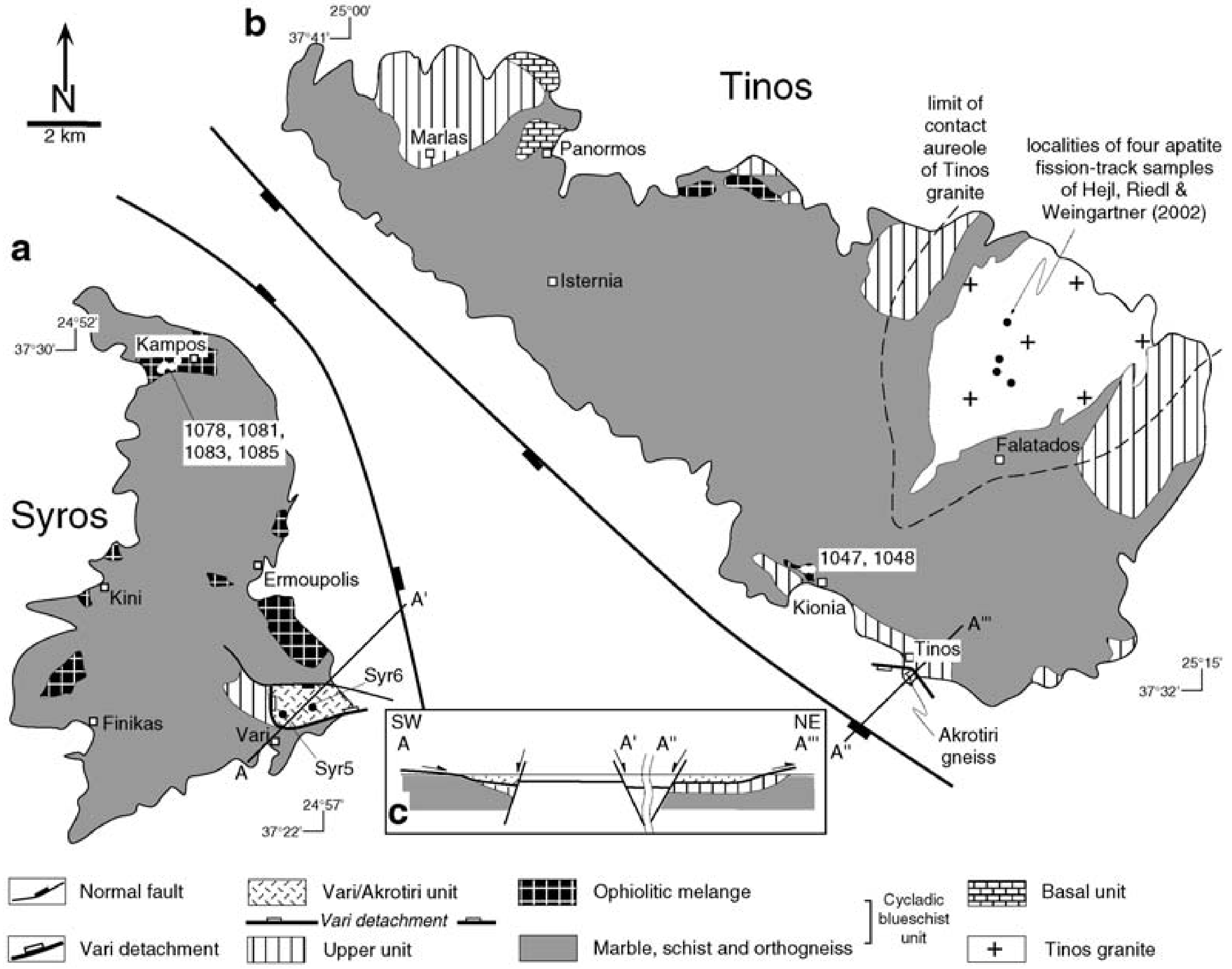

Figure 2. Geological maps of Syros (a) and Tinos (b) islands (Syros map simplified from J. C. Schumacher, unpub. map; Tinos map modified from Bröcker & Franz, 1998); sample localities and Vari detachment are shown. Note that the two maps do not represent the true geographic positions of the islands with respect to one another. (c) Schematic NE–SW cross-section showing geometry of Vari detachment.

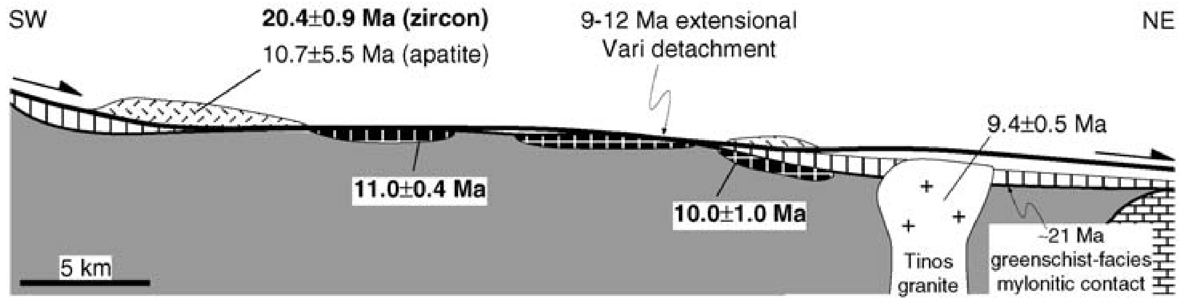

Figure 3. Schematic cross-section at onset of detachment faulting showing tectonic units and fission-track ages (zircon ages in bold) (apatite ages from Tinos granite from Hejl, Riedl & Weingartner, 2002); greenschist-facies mylonitic contact between Cycladic blueschist unit and Upper unit (dated at ~ 21 Ma; Bröcker & Franz, 1998) cuts contact between Cycladic blueschist and Basal unit and is itself cut by 14–17 Ma Tinos granite (S. Keay, unpub. Ph.D. thesis, Australian National Univ., 1998); Vari detachment formed ~ 10 Ma later than greenschist-facies contact and brought Vari/Akrotiri unit from the southwest into present position on Syros and Tinos; timing and cross-cutting relationships indicate that proposed greenschist-facies extensional contact between Cycladic blueschists and Upper unit was not reactivated during intra-arc detachment faulting at 9–12 Ma. For legend see Figure 2.

Table 1. Fission-track data from the islands of Syros and Tinos

Sample no. (rock type)	Mineral	No. of crystals	Track density ($\times 10^6$ tr cm^{-2}) ρ_s (N_s)	ρ_i (N_i)	ρ_d (N_d)	Age dispersion ($P\chi^2$)	Central age (Ma) ($\pm 1\sigma$)
Syr 5 (Orthogneiss)	Apatite	5	0.01073 (4)	0.2146 (80)	1.193 (8237)	12 % (50 %)	10.7 ± 5.5
	Zircon	20	1.581 (607)	1.722 (661)	0.3546 (4898)	0 % (99 %)	21.2 ± 1.3
Syr 6 (Orthogneiss)	Zircon	8	6.336 (490)	7.810 (604)	3.701 (5111)	0 % (90 %)	19.6 ± 1.3
1047 (Eclogite)	Zircon	9	0.2380 (47)	0.5823 (115)	3.604 (4978)	0 % (94 %)	9.6 ± 1.7
1048 (Eclogite)	Zircon	20	0.3031 (108)	0.7381 (263)	3.797 (5244)	0 % (99 %)	10.2 ± 1.2
1078 Jadeitite)	Zircon	20	0.3727 (368)	0.8892 (878)	3.672 (5071)	0 % (97 %)	10.1 ± 0.7
1081 (Ompacitite)	Zircon	20	0.2463 (663)	0.5127 (1360)	3.788 (5231)	0 % (96 %)	11.9 ± 0.6
1083 (Ompacitite)	Zircon	20	0.2735 (227)	0.5747 (477)	3.527 (4871)	0 % (99 %)	11.0 ± 0.9
1085 (Ompacitite)	Zircon	20	0.4907 (288)	1.024 (601)	3.556 (4911)	0 % (99 %)	11.1 ± 0.9

Analyses by external detector method using 0.5 for the $2\pi/4\pi$ geometry correction factor.
Ages calculated using dosimeter glasses: CN5 (apatite) with $\zeta_{CN5} = 358.8 \pm 12.7$; CN2 (zircon) with $\zeta_{CN2} = 130.7 \pm 2.8$.
$P\chi^2$ is the probability of obtaining a χ^2 value for v degrees of freedom where v = no. of crystals – 1.

listed in Table 1. Fission tracks were analysed using the external detector and ζ-calibration approach (Hurford & Green, 1982; Hurford, 1990). Ages were calculated using the central-age method of Galbraith & Laslett (1993) which allows for non-Poissonian variation within a population of single-grain ages belonging to an individual sample. We analysed zircons from six samples of the ophiolitic mélange at the top of the Cycladic blueschist unit. In the hangingwall of the detachment, we dated zircon and apatite from two samples collected in Vari gneiss. The usually assumed closure temperature for fission tracks in zircon varies between ~240 °C and ~280 °C, being higher for zircons cooled quickly from high temperatures in which natural α-damage is very low (Brandon, Roden-Tice & Garver, 1998) and ~110 ± 10 °C for apatite (Gleadow & Duddy, 1981).

The zircon ages from the ophiolitic mélange range from 10.1 ± 0.7 to 11.9 ± 0.6 Ma (weighted mean age 11.0 ± 0.4 Ma) in the Kampos section of Syros Island and 9.6 ± 1.7 to 10.2 ± 1.2 Ma (weighted mean age 10.0 ± 1.0 Ma) at Kionia on Tinos Island (Table 1, Fig. 2). Hejl, Riedl & Weingartner (2002) reported four apatite fission-track ages ranging between 8.4 ± 0.7 and 9.5 ± 0.8 Ma (weighted mean age of 9.4 ± 0.5 Ma) from the Tinos granite. In the Vari gneiss in the hangingwall of the detachment, zircon fission-track ages range from 19.6 ± 1.3 to 21.2 ± 1.3 Ma (weighted mean age 20.4 ± 0.9 Ma); sample Syr5 yielded an apatite fission-track age of 10.7 ± 5.5 Ma.

5. Discussion

The consistent fission-track ages indicate a marked difference in the cooling history between the ophiolitic mélange of the Cycladic blueschist unit and the Vari/Akrotiri unit. The mean of our zircon fission-track data from Tinos Island (10.0 ± 1.0 Ma) combined with the mean apatite fission-track age of Hejl, Riedl & Weingartner (2002) from the Tinos granite (9.4 ± 0.5 Ma) allows the derivation of a fast minimum cooling rate of ~60 °C Myr^{-1} for the footwall of the Vari detachment. As the ages overlap within error, the derived maximum cooling rate is unlimited. The mean track lengths in apatite reported by Hejl, Riedl & Weingartner (2002) are ~14–15 μm and support fast cooling. For the hangingwall, the metamorphic temperature of 530–610 °C at 66–77 Ma yields a time-averaged cooling rate of < 10 °C Myr^{-1} for the interval between 20 and 70 Ma. Our zircon and apatite fission-track data indicate a cooling rate of 10–15 °C Myr^{-1} between 10 and 20 Ma. The distinct difference in the cooling history of the hanging- and footwall is consistent with an extensional interpretation for the Vari detachment (Wheeler & Butler, 1994; Thomson, 1998; Ring *et al.* 1999).

The mean zircon fission-track ages young from 11.0 ± 0.4 Ma in the Kampos section on Syros Island to 10.0 ± 1.0 Ma at Kionia on Tinos Island. Both ages overlap within error suggesting very fast extension. If the ~3 km of post-detachment normal faulting between Syros and Tinos islands is restored, then the distance parallel to top-to-the-NE tectonic transport on the Vari detachment between both outcrops is ~15 km and results in a time-averaged minimum displacement rate of at least ~6.5 km Myr^{-1} for the Vari detachment. The apatite fission-track data of Hejl, Riedl & Weingartner (2002) from the footwall of the Mykonos detachment (Fig. 1b) yield a similar slip rate. We propose that such great slip rates are due to faulting in the hot and therefore softened magmatic arc of the Middle to Late Miocene Hellenic subduction zone. The Kallithea, Moutsuna and Ios detachments (Fig. 1) are also associated with syn-tectonic arc-related granites (Lister & Forster, 1996; Ring, Laws & Bernet, 1999) and we speculate that these detachments moved at similar rates. For the Cretan detachment in the fore-arc of the Hellenic subduction zone, Ring & Reischmann (2002) reported a slip rate of >20 km Myr^{-1}.

Our estimates of slip rates from cooling rates derived from thermochronological data assume that the isotherms were immobile at the time of active extensional detachment faulting. Although isotherms may rise owing to heat advection during fast unroofing, Ketcham (1996) has demonstrated using thermal models that the thermal structure quickly approaches a steady state after the onset of extension. Ketcham (1996) also showed that as the isotherms in the footwall rise in the footwall slip direction, slip rates determined from thermochronological data will actually underestimate the true slip rate. Also, the underestimate decreases for systems with lower closure temperatures, and is generally minimal for slip rates determined from fission-track data. Therefore, our derived minimum slip rate requires no adjustment.

The zircon and apatite fission-track ages from the footwall indicate that the Vari detachment was active at about 9–12 Ma. The displacement rate and the duration of detachment faulting imply a total displacement of ~> 20 km on the Vari detachment. Similar ages and possibly displacements have been proposed for the Mykonos, Montsuna and Kallithea detachments (Fig. 1) (Lee & Lister, 1992; Lister & Forster, 1996; Ring, Laws & Bernet, 1999). Further south, the Ios detachment was active at 12–14 Ma (Lister & Forster, 1996) and the Cretan detachment developed sometime between 17 and 24 Ma (Thomson, Stöckhert & Brix, 1998, 1999). Displacement on each of the latter two detachments was on the order of 50 to > 100 km (Lister & Forster, 1996; Ring, Layer & Reischmann, 2001; Ring, Brachert & Fassoulas, 2001). These displacements estimates show that fast detachment faulting in the Miocene accomplished > 200 km of horizontal extension and was therefore the dominant tectonic process that formed the Aegean Sea. Ring (1998) estimated that vertical ductile thinning associated with a subhorizontal foliation contributed ~9–10 km to the exhumation of the Cycladic blueschist unit on Samos Island. If this value is assumed to be representative for the Aegean and volume-constant plane-strain deformation is also assumed, homogeneous stretching must have caused < 30 km of horizontal extension. It follows that homogeneous stretching of the lithosphere was not an important extension mechanism in the Aegean.

The final exhumation of the Cycladic blueschist unit on Syros and Tinos islands was achieved by the Vari detachment. Assuming a thermal field gradient of 30–40 °C km^{-1} in the magmatic arc yields a closure depth for zircon fission tracks of 6–9 km. Given the cataclastic deformation conditions at the Vari detachment, the detachment appears to have operated at temperatures < 240–280 °C, that is, the zircon fission-track ages approximately date the onset of detachment faulting. Hence, the final ~6–9 km of exhumation of the Cycladic blueschist unit from depths of ~60 km was accomplished by Middle/Late Miocene detachment faulting in an intra-arc setting. The Vari detachment was only responsible for the final 10–15 % of total exhumation of the Cycladic blueschists and their eventual exposure at the Earth's surface by Late Miocene times. The Cycladic blueschists evidently achieved most of their exhumation before the onset of intra-arc detachment faulting and therefore in a fore-arc position.

6. Conclusions

Fission-track dating reveals that the Vari detachment on the Cycladic islands of Syros and Tinos operated at 9–12 Ma in the magmatic arc of the Hellenic subduction zone. Our data imply a minimum displacement rate of ~6.5 km Myr^{-1} and a total offset of about > 20 km. Fast slip and large offset were aided by the development of the Vari detachment in the hot and thus weak magmatic arc. The Vari detachment achieved the final ~6–9 km of exhumation of the Cycladic blueschist unit on Syros and Tinos islands. It was therefore not important for overall blueschist exhumation, but fast-slipping detachments were the primary agent for the opening of the Aegean Sea.

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References

Altherr, R., Kreuzer, H., Wendt, I., Lenz, H., Wagner, G. H., Keller, J., Harre, W. & Höhndorf, A. 1982. A late Oligocene/early Miocene high temperature belt in the Attic-Cycladic crystalline complex (SE Pelagonian, Greece). *Geologisches Jahrbuch* **E23**, 97–164.

AVIGAD, D. & GARFUNKEL, T. 1989. Low-angle faults above and below a blueschist belt–Tinos Island, Cyclades, Greece. *Terra Nova* **1**, 182–7.

BRANDON, M. T., RODEN-TICE, M. K. & GARVER, J. I. 1998. Late Cenozoic exhumation of the Cascadia accretionary wedge in the Olympic Mountains, NW Washington State. *Geological Society of America Bulletin* **110**, 985–1009.

BRÖCKER, M. & ENDERS, M. 1999. U–Pb zircon geochronology of unusual eclogite-facies rocks from Syros and Tinos (Cyclades, Greece). *Geological Magazine* **136**, 111–18.

BRÖCKER, M. & FRANZ, L. 1998. Rb–Sr isotope studies on Tinos Island (Cyclades, Greece): additional time constraints for metamorphism, extent of infiltration-controlled overprinting and deformational activity. *Geological Magazine* **135**, 369–82.

BRÖCKER, M. & FRANZ, L. 2000. The contact aureole on Tinos (Cyclades, Greece): tourmaline–biotite geothermometry and Rb–Sr geochronology. *Mineralogy and Petrology* **70**, 257–83.

BRÖCKER, M., KREUZER, H., MATTHEWS, A. & OKRUSCH, M. 1993. $^{39}Ar/^{40}Ar$ and oxygen isotope studies of polymetamorphism from Tinos Island, Cycladic blueschist belt. *Journal of Metamorphic Geology* **11**, 223–40.

DOUTSOS, T. & KOKKALAS, S. 2001. Stress and deformation patterns in the Aegean region. *Journal of Structural Geology* **23**, 455–72.

DÜRR, S., ALTHERR, R., KELLER, J., OKRUSCH, M. & SEIDEL, E. 1978. The median Aegean crystalline belt: Stratigraphy, structure, metamorphism, magmatism. In *Alps, Appenines, Hellenides* (eds H. Closs *et al.*), pp. 537–64. Stuttgart: Schweizerbart.

FOSTER, D. A. & JOHN, B. E. 1999. Quantifying tectonic exhumation in an extensional orogen with thermochronology: examples from the southern Basin and Range province. In *Exhumation processes: Normal faulting, ductile flow and erosion* (eds U. Ring *et al.*), pp. 343–64. Geological Society of London, Special Publication no. 154.

FYTIKAS, M., INNOCENTI, F., MANETTI, P., MAZZUOLI, R., PECCERILLO, A. & VILLARI, L. 1984. Tertiary to Quaternary evolution of volcanism in the Aegean region. In *The geological evolution of the eastern Mediterranean* (eds A. H. F. Robertson and J. E. Dixon), pp. 687–99. Geological Society of London, Special Publication no. 17.

GALBRAITH, R. F. & LASLETT, G. M. 1993. Statistical models for mixed fission track ages. *Nuclear Tracks and Radiation Measurements* **21**, 459–70.

GANS, P. B. 1987. An open-system, two-layer crustal stretching model for the eastern Great Basin. *Tectonics* **6**, 1–12.

GLEADOW, A. J. W. & DUDDY, I. R. 1981. A natural long-term track annealing experiment on apatite. *Nuclear Tracks* **5**, 169–74.

HEJL, E., RIEDL, H. & WEINGARTNER, H. 2002. Post-plutonic unroofing and morphogenesis of the Attic-Cycladic complex (Aegea, Greece). *Tectonophysics* **349**, 37–56.

HURFORD, A. J. 1990. Standardization of fission-track dating calibration: Recommendation by the Fission Track Working Group of the I.U.G.S. Subcommission on Geochronology. *Chemical Geology* **80**, 171–8.

HURFORD, A. J. & GREEN, P. F. 1982. A users' guide to fission track dating. *Earth and Planetary Science Letters* **59**, 343–54.

KETCHAM, R. A. 1996. Thermal models of core-complex evolution in Arizona and New Guinea: Implications for ancient cooling paths and present-day heat flow. *Tectonics* **15**, 933–51.

LEE, J. & LISTER, G. S. 1992. Late Miocene ductile extension and detachment faulting, Mykonos, Greece. *Geology* **20**, 121–4.

LISTER, G. S., BANGA, G. & FEENSTRA, A. 1984. Metamorphic core complexes of Cordilleran type in the Cyclades, Aegean Sea, Greece. *Geology* **12**, 221–5.

LISTER, G. S. & FORSTER, M. 1996. Inside the Aegean metamorphic core complexes. *Technical Publications of the Australian Crustal Research Centre* **45**, 110 pp.

MALUSKI, H., BONNEAU, M. & KIENAST, J.-R. 1987. Dating the metamorphic events in the Cycladic area: $^{39}Ar/^{40}Ar$ data from metamorphic rocks of the island of Syros (Greece). *Bulletin Societé Geologique de France* **5**, 833–42.

MCKENZIE, D. 1978. Active tectonics of the Alpine-Himalayan belt: The Aegean Sea and surrounding regions. *Royal Astronomical Society Geophysical Journal* **55**, 217–54.

PATZAK, M., OKRUSCH, M. & KREUZER, H. 1994. The Akrotiri unit on the island of Tinos, Cyclades, Greece: witness to a lost terrane of Late Cretaceous age. *Neues Jahrbuch Geologisch Paläontologische Abhandlungen* **194**, 211–52.

PLATT, J. P., SOTO J. I., WHITEHOUSE, M. J., HURFORD, A. J. & KELLEY, S. P. 1998. Thermal evolution, rate of exhumation, and tectonic significance of metamorphic rocks from the floor of the Alboran extensional basin, western Mediterranean. *Tectonics* **17**, 671–89.

RING, U. 1998. Exhumation of blueschists from Samos Island, Greece. *Bulletin Geological Society of Greece* **32**, 97–104.

RING, U., BRACHERT, T. & FASSOULAS, C. 2001. Middle Miocene graben development in Crete and its possible relation to large-scale detachment faults. *Terra Nova* **13**, 297–304.

RING, U., BRANDON, M. T., WILLETT, S. D. & LISTER, G. S. 1999. Exhumation processes. In *Exhumation processes: Normal faulting, ductile flow and erosion* (eds U. Ring *et al.*), pp. 1–27. Geological Society of London, Special Publication no. 154.

RING, U., LAWS, S. & BERNET, M. 1999. Structural analysis of a complex nappe sequence and late-orogenic basins from the Aegean Island of Samos, Greece. *Journal of Structural Geology* **21**, 1575–1601.

RING, U. & LAYER, P. W. 2003. High-pressure metamorphism in the Aegean, eastern Mediterranean: Underplating and exhumation from the Late Cretaceous until the Miocene to Recent above the retreating Hellenic subduction zone. *Tectonics* (in press).

RING, U., LAYER, P. W. & REISCHMANN, T. 2001. Miocene high-pressure metamorphism in the Cyclades and Crete, Aegean Sea, Greece: Evidence for large-magnitude displacement on the Cretan detachment. *Geology* **29**, 395–8.

RING, U. & REISCHMANN, T. 2002. The weak and superfast Cretan detachment, Greece: Exhumation at subduction rates in extrusion wedges. *Journal of the Geological Society, London* **159**, 225–8.

ROBERTSON, A. H. F., CLIFT, P., DEGNAN, P. J. & JONES, G. 1991. Palaeogeographic and palaeotectonic evolution of the Eastern Mediterranean Neotethys. *Palaeogeography, Palaeoclimatology, Palaeoecology* **87**, 289–343.

THOMSON, S. N. 1998. Assessing the nature of tectonic contacts using fission-track thermochronology: an example from the Calabrian Arc, southern Italy. *Terra Nova* **10**, 32–6.

THOMSON, S. N., STÖCKHERT, B. & BRIX, M. A. 1998. Thermochronology of the high-pressure metamorphic rocks of Crete, Greece: Implications for the speed of tectonic processes. *Geology* **26**, 259–62.

THOMSON, S. N., STÖCKHERT, B. & BRIX, M. A. 1999. Miocene high-pressure metamorphic rocks of Crete, Greece: rapid exhumation by buoyant escape. In *Exhumation processes: Normal faulting, ductile flow and erosion* (eds U. Ring *et al.*), pp. 87–108. Geological Society of London, Special Publication no. 154.

WEIDMANN, M., SOLOUNIAS, N., DRAKE, R. E. & CURTIS, G. H. 1984. Neogene stratigraphy of the eastern basin, Samos island, Greece. *Geobios* **17**, 477–90.

WHEELER, J. & BUTLER, R. W. H. 1994. Criteria for identifying structures related to true crustal extension in orogens. *Journal of Structural Geology* **16**, 1023–7.

WIJBRANS, J. R., SCHLIESTEDT, M. & YORK, D. 1990. Single grain argon laser probe dating of phengites from the blueschist to greenschist transition on Sifnos (Cyclades, Greece). *Contributions to Mineralogy and Petrology* **104**, 582–93.