APATITE FISSION-TRACK THERMOCHRONOLOGY OF THE UPPERMOST TECTONIC UNIT OF CRETE, GREECE:
IMPLICATIONS FOR THE POST-EOCENE TECTONIC EVOLUTION OF THE HELLENIC SUBDUCTION SYSTEM

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Abstract

Apatite fission-track thermochronology is applied to 31 samples from various components of the uppermost tectonic unit of the Island of Crete, Greece. This unit is one of several that presently lie in the hanging wall to a major extensional detachment fault that juxtaposes rocks metamorphosed at high pressure and low temperature during the Late Oligocene - Early Miocene below against rocks that lack any Oligo-Miocene metamorphism. The data reveal a phase of accelerated Middle Miocene denudation that can be linked to erosion between ca. 17 Ma and 11 Ma. The discovery of the base of a denuded apatite partial annealing zone limits the total amount of denudation during this time period to ca. 4km. This implies a mean denudation rate of ca. 650 m/m.y.

Apatite fission-track ages of up to ca. 30 Ma and shortened confined tracks from high-grade metamorphic rocks of the uppermost tectonic unit require that no significant denudation of these rocks occurred during accretion of the other Cretan tectonic units in the Oligocene / Early Miocene. This information means that significant re-evaluation of previous tectonic models of the post-Eocene tectonic development of the Cretan segment of the Hellenic Subduction Zone is required. It is proposed that the Hellenic Subduction Zone has acted as a retreating plate boundary since at least the Late Eocene.

1. Introduction

The Island of Crete consists of several tectonic units accreted during northward directed subduction and collision of the continental margin of the Apulian Microplate with Europe during the Oligocene (Creutzburg & Seidel, 1975; Seidel et al., 1982; Bonneau, 1984; Hall et al., 1984; Fassoulas et al., 1994; Jolivet et al., 1994). These units are unconformably overlain by Late Miocene and younger sedimentary rocks (Postma et al., 1993). Subsequent 'roll-back' of the subduction zone since ca. 12 Ma has resulted in crustal thinning beneath the Cretan Sea and the disruption of pre-Neogene tectonic units by normal faulting into horsts and basins (Meulenkamp et al., 1988). The present day tectonic setting of the eastern Mediterranean is shown in Figure 1. Today Crete represents a structural high within the

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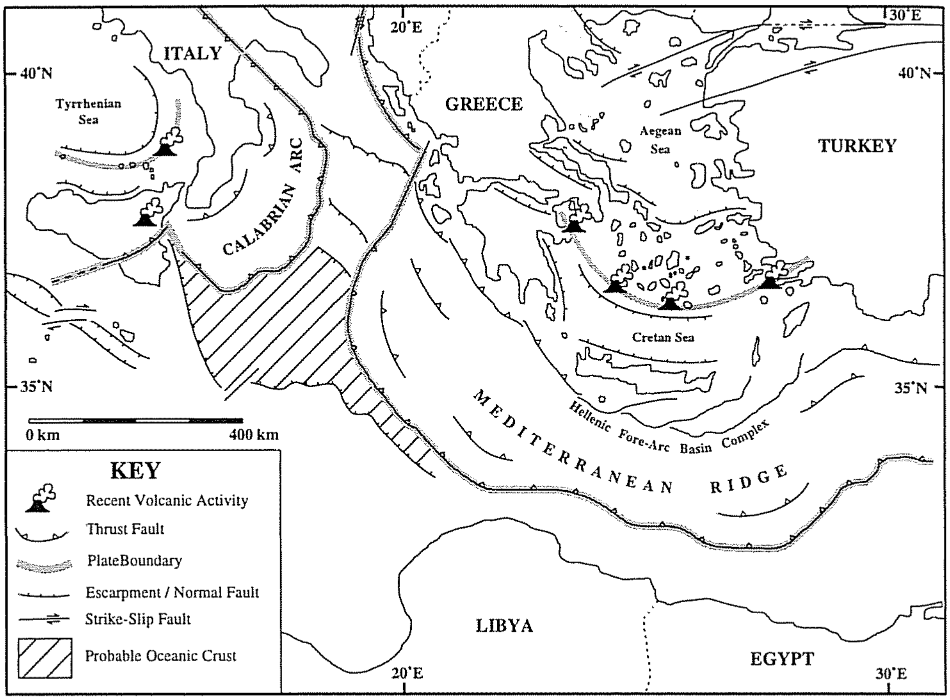


Figure 1. Simplified tectonic map of the present day eastern Mediterranean area summarised from Jolivet et al. (1994), Meulenkamp et al. (1988) & Van Dijk & Scheepers (1995).

'fore-arc' of the active northward directed subduction of the African Plate beneath the Aegean Sea.

There are five major tectonic units, commonly referred to as nappes, exposed on Crete (Figure 2 & 3) that, based on metamorphism, belong to two main groups. The two lowermost units, the mainly carbonate Plattenkalk Unit and tectonically above, the largely clastic, partly carbonate Phyllite-Quartzite Unit, show high-pressure-low temperature (HP-LT) metamorphism. This has been shown by K-Ar dating to be of Oligo-Miocene Age (ca. 20 to 25 Ma - Seidel et al., 1982). Above are three tectonic units that lack any Oligo-Miocene HP-LT metamorphism. Recent interpretations of the nappe pile (e.g. Kilias et al., 1994; Fassoulas et al., 1994 and Jolivet et al., 1994) propose that the HP-LT metamorphic nappes were brought to the surface by extensional tectonism and separated from the unmetamorphic 'upper plate' nappes above by a low-angle detachment fault. Directly above this fault lies the Tripolitza Unit. This consists largely of massive Mesozoic-Early Tertiary platform carbonate rocks grading into Tertiary flysch. Above this is the Pindos Unit comprised of deeper water Mesozoic-Early Tertiary carbonates and cherts and also overlain by Tertiary flysch. The subject of this study, the so-called uppermost tectonic unit (UM Unit) of the nappe pile in Crete (Seidel et al., 1976; 1981), is a mélange that contains serpentinitised mantle fragments, oceanic pillow basalt, various carbonate rocks, 70 Ma old high-grade metamorphic rocks, and other Mesozoic metamorphic slices. This unit is described in more detail in the next section.

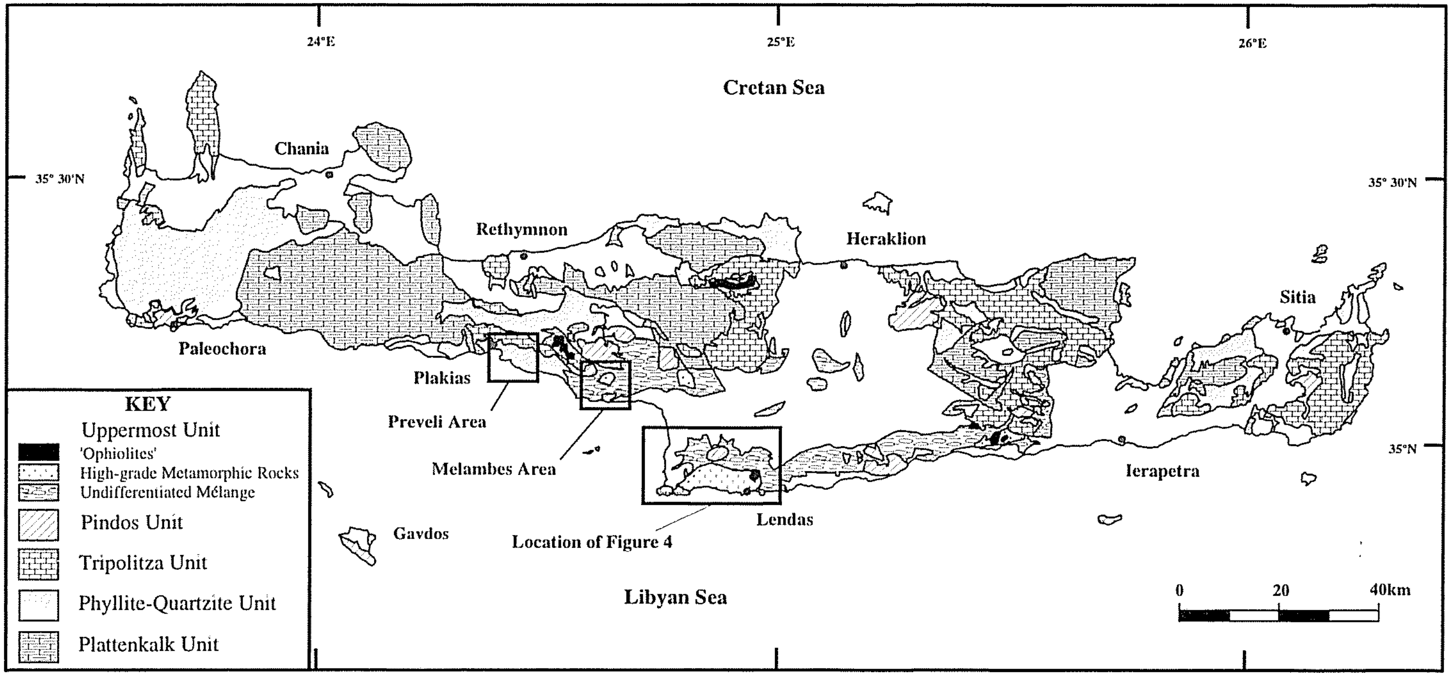
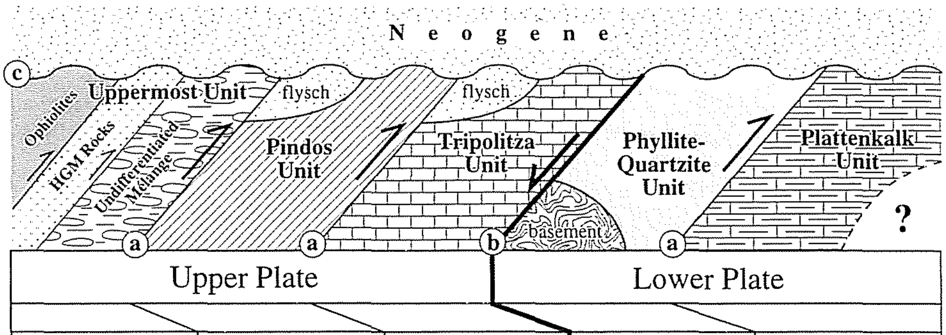


Figure 2. A sketch map of the geology of Crete based on Creutzburg et al. (1977). The sampling localities of Melambes and Preveli are shown along with the location of Figure 4 (the Lendas area).



THE UPPERMOST UNIT (see text for details)	THE PINDOS UNIT	THE TRIPOLITZA UNIT	THE PHYLLITE-QUARTZITE UNIT	THE PLATTENKALK UNIT
Ophiolites - L. Jurassic to E. Cretaceous, mainly serpentinites. **HGM Subunit** - HT amphibolites, marble, migmatites and leucogranites (K-Ar : ~70Ma - Seidel et al., 1981). **Undifferentiated Mélange** - includes the Preveli Subunit Unit and the 'Very-Low Grade' Metamorphic Subunit	Unmetamorphosed Triassic - Palaeocene pelagic sequence including cherty limestones, radiolarites, calc-turbidites and calc-breccias. These pass upwards into Eocene turbidite sandstones and shales with intercalated carbonate conglomerates.	Unmetamorphosed Triassic - Eocene platform carbonate rocks overlain by late Eocene calcareous turbidites and later flysch-like sandstone / shale turbidites.	Deformed Permian - Triassic shallow marine clastic rocks with some carbonate, volcanic, evaporite, and Hercynian basement rocks. This Unit shows HP/LT metamorphism (peak conditions: 300-400°C, 8-10 kbar - Theye et al., 1992). K-Ar data suggest an age of ~20 to 25Ma for this metamorphism (Seidel et al., 1982).	Permian - Eocene recrystallised mainly pelagic cherty limestones and shallow marine carbonate rocks overlain by several metres of L. Eocene-Oligocene marls and shales. Metabauxites reveal HP/LT metamorphism (~350°C, ~10kbar - Theye et al., 1993).

Figure 3. Simplified tectono-stratigraphy of the five main tectonic units described from Crete (loosely based on Seidel et al., 1982). The main contacts shown are (a) Thrusts / accretion of Oligocene age (Bonneau, 1984), (b) ?Miocene extensional detachment fault (Fassoulas et al., 1994; Jolivet et al., 1994; Kilias et al., 1994) separating HP-LT metamorphic rocks below (lower plate) from rocks lacking Tertiary metamorphism (upper plate) above, and (c) Neogene unconformity, rocks immediately above which are of ?Langhian to Tortonian in age (Postma et al., 1993; Meulenkamp et al., 1994).

This study applies apatite fission-track (FT) thermochronology to the UM Unit of the Cretan Nappe pile. Apatite FT thermochronology uses both qualitative interpretation, such as the concept of a denuded partial annealing zone (Gleadow & Fitzgerald, 1987; Fitzgerald et al., 1995) and recently developed quantitative techniques, such as the inverse thermal modelling of apatite fission-track data outlined by Gallagher (1995). In compressional tectonic environments these can be used to resolve low-temperature cooling histories resulting from both erosional and tectonic denudation processes. Here it is used to help constrain the tectonic history of Crete between HP-LT metamorphism of the 'lower plate' units at ca. 25Ma and post-denudation Neogene sedimentation at ca. 12Ma and in addition, to obtain more information on the age and development of the various components of the still poorly understood UM Unit. This work forms a part of a more substantial study that aims to construct low temperature thermal histories for the various tectonic units exposed on Crete. This will eventually allow a detailed reconstruction of Late Tertiary tectonic development, and in particular allow assessment of the importance of extension to the overall denudation that brought the HP-LT Plattenkalk and Phyllite-Quartzite Unit rocks from depths of up to 35 km at ca. 25 Ma (Late Oligocene) to the surface by Middle to Late Miocene times. Although the orogenic belt exposed on Crete has been disturbed by much subsequent Neotectonism, the lack of significant post-tectonic erosion means that many shallow level crustal orogenic features are still preserved. This includes syn-orogenic sedimentary rocks, late-stage extensional tectonic features and the 'upper plate' rocks in the hanging wall to the low angle detachment fault. Such features are often only poorly preserved in other more eroded orogenic belts such as the European Alps. The UM Unit rocks of the 'upper plate' comprise the most suitable lithologies (sandstones and metamorphic rocks as opposed to mainly carbonate rocks within the Tripolitza and Pindos Units) from which to obtain apatite for fission-track analysis from above the 'Cretan Detachment Fault'. Thus apatite FT thermochronology from the UM Unit rocks should also allow the low temperature cooling history in response to denudational processes above the major detachment fault to be assessed.

2. The Uppermost Tectonic Unit of Crete

The uppermost tectonic unit (UM Unit) of the Cretan nappe pile (or uppermost tectonic nappe of Seidel et al., 1976) comprises a number of differing components. For the purposes of this study these are divided into five separate sub-units.

2.1. UNMETAMORPHOSED FLYSCH SUBUNIT (PINDOS UNIT *SENSU STRICTU*)

Directly underlying the UM Unit proper is a sequence of Lower to Middle Eocene (Aubouin et al., 1965) sandstones, shales and calc-turbidites with a flysch-like character. These pass downward into a typical Pindos facies of basinal sedimentary rocks of Late Triassic to Palaeocene age that include pelagic limestones, radiolarites, calc-turbidites and calc-breccias (Seidel, 1971). In places (e.g. Asteroussia Mountains of southern Crete) the sequence passes up into a 'Blocky Flysch' that contains large (100's meter scale) shelf limestone blocks of Mesozoic to Eocene age as well as abundant clasts of granite, metamorphic rocks and serpentinite (Bonneau, 1984).

2.2. THE VERY LOW GRADE (VLG) METAMORPHIC SUBUNIT

This subunit, parts of which have previously been described as the 'Arvi Nappe' (Bonneau, 1972), includes pillow-basalts, tuffs, dolerite dykes, turbiditic psammites and sedimentary 'mass-flows' and red pelagic limestones of Late Cretaceous age. Petrologic studies (Robert & Bonneau, 1982; Hall, 1987) show these rocks have been altered at low temperatures, with formation of pumpellyite, epidote, chlorite, calcite and muscovite, commonly in amygdales and veins. This has been considered to represent sub-sea floor metamorphism due to hydrothermal circulation (Bonneau, 1984). This subunit tectonically overlies, but is always found in close association with the Pindos Unit.

2.3. THE PREVELI SUBUNIT

Rocks of this subunit have also been described as the Vatos Nappe (Bonneau & Lys, 1978), the Kalypso Unit of Gavdos Island (Vicente, 1970) and the Miamou Unit of central Crete (Bonneau et al., 1974). It includes meta-basalts, meta-rhyolites, meta-sediments and pegmatitic gabbro dykes that show a greenschist to HP/LT glaucophane metamorphism. It has been dated by the K-Ar method on phengite and hornblende from the rocks of Gavdos as ca. 148 Ma (Seidel et al., 1977). These pass up into a flysch-like formation containing Jurassic-Cretaceous limestone clasts. The whole sequence is overlain by pelagic red marls of Late Cretaceous age. This subunit is thrust upon rocks of the Pindos Unit on the Island of Gavdos (Vicente, 1970), and appears to lie tectonically below the high-grade metamorphic rocks near Miamou (Bonneau, 1984).

2.4. THE HIGH GRADE METAMORPHIC (HGM) SUBUNIT

This subunit, often referred to as the 'Asteroussia Nappe' (Bonneau, 1972), consists of high-grade metamorphic rocks that include amphibolites, marbles, mica schists, migmatites and leucogranites (Creutzburg & Seidel, 1975). Seidel et al. (1976; 1981) have demonstrated high temperature-low pressure conditions of metamorphism and K-Ar ages from hornblende and biotite of ca. 70-75Ma (Late Cretaceous). Granitic intrusions in the Kalo Chorio region of northeastern Crete also give Late Cretaceous K-Ar ages (Baranyi et al., 1975). The much larger former extent of this subunit is indicated by the widespread presence of gneissic pebbles within Neogene sediments, particularly in eastern Crete (Fortuin, 1977; Postma et al., 1993).

2.5. THE 'OPHIOLITE' SUBUNIT

The highest rocks of the Cretan nappe pile comprise mainly serpentinite with, in places, associated basic dykes and Jurassic-Cretaceous sedimentary rocks. These are found as relict nappes thrust upon the rocks of the HGM Subunit. K-Ar age determinations yield ages of 140 to 156 Ma (Seidel et al., 1981). These authors also propose that these rocks were formed as ophiolites in either an island arc or continental margin environment.

Various interpretations of the UM Unit rocks are proposed in the literature. Creutzburg and Seidel (1975) and Seidel et al. (1981) regard the rocks above the unmetamorphosed Eocene Pindos flysch as a 'serpentinite-amphibolite association' forming a composite nappe consisting of ophiolites at the top, and an ophiolitic mélange, comprising the VLG, Preveli and HGM Subunits, at the base. Hall et al. (1984) interpret the various rocks of the UM Unit as exotic blocks of varying size within a 'blocky flysch' that forms a major olistostrome in the upper part of the Pindos Unit. In contrast, Bonneau (1984) proposes that the rocks of the VLG Subunit form an 'ophiolitic olistostrome' related to the rocks of the Pindos Unit, whereas the Preveli, HGM and Ophiolite Subunits are 'mappable units with a different geodynamic significance' that form a series of individual nappes.

3. Apatite Fission-track Thermochronology

3.1. ANALYTICAL DETAILS

Separated apatites were mounted, polished and etched according to the techniques outlined by Hurford et al. (1991). All the samples were analysed using the external detector method. The samples were irradiated in the graphite reflector of the Risø reactor at the National

Research Centre, Roskilde, Denmark, the neutron fluence being monitored using Corning CN-5 glass.

Ages were calculated using the IUGS recommended Zeta-Calibration approach (Hurford & Green, 1983). The apatite CN-5 zeta was obtained using the Fish Canyon, Durango and Mount Dromedary age standards (see Hurford 1990).

Spontaneous and induced fission-track densities were determined using a Zeiss Axioplan microscope at ×1250 magnification with the help of an automated Märzhäuser stage. Apatite fission-track lengths were measured using an attached drawing tube and digitising tablet calibrated against a stage micrometer.

3.2. DATA PRESENTATION

31 apatite FT ages and 20 apatite confined FT length measurements have been obtained from the rocks of the UM Unit in the areas of Lendas, Melambes and Preveli (see Figure 2). Table 1 presents the data in IUGS standard format (Hurford 1990). The ages are quoted as 'central ages' as recommended by Galbraith & Laslett (1993). The Central Age is a modal age that is weighted to allow for differing precision of individual grain ages. It contains two uncertainties. The main age error is a measure of analytical error (quoted here at the 1σ level), whereas the 'age dispersion' is a measure of the spread in individual grain ages. A low age dispersion (<20%) is indicative of a single grain age population.

3.3. QUALITATIVE DATA INTERPRETATION

For the purposes of interpretation the data are split into three groups. The first group comprises samples collected from unmetamorphosed Paleocene-Eocene flysch-like sedimentary rocks (UMF - UnMetamorphosed Flysch), the second group comprises rocks from the 'Very Low Grade Metamorphic Subunit' (VLG) and the final group are rocks from the 'High Grade Metamorphic Subunit' (HGM) that tectonically overlie the VLG and UMF Subunits.

The majority of data were obtained from samples collected from the area around Lendas, southern Crete. These are shown on a geological sketch map of the area in Figure 4. Other data were obtained from samples in the Melambes area (TH71 to 74) and the Preveli area (TH121 & 122). The locations of these latter two areas are shown in Figure 2.

In the Lendas area the apatite FT ages show a relatively wide spread from 14.0±1.7 Ma to 32.0±8.8 Ma. The apatite confined track length measurements show a similar spread from 12.31μm to 14.84μm with standard deviations between 0.68μm and 2.70μm.

The data from the UMF Subunit give apatite FT ages of between 14.0±1.7 Ma and 17.7±1.0 Ma. The mean track length measurements are all over 14μm (14.27μm to 14.84μm) with correspondingly low standard deviations of between 0.68μm and 1.25μm. Qualitative interpretation of these results indicates that all the UMF rocks of the UM Unit cooled quickly through the apatite partial annealing zone between ca. 19 and 13 Ma.

The apatite FT ages from the VLG rocks of the Lendas area are generally slightly older, being between 15.1±2.1 Ma and 20.0±2.5Ma (this excludes imprecise ages from samples Ra93030, TH97 & TH 105). The corresponding track lengths distributions are

TABLE 1. Apatite fission-track data from the uppermost tectonic unit of Crete, Greece.

Notes: (i). analyses by external detector method using 0.5 for the $4\pi/2\pi$ geometry correction factor; (ii). ages calculated using dosimeter glasses: CN5 with $\zeta_{CN5}=368.9\pm8$; (iii). $P\chi^2$ is the probability of obtaining a χ^2 value for v degrees of freedom where v = no. of crystals - 1; (iv). VLG = Very Low Grade Metamorphic Unit, HGM = High-grade Metamorphic Unit, UMF = Unmetamorphosed Flysch;

Sample Number Rock Type (Geological Unit)	Location Latitude, Longitude	Height	No. of Crystals	Track Density (x 10^6 tr cm^{-2})			Age Dispersion ($P\chi^2$)	Apatite FT Central Age ($\pm1\sigma$)	Apatite Mean Track Length (µm ± 1 s.e.) (no. of tracks)	Standard Deviation (µm)
				Spontaneous ρ_s (N_s)	Induced ρ_i (N_i)	Dosimeter ρ_d (N_d)				
Lendas Area										
Ra 93030 Quartzite (VLG)	Acri Tracheli 34°56'01"N, 24°52'51"E	5m	6	0.0777 (22)	0.8089 (229)	1.288 (8899)	0.1% (49%)	**22.8±5.1**	-	
TH 82 Mica Schist (HGM)	Kali Limenes 34°57'55"N, 24°49'13"E	250m	20	0.7423 (489)	5.732 (3776)	1.262 (8717)	0% (96%)	**30.1±1.5**	**12.76±0.22** (100)	**2.17**
TH 83 Volcanic (VLG)	Antiskari 34°57'33"N, 24°52'09"E	140m	11	0.0738 (21)	0.5413 (154)	1.159 (8003)	0% (99%)	**29.1±6.8**	-	
TH 84 Amphibolite (VLG)	Platio Peramata 34°56'16"N, 24°52'16"E	60m	16	0.2044 (70)	2.181 (747)	1.160 (8014)	0% (99%)	**20.0±2.5**	**14.09±0.48** (7)	**1.19**
TH 88 Leucogranite (HGM)	Lendas 34°56'50"N, 24°54'20"E	310m	20	1.053 (394)	9.935 (3718)	1.160 (8012)	0% (97%)	**22.6±1.2**	**13.46±0.19** (100)	**1.87**
TH 90 Bi. Gneiss (HGM)	Kali Limenes 34°56'41"N, 24°49'25"E	145m	20	0.3999 (243)	3.076 (1869)	1.161 (8020)	0% (99%)	**27.8±1.9**	**13.08±0.25** (27)	**1.28**
TH 92 Arenite (UMF)	Apessokari 35°00'09"N, 24°57'12"E	210m	20	0.3161 (213)	4.205 (2834)	1.161 (8015)	0% (>99%)	**16.1±1.2**	**14.84±0.09** (78)	**0.82**
TH 93 Greywacke (UMF)	Apessokari 34°59'25"N, 24°57'01"E	380m	20	0.4727 (393)	5.718 (4754)	1.159 (8002)	3% (48%)	**17.7±1.0**	**14.77±0.10** (76)	**0.83**
TH 94 Greywacke (UMF)	Miamou 34°59'10"N, 24°56'51"E	400m	5	0.0424 (12)	0.6075 (172)	1.278 (8825)	0% (65%)	**16.4±4.9**	-	
TH 97 Calc-arenite (VLG)	Krotos/Lutra 34°56'20"N, 24°57'44"E	190m	4	0.0690 (12)	0.6207 (108)	1.159 (7999)	0% (65%)	**23.7±7.2**	-	
TH 101 Pegmatite (HGM)	Krotos/Lutra 34°56'34"N, 24°57'43"E	350m	20	1.326 (793)	12.43 (7431)	1.159 (8000)	0% (99%)	**22.8±0.9**	**13.17±0.20** (100)	**2.03**
TH 102 Migmatite (HGM)	Krotos/Lutra 34°56'34"N, 24°57'43"E	350m	20	0.6852 (564)	6.188 (5093)	1.161 (8017)	0% (98%)	**23.7±1.1**	**12.99±0.19** (100)	**1.93**
TH 103 Quartzite (VLG)	Kali Limenes 34°55'26"N, 24°47'48"E	5m	8	0.1853 (54)	2.615 (762)	1.160 (8008)	0% (98%)	**15.1±2.1**	-	
TH 104 Granodiorite (HGM)	Miamou 34°57'57"N, 24°56'16"E	460m	4	0.0312 (15)	0.2310 (111)	1.286 (8883)	0% (>99%)	**32.0±8.8**	-	
TH 105 'Phyllite' (VLG)	Ag. Kirillos 34°59'14"N, 24°55'38"E	340m	20	0.1993 (90)	2.704 (1221)	1.291 (8916)	0% (>99%)	**17.5±1.9**	**14.40±0.38** (8)	**1.00**
TH 106 'Phyllite' (VLG)	Ag. Kirillos 34°59'14"N, 24°55'38"E	340m	9	0.0203 (6)	0.2301 (68)	1.294 (8941)	0% (96%)	**21.0±9.0**	**14.65±0.25** (13)	**0.86**
TH 108 Greywacke (UMF)	Plagia Peramata 34°56'33"N, 24°50'48"E	60m	20	0.4324 (369)	5.448 (4650)	1.290 (8908)	0% (92%)	**18.9±1.0**	**14.54±0.11** (100)	**1.08**
TH 109 Sandstone (UMF)	Pombia 35°00'07"N, 24°51'54"E	300m	20	0.1143 (74)	1.938 (1255)	1.287 (8891)	0% (99%)	**14.0±1.7**	-	
TH 110 Sandstone (?UMF)	Pombia 34°59'33"N, 24°51'54"E	420m	20	0.1460 (74)	2.184 (1107)	1.280 (8841)	0% (>99%)	**15.8±1.9**	**14.70±0.23** (10)	**0.68**
TH 112 Quartzite (UMF)	Moni Ampezarion 34°56'20"N, 24°52'57"E	450m	20	0.4412 (418)	5.951 (5638)	1.275 (8808)	0% (99%)	**17.4±0.9**	**14.68±0.14** (52)	**0.98**
TH 113 Greywacke (UMF)	Antiskari 34°58'15"N, 24°53'35"E	400m	20	0.1318 (128)	1.944 (1887)	1.274 (8800)	0% (>99%)	**15.9±1.5**	**14.27±0.44** (9)	**1.25**
TH 114 Sandstone (UMF)	Antiskari 34°58'18"N, 24°54'34"E	420m	3	0.2102 (18)	3.340 (286)	1.276 (8816)	0% (83%)	**14.8±3.6**	-	
TH 115 Sandstone (?VLG)	Antiskari 34°58'18"N, 24°54'34"E	420m	17	0.2849 (157)	4.103 (2261)	1.293 (8933)	0% (>99%)	**16.5±1.4**	-	
TH 116 Quartzite (VLG)	Plagia Peramata 34°56'24"N, 24°50'25"E	10m	20	0.4723 (392)	5.683 (4717)	1.292 (8924)	0% (67%)	**19.8±1.1**	**14.68±0.10** (100)	**1.01**
TH 118 Greywacke (UMF)	Krotos 34°57'45"N, 24°57'33"E	470m	4	0.1317 (14)	1.834 (195)	1.279 (8833)	0% (99%)	**16.9±4.7**	-	
Melambes Area										
TH 71 Conglom. (UMF)	Melambes 35°08'30"N, 24°40'22"E	190m	40	0.0956 (91)	1.298 (1239)	1.160 (8011)	0% (99%)	**15.7±1.7**	**14.50±0.41** (6)	**0.91**
TH 72 Greywacke (UMF)	Melambes 35°06'27"N, 24°41'11"E	210m	20	0.3358 (269)	4.601 (3685)	1.160 (8009)	0% (98%)	**15.6±1.0**	**14.05±0.25** (16)	**0.97**
TH 73 Gneiss (HGM)	Melambes 35°07'56"N, 24°39'38"E	510m	9	0.1448 (19)	2.470 (324)	1.161 (8018)	0% (>99%)	**12.6±3.0**	-	
TH 74 Greywacke (UMF)	Saktouria 35°07'29"N, 24°37'03"E	500m	20	0.4063 (335)	5.526 (4556)	1.159 (8005)	0% (99%)	**15.7±0.9**	**14.37±0.13** (51)	**0.93**
Plakias Area										
TH 121 Phyllite (Preveli)	Moni Preveli 35°09'26"N, 24°27'45"E	200m	20	0.3434 (175)	2.632 (1341)	1.283 (8860)	0% (>99%)	**30.8±2.5**	**12.31±0.49** (17)	**1.97**
TH 122 Phyllite (Preveli)	Kato Moni Preveli 35°10'00"N, 24°28'09"E	90m	20	0.3103 (207)	2.445 (1631)	1.275 (8806)	0% (90%)	**29.8±2.2**	**12.44±0.39** (50)	**2.70**

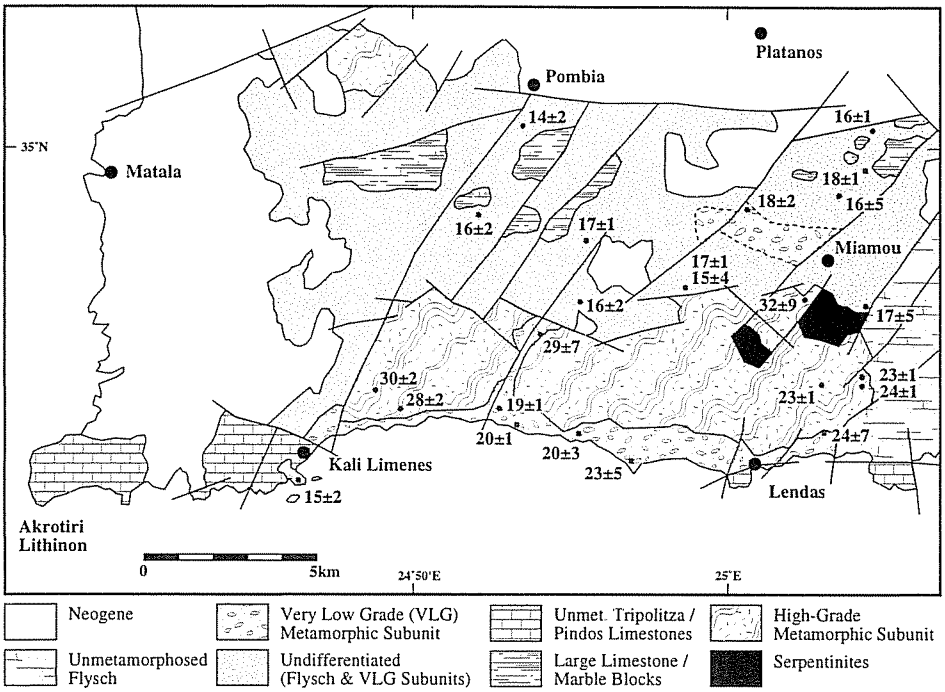


Figure 4. Simplified geological and location map showing the apatite fission-track central ages obtained from the various components of the uppermost tectonic unit exposed in the region of Lendas, southern Crete.

similar to those from the unmetamorphosed sedimentary rocks, with mean track lengths between 14.09μm and 14.68μm and standard deviations between 0.86μm and 1.19μm.

The HGM Subunit rocks of the UM Unit give significantly older apatite FT ages, ranging from 20.0±2.5 Ma to 30.8±2.5 Ma (excluding the imprecise age from sample TH104). The apatite confined track length distributions all show a significant proportion of short tracks (< 14μm). This results in low mean track lengths of between 12.31μm and 13.46μm, and large standard deviations of between 1.28μm and 2.70μm (this excludes sample TH84, where only 7 tracks were measured). Several of the track length distributions (see Figure 6) suggest the presence of two groups of track lengths (a bimodal distribution), especially samples TH82, TH88 and TH102. Such a bimodal distribution is indicative of a sample that has spent some time within the apatite partial annealing zone (between ca. 60°C and 110±10°C) to produce the shorter tracks, then later cooled to below 60°C to allow the accumulation of the longer tracks (Gleadow & Fitzgerald, 1987).

The apatite FT ages of all the units discussed are plotted against both their mean track length and standard deviation of the track length distribution in Figure 5, to produce so-called 'boomerang plots' (Brown et al., 1994; Gallagher & Brown, 1997). The plots both indicate the presence of a thermal event at ca. 17Ma, probably linked to the initiation of a phase of accelerated denudation, that affected all of the rocks of the UM Unit.

This pattern of ages is indicative of the presence of a denuded fossil apatite partial annealing zone (PAZ) where different levels of a former apatite fission-track 'stratigraphy'

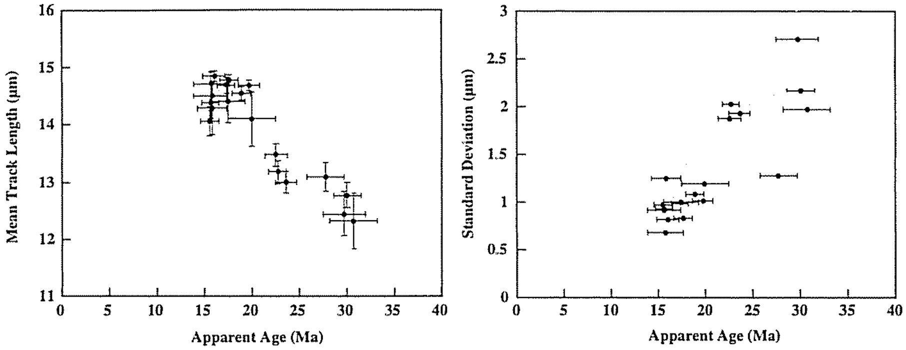


Figure 5. Apatite age data from the Uppermost Unit plotted against mean track length and the standard deviation of the track length distribution to produce 'boomerang plots'. Both plots indicate a thermal event at ca. 17Ma.

are now exposed at the surface (Fitzgerald, 1994; Gallagher & Brown, 1997). However, Neogene fault block tilting and extensional faulting on Crete (Meulenkamp et al., 1994) means that plotting an apatite age vs. elevation profile (e.g. Fitzgerald et al., 1995) for most profiles or regions on Crete, including the UM Unit in the area around Lendas, are of no use when looking for the presence of a 'break-in-slope', which can be used to estimate the timing of initiation of an accelerated denudation event.

To try to avoid this we attempted to plot the apatite FT age data against the perpendicular distance from a reference plane that existed prior to Neogene deformation. A similar approach has also been used by Lihou et al. (1995). For the Lendas area the ?Oligocene (Bonneau, 1984) thrust contact at the base of the HGM Subunit rocks is used. The result is shown in Figure 6. To aid interpretation the apatite track length distributions and corresponding radial plots are also shown. What emerges is a relatively well-defined 'break-in-slope' representing the base of an uplifted fossil apatite PAZ with the break-in-slope marking the onset of rapid cooling at ca. 17 Ma. This is in good agreement with the boomerang plot shown in Figure 5. The interpretation of such plots is dealt with in detail by Fitzgerald et al. (1995). In the profile here, some spread in the data occurs due to the regional nature of the data set, the use of a reference plane rather than a true vertical profile (the HGM Subunit thrust contact was unlikely to have been totally horizontal and planar over the area of study during cooling or denudation) and the relatively small vertical profile (<1000m). It should thus not be treated as a 'vertical profile' *sensu strictu* .

However it allows some interpretation to be made. First, the onset of rapid cooling may have occurred slightly earlier in places, probably the western part of the Lendas area, as here the older apatite ages are found, or second and more likely, the former apatite fission-track stratigraphy has been slighly more eroded since the onset of accelerated denudation in the eastern part of the Lendas area.

The confined track lengths distributions below the break-in-slope have long track lengths (>14.5μm) and narrow standard deviations (<1.08μm), and confirm rapid cooling through the apatite PAZ after ca. 17 Ma. The profile above the break-in-slope represents rocks that lay within the apatite PAZ prior to the onset of rapid cooling. This slope does not quantify a denudation rate, but instead reflects the shape of the fossil PAZ or apatite fission-

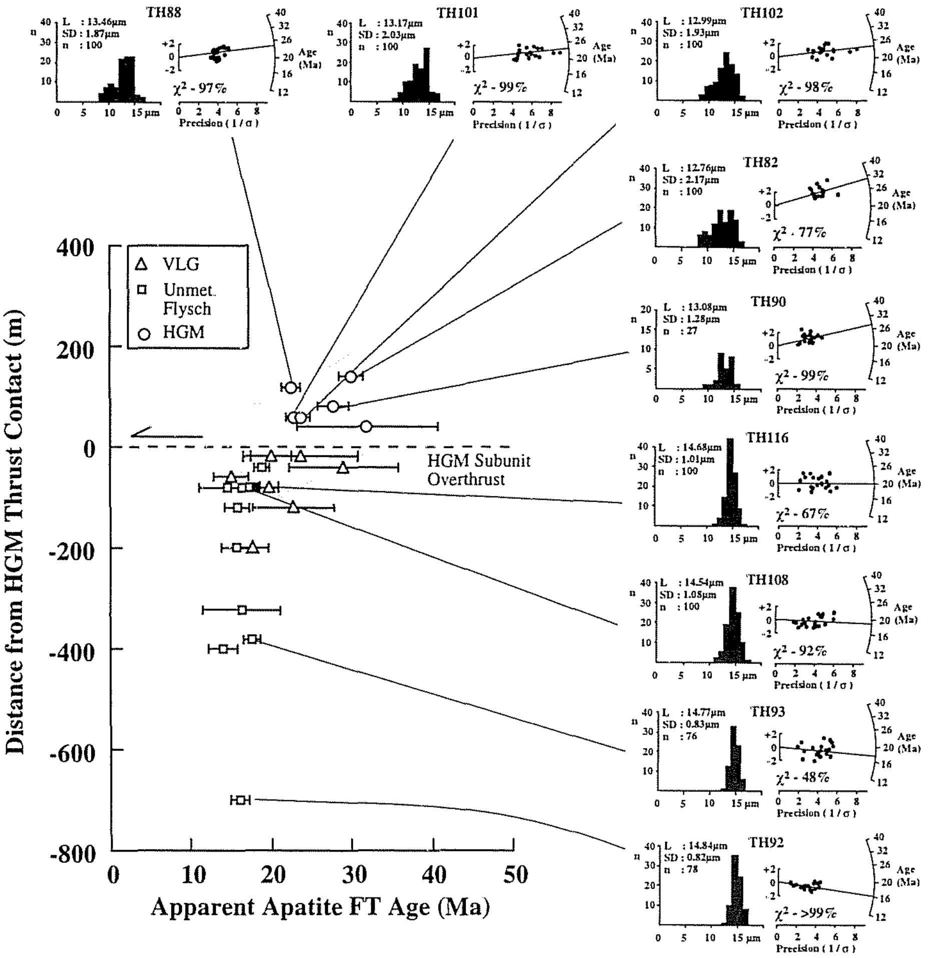


Figure 6. Apatite age profile from the samples of the Lendas area including apatite confined track length distributions and radial plots (Galbraith, 1990), showing apparent age (± 1 σ) against perpendicular distance from the High-grade Metamorphic Unit overthrust. Although the data show some scatter, a distinct break-in-slope is seen at ca. 17Ma, marking the onset of accelerated cooling.

track stratigraphy. The shape of this fossil PAZ is dependent on the original age of the apatites, the duration of land surface stability and the geothermal gradient. The shape of the fossil PAZ is also relatively sensitive to low denudation rates. The effects of varying these parameters have been modelled by Brown et al. (1994). The age profile from the Lendas area indicates that before the onset of rapid cooling at ca. 17 Ma the land surface and geotherm of the UM Unit must have been relatively stable for at least 15 Ma, with cooling rates not exceeding 5°C/m.y. This indicates that the overthrusting of the HGM Subunit rocks of the Lendas area upon the VLG Subunit and the unmetamorphosed Eocene flysch probably occurred very soon after the deposition of the sedimentary rocks themselves, probably in the Late Eocene or Early Oligocene.

One other factor that can influence the shape of the age profile above the break-in-slope is apatite chemistry, and in particular the Cl / Cl+F ratio. O'Sullivan & Parrish (1995) have demonstrated that when a spread in apatite composition exists between grains within a single sample, the apparent age of fluorine-rich grains at temperatures within the apatite PAZ (110±10°C to ca. 60°C) will be reduced relative to the chlorine-rich grains. This results in a spread of ages on a radial plot and lowers the χ^2 probability. However, although the single grain apatite ages in the samples from above the break-in-slope in Figure 6 are older, the spread in single grain ages is not significant indicating that the apatite composition within these samples is similar.

The apatite FT data in the Melambes area (Figure 2) all have apatite FT ages and track length distributions all indicating rapid cooling at ca. 15-17 Ma. It is likely that here the fossil apatite PAZ has been totally removed, implying that the UM Unit in this region is more denuded than that in the Lendas area.

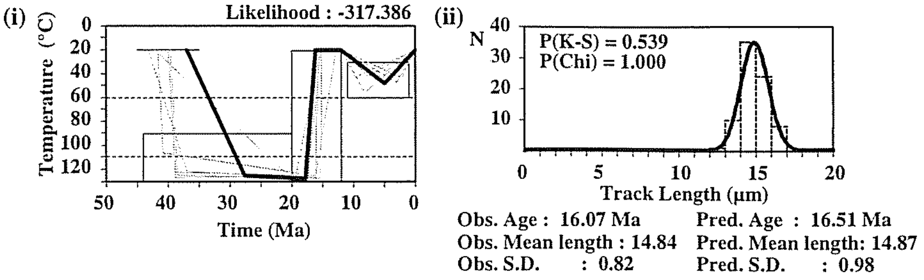
Apatite FT data have also been obtained from two samples of the Preveli Subunit near to the Preveli Monastery (Figure 2). They give ages of ca. 30Ma and the form of the confined track length distributions, with mean lengths <13μm and large standard deviations >1.97μm, indicate that these samples lie within a denuded fossil apatite PAZ as is also seen in the UM Unit rocks of the Lendas area.

3.4. QUANTITATIVE THERMAL HISTORY MODELLING

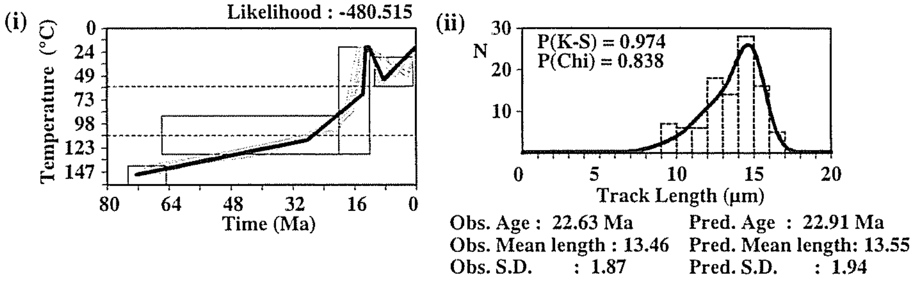
Detailed thermal history analyses have been carried out on three samples from the UMF, VLG and HGM subunits of the UM Unit. The 'MonteTrax' thermal modelling method used in this study has been outlined in detail by Gallagher (1995). This method uses a stochastic approach, whereby the bounds of possible time-temperature points are specified and then thermal histories are selected from within these bounds. A genetic algorithm is used to search the parameter space and define time-temperature histories that show a good-fit to the observed data with a maximum likelihood approach used to define the confidence limits of predicted versus observed fitting of the data.

Figure 7 shows the results of thermal history modelling of the apatite FT data from the UM Unit. Several time-temperature constraints confine the time-temperature space in which the models are run. The UM Unit rocks must have been at the surface (taken here as 20°C) when they were unconformably overlain by the onset of Neogene sedimentation between ca. 15 Ma and 12 Ma (Postma et al., 1993). The majority of the unmetamorphosed flysch was deposited during the Eocene, thus these samples are constrained by their depositional age. However as these rock samples have been totally annealed during the Miocene, the older 'burial' or heating of these samples cannot be predicted by thermal history modelling. The depositional age is included only to illustrate that these rocks must have been significantly buried after deposition. The VLG metamorphic rocks of probable late Mesozoic age (Seidel et al., 1977), were probably not buried during the late Eocene / early Oligocene. Hence for these samples the T-t history starts from below the apatite annealing zone. The thermal history of the HGM rocks are constrained by ca. 70 Ma K-Ar hornblende, muscovite and biotite ages (Seidel et al., 1981) that indicate rapid late

(a) TH92 (Unmetamorphosed Flysch, Sandstone)



(b) TH88 (High-Grade Metamorphic Subunit, Leucogranite)



(c) TH116 (Very Low Grade Metamorphic Subunit, Quartzite)

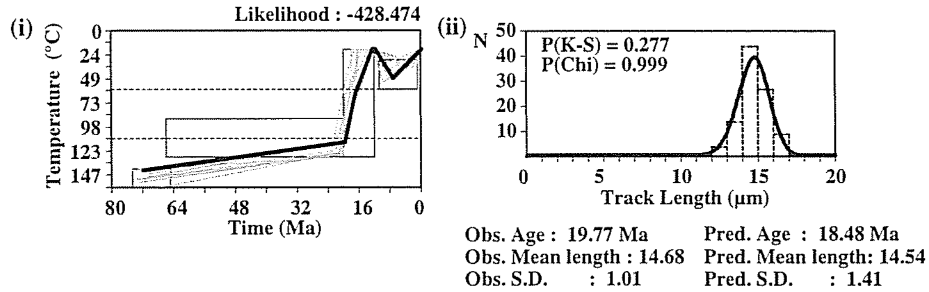


Figure 7. 'Best-fit' thermal histories, obtained from modelling apatite fission-track data using the approach of Gallagher (1995), from three different components of the uppermost tectonic unit in the Lendas area. Parts (i) show the 'best fit' thermal history in bold, that produces the predicted results in (ii), with other thermal histories that fit the observed apatite age and length data in grey. Parts (ii) show the predicted track-length distribution in bold, and the observed track length data in grey. The results of comparing the two distributions using the χ^2 (Chi) and the Kolmogorov-Smirnoff (K-S) statistical fitting methods are also shown (see Gallagher, 1995 for details).

Cretaceous cooling to below the closure temperature of Ar in biotite (ca. 320°C - Harrison et al., 1985). A confining box at 70±5 Ma and 150±10°C (an arbitrary temperature between the closure temperature of Ar in biotite and the base of the apatite PAZ) is applied to the model of the HGM rocks. Zircon fission-track data from the UM Unit rocks are in the process of being acquired to better constrain the cooling history and hence the T-t model between ca. 230°C and 310°C.

The modelling applied to the apatite FT data from the UMF rocks confirms the interpretation made from the data as an apatite FT age profile (Figure 6) with relatively fast rates cooling (15-25°C / Ma) between the base of the apatite annealing zone (110±10°C) and the surface (ca. 20°C) between ca. 19 Ma and 13 Ma.

The modelled thermal histories from the HGM rocks of the UM Unit require that these rocks entered the apatite PAZ (i.e. cooled to below 110±10°C) at a relatively slow cooling rate (<1°C / Ma) between ca. 40 Ma and ca. 30 Ma with continued slow cooling within the apatite PAZ until the onset of a period of accelerated cooling between ca. 18-14 Ma. The slow cooling within the apatite annealing zone allowed the development of the apatite age-depth profile between ca. 40 Ma and 20Ma that was later denuded, and is represented today by the break-in-slope discovered within the UM Unit rocks of the Lendas area. The accelerated cooling of these rocks was initiated when they were at a temperature of about 70-80°C.

The apatite FT data from the VLG rocks require a thermal history similar to that experienced by the HGM rocks. One difference is that the accelerated cooling of these rocks needs to have been initiated slightly earlier (between 18 and 20Ma) and from slightly higher temperatures, very close to the base of the apatite PAZ (ca. 110±10°C).

Some of the apparent Neogene heating of the samples between 12Ma and present is probably an artefact of the Laslett et al. (1987) annealing model used. This model tends to overestimate apatite fission-track annealing over geological time at temperatures <60°C (P. Green pers. comm.).

4. Discussion

A proposed late Tertiary cooling history for the components of the UM Unit in the area around Lendas, southern Crete is illustrated in Figure 8. According to Bonneau (1984) the VLG Subunit rocks and the HGM Subunit rocks were emplaced upon the Eocene flysch during the early Oligocene. This can be correlated with the results of apatite FT thermochronology that reveal the cooling of the HGM rocks into the apatite PAZ (to below 110±20°C) sometime between ca. 40 Ma and ca. 30 Ma. This must have caused the consequent burial and hence heating of the Eocene flysch-like sedimentary rocks to above 110±10°C, shortly after their deposition. The VLG Subunit rocks, that lie tectonically below the HGM Subunit rocks must have remained above 110±10°C during this time. To allow the development of an apatite FT age stratigraphy, all the rocks of the UM Unit must have then cooled very slowly until the onset of accelerated cooling between ca. 18 and 16Ma. This is confirmed by the thermal history modelling of the apatite data from the HGM Subunit rocks. Quantitative and qualitative interpretation of the apatite FT data reveal that all the rocks of the UM Unit underwent a period of rapid accelerated cooling from ca. 17 Ma, until they were unconformably overlain by coarse grained clastic sedimentary rocks possibly as early as the Langhian (ca. 15Ma) (the Mithi Formation of Fortuin, 1977). Some later Neogene burial of these rocks has been revealed by Meulenkamp et al. (1994), deduced from an examination of the Neogene sedimentary rocks of the Iraklion Basin of central Crete.

The presence of a break-in-slope or base of a fossil apatite PAZ (Figure 6) allows the

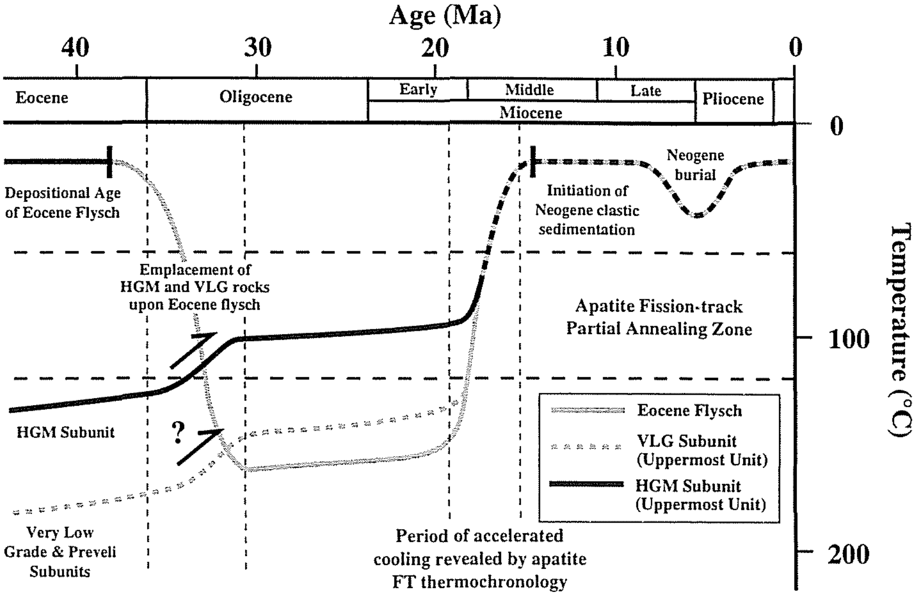


Figure 8. Proposed late Tertiary cooling history of the components of the uppermost tectonic unit in the area around Lendas, southern Crete deduced from apatite fission-track thermochronology, with other structural and stratigraphic constraints.

total amount of denudation since the onset of accelerated cooling in the UM Unit rocks at ca. 18-16Ma to be estimated. This is done using the equation given in Brown (1991):

$$\text{Total Denudation} = ((T_{PAZ} - T_S) / G) + d \qquad (1)$$

where T_{PAZ} is the temperature at the base of the fossil apatite PAZ, taken as 110±10°C, T_S is the palaeo-mean surface temperature, G is the palaeo-geothermal gradient, and d is the elevation difference between the base of the fossil PAZ and the present day mean surface elevation. The value for palaeo-mean surface temperature is taken to be ca. 15°C. Work on fluid inclusions from the rocks of the Phyllite-Quartzite Unit of Crete (Küster & Stöckhert, 1995) indicates a palaeo-geothermal gradient at ca. 17 Ma of ca. 25°C / km, and the value for d in the Lendas area is ca. 0 km. Putting these values into (1), means that 3.8 ± 0.4 km of overburden has been removed from the rocks of the UM Unit in the Lendas area since ca. 17 Ma. Meulenkamp et al. (1994) show that by the Tortonian (ca. 11 Ma) the Asteroussia region was undergoing subsidence. Thus the phase of accelerated denudation responsible for the removal of ca. 4km of overburden took place during a relatively short time period of ca. 6 Ma. This requires a mean denudation rate of ca. 650m / Ma.

This period of accelerated denudation revealed by apatite FT thermochronology is contemporaneous with the initiation of large scale clastic sedimentation in the Ierapetra Basin of eastern Crete (Fortuin, 1977; Fortuin & Peters, 1984; Postma et al., 1993). Here the onset of sedimentation is marked by probable Langhian (ca. 15Ma) continental red-bed sedimentary rocks (the Mithi Formation) derived from the UM Unit. It is therefore most probable that the mid-Miocene phase of accelerated denudation was a result of increased erosion.

The results of apatite FT thermochronology from the UM Unit rocks of Crete have several important implications for the tectonic development of the Hellenic Subduction System. The most significant is the discovery that the rocks in the so-called 'upper plate' of the Cretan nappe pile underwent no significant denudation between the Late Eocene - Early Oligocene (ca. 35Ma) and the Middle Miocene (ca. 15Ma). This implies that during ongoing 'accretion' associated with deformation and high-pressure metamorphism of the 'lower plate' rocks, little or no erosion (or denudation) took place at the surface. This implies a lack of topographic elevation at this time that contradicts the tectonic model of Jolivet et al. (1994) which proposes that during convergence in the Oligocene, collision with the Adria or 'Ionian' microplate formed an accretionary wedge. Then as a result of underplating, with coeval HP-LT metamorphism, an overall 'cold crust' with a deep brittle-ductile transition was developed. This resulted in a thickened crustal wedge that supported a high topography with subsequent unroofing of the HP-LT rocks occurring due to collapse of this thick crust when it entered the warmer back-arc region.

However the lack of significant erosion during accretion of the tectonic units of Crete leads us to propose that the Hellenic Subduction Zone was acting as a 'retreating plate boundary' (in the sense of Royden, 1993a) as early as the Late Eocene. With this model, the main driving force of subduction is caused by the negative buoyancy of the subducted plate. Royden (1993a) states that orogenic belts formed at retreating plate boundaries are commonly typified by topographically low mountains, the development of regional extension in the overriding plate, little or no erosion or denudation, low-grade metamorphism, little involvement of the crystalline basement in thrusting and flysch deposition within adjacent foredeep basins. These features fit remarkably well with what is observed in the rocks of Crete. A lack of erosion (or denudation) and hence relief during the Oligocene and early Miocene is confirmed by apatite FT analysis, with the uppermost tectonic unit of Crete having remained in the upper ca. 4km of the upper crust through the entire Oligo-Miocene accretionary process. During this accretion the lower plate Phyllite-Quartzite and Plattenkalk Units were buried to depths of up to 35 km associated with HP-LT metamorphism and subsequently brought back to the surface by regional extensional processes (Kilias et al., 1994; Fassoulas et al., 1994; Jolivet et al., 1994). In addition, almost no crystalline basement is seen within the tectonic units of Crete (see Creutzburg & Seidel, 1975). Finally the present day Mediterranean Ridge accretionary complex (Kastens, 1991) to the south of Crete contains significant amounts of largely undated sedimentary rocks that were probably deposited in the fore-deep basin adjacent to the orogenic belt.

The second discovery made from the results of apatite FT thermochronology on the rocks of the UM Unit is the period of accelerated denudation related to ca. 4km of erosion between ca. 17Ma and ca. 11Ma, likely to be related to an increase in topography and hence relief. The cause of this is probably related to isostatic rebound caused by a change in the tectonic regime during the Middle Miocene, after the accretion of the Adria microplate continental fragment upon which the Pindos, Tripolitza and HP-LT Units were deposited.

5. Conclusions

Apatite FT thermochronology carried out on the rocks of the uppermost tectonic unit of Crete reveals that the rocks in the 'upper plate' to extension underwent a phase of accelerated Middle Miocene denudation linked to erosion between ca. 17-11Ma. The presence of the base a denuded apatite partial annealing zone allows the total amount of erosion (or denudation) during this time to be estimated as ca. 4km. This implies a mean denudation rate of ca. 650m/m.y.

In addition, the presence of older apatite FT ages with corresponding bi-modal track length distributions from the high-grade metamorphic rocks of the uppermost tectonic unit, require that no significant denudation occurred at the surface during the accretion of the Cretan tectonic units, including the burial to ca. 35km and subsequent denudation of the HP-LT Phyllite-Quartzite and Plattenkalk Units, between the Oligocene and Early Miocene.

In light of this information a new tectonic model for the evolution of the Cretan segment of the Hellenic Subduction Zone is proposed. This advocates that the subduction zone has acted continuously as a retreating plate boundary since at least the Late Eocene. The subsequent onset of accelerated denudation at ca. 17 Ma is attributed to a change in the plate tectonic regime subsequent to the accretion of the Adria microplate continental fragment upon which the Pindos, Tripolitza and HP-LT Units were deposited.

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