Dextral strike-slip and normal faulting during middle Miocene back-arc extension and westward Anatolia extrusion in Central Greece

Agathe Faucher1 ; Frédéric Gueydan1 ; Marc Jolivet2 ; Manar Alsaif 1 ; Bernard Célérier1

1 Géosciences Montpellier, Université de Montpellier, CNRS, Rue Eugène Bataillon, 34095 Montpellier, France.

2 Laboratoire Géosciences Rennes, Université Rennes 1, CNRS, avenue Général Leclerc, 35042, Rennes, France.

Corresponding author: Frédéric Gueydan (frederic.gueydan@umontpellier.fr), Université de Montpellier, Géosciences Montpellier, Place Eugène Bataillon, 34090 Montpellier France

Key Points

- *Central Greece middle Miocene basins are controlled by the coeval activity of NE-striking dextral strike-slip and NW-striking normal faults*
- *The middle Miocene Pelagonian dextral strike-slip fault accommodated the differential extension rate between the Cyclades and Central Greece*
- *Plio-Quaternary deformation is controlled by E-striking normal faults and NW-striking fault zones, forming oblique rifts (Evvia, Corinth)*

Abstract

Present-day Aegean tectonics is marked by the interplay between Hellenic slab rollback and Anatolia extrusion, explaining the formation of extensional basins and dextral strike-slip faults. We aim to constrain, with structural analysis and low-temperature data, middle Miocene activity of dextral strike-slip and normal faults in Central Greece. We show that onshore middle Miocene basins are controlled by both NW-striking normal faults and NE-striking dextral strike-slip faults. E-striking normal faults developed during the Plio-Quaternary inside pre-existing NW-striking fault zones. Stress tensor calculations show that in middle Miocene, NW-striking normal faults and NE-striking dextral faults are compatible, confirming their coeval activity. In contrast, the Plio-Quaternary stress tensor suggests an almost N-S radial extension, which is not compatible with NE-striking dextral faults in Central Greece. Apatite Fission Track data additionally constrain middle Miocene local cooling near NW-striking normal faults. They also support a difference in the amount of exhumation between Central Greece and the Cyclades, likely accommodated by the Pelagonian dextral strike-slip fault. We propose that in the middle Miocene, the co-existence of dextral strike-slip and normal faults is associated with an almost N-S extension related to trench retreat and an E-W compression related to westward extrusion of Anatolia. The progressive trench curvature during rollback implies block rotation, accommodated by the Pelagonian fault, and subsequent normal fault and extensional stress rotation. During the Plio-Quaternary, a change in extensional direction from NE-SW to N-S implies the formation of E-striking normal faults inside NW-striking fault zone, defining oblique rift systems.

1. Introduction

Present-day Aegean tectonics activity is marked by the interplay between westward Anatolian extrusion and southward Hellenic slab rollback (Fig. 1, inset for GPS velocity field - Reilinger et al., 2006; Hollenstein et al., 2008; Pérouse et al., 2012). The Aegean domain is the upper plate of the Hellenic subduction that is active since Jurassic times (Clift and Dixon, 1998; Papanikolaou, 2013). The lower subducting plate was composed of three main micro-continents separated by two main oceans or deep basins. Subduction led to the progressive accretions of these continental terranes and the formation of the nappe stack that characterizes the Aegean domain; from bottom to top: Adria with some fragments of Pindos ocean, Pelagonia and minor fragments of Vardar ocean in Rhodope (Fig. 1 – Aubouin, 1965; Papanikolaou, 1997, 2013). Southward Hellenic subduction slab rollback caused subsequent upper plate extension that is proposed to be mainly accommodated by several low-angle detachment systems with the formation of Metamorphic Core Complexes (MCC – Lister et al., 1984; Gautier et al., 1993; Vandenberg and Lister, 1996; Faccenna et al., 2003; Jolivet, 2003; Jolivet et al., 2010a; Brun and Faccenna, 2008; Brun et al., 2016; Brun and Sokoutis, 2018; Grasemann et al., 2012, 2018). From the middle Miocene to present, trench retreat accelerated and led to both ongoing activity of low-angle normal faults (Avigad and Garfunkel, 1989; Forster and Lister, 1999; Tschegg and Grasemann, 2009; Krohe et al., 2010; Iglseder et al., 2011) and the development of NW-striking high-angle normal faults (e.g parallel to the retreating trench) and extensional basins at the scale of the whole Aegean (Fig. 1, orange basins- Mascle and Martin, 1990; Brun et al., 2016). In this context, Central Greece, the Peloponnese and the North West Cyclades rotated clockwise by 25 to 50° (Horner and Freeman, 1983; Kissel et al., 1986, 2003; Duermeijer, 2000; van Hinsbergen et al., 2005, 2006; Bradley et al., 2013) around the Scutari Pec pole (Speranza et al., 1992), and the South East Cyclades rotated counter-clockwise (~30˚ - van Hinsbergen et al., 2007, 2010; van Hinsbergen and Schmid, 2012 - Fig. 1).

During the Plio-Quaternary, the formation of the large dextral North Anatolian strike-slip Fault (NAF) accommodating westward Anatolian extrusion, is associated with plate kinematics re-organisation and a modification of Aegean extension (Fig. 1 - Armijo et al., 1999, 2004; Hubert-Ferrari et al., 2002, 2003; Flerit et al., 2004). This plate re-organisation led to the formation of the Aegean/Anatolia microplate (highlighted by the GPS velocity field in Fig 1). The connection from the NAF to the subduction zone (near Kephalonia) marked diffuse Anatolia/Aegean plate boundary, also called the Central Hellenic Shear zone (CHSZ – Fig. 1- McClusky et al., 2000; Goldsworthy et al., 2002; Papanikolaou & Royden, 2007; Royden & Papanikolaou, 2011). It is characterized by major strike-slip zones to the North and South (NAF, Kephalonia) and major E-striking normal faults in the centre (Corinth and Evvia rift – Fig. 1). The Corinth and Evvia rifts have been proposed to have opened at the tip of the propagating NAF during the Plio-Quaternary (Armijo et al., 1996; Flerit et al., 2004). Note that several NE-striking dextral strike-slip systems are also identified from seismological and geodetic data inside the Aegean domain, with assumed Plio-Quaternary activity (bolded lines in Fig. 1 - Sakellariou & Tsampouraki-Kraounaki, 2019).

Several observations, however, question this classical view of Aegean tectonics, suggesting active strike-slip faulting also during middle Miocene times. First, the extrusion of Anatolia could have started earlier during the middle/early Miocene as recently suggested by syn-tectonics calcite dating of the NAF fault plane (Nuriel et al., 2019). At this time, extrusion was accommodated in a broader deformation zone called the North Anatolian Shear Zone (Şengör et al., 2005). Second, the presence of syn-kinematic dextral structures in middle Miocene plutons in the Cyclades suggest middle Miocene activity of at least some NE-striking dextral strike-slip faults (Kokkalas, 2001; Koukouvelas and Kokkalas, 2003; Kokkalas and Aydin, 2013). Note, however, that these middle Miocene plutons are proposed to be potentially associated with detachment faulting or extensional shear zones (van Hinsbergen and Schmid, 2012; Rabillard et al., 2015; Menant et al., 2016; Malandri et al., 2017; Bessiere et al., 2018). The Myrthes-Ikaria Fault (also called the mid-Cycladic lineament – Fig. 1, Walcott & White, 1998) is moreover proposed to be a major dextral strike-slip fault during the middle Miocene. This fault may have accommodated Miocene block rotation in the Cyclades, as suggested by the differences in the lineation trends between the North-West Cyclades and the Central Cyclades (Philippon et al., 2012; Brun et al., 2016).

In order to provide new constraints on potential middle Miocene activity of NE-striking strike-slip faults, Central Greece (including the Attica and Evvia regions) is a key place for the three following main reasons. First, the majority of NE-striking faults of the Aegean domain are described offshore (Fig. 1, Sakellariou and Tsampouraki-Kraounaki, 2019). The Pelagonian fault in Evvia (Central Greece, Fig. 1), is one of the rare NE-striking structures cropping out onshore over a long horizontal distance. This fault is a first order structure since it separates Pelagonia-derived rocks from Adria/Pindos (structurally below Pelagonia)-derived rocks (Fig. 1). However, its kinematics is still discussed: normal slip (Papanikolaou and Royden, 2007; Diamantopoulos et al., 2009) or dextral strike slip (Kokkalas, 2001; Xypolias et al., 2003). The age of its activity is also debated, as it is not clear if it has been active only during the Plio-Quaternary or also during the middle Miocene (Kokkalas, 2001; Xypolias et al., 2003; Bradley, 2012; Sakellariou et al., 2013). Second, Miocene extensional tectonics activity in the Cyclades has been widely studied, with the existence of several major detachment systems (Gautier et al., 1993; Jolivet et al., 2010b; Iglseder et al., 2011; Scheffer et al., 2016), while Miocene tectonics of Central Greece is less constrained. The presence of strike-slip deformation together with NW- striking high-angle normal faulting in Central Greece is proposed to be active since the middle Miocene inside the Central Hellenic shear Zone (Fig. 1, Papanikolaou & Royden, 2007; Royden & Papanikolaou, 2011). Miocene deformation is also well-marked in the area through numerous middle Miocene basins whose tectonics context of deposition remains to be characterized (Fig. 1, Bornovas and Rondogianni-Tsiambaou, 1983). Third, low-temperature thermochronology ages provide an important constraint on the deformation history of rocks during their last stage of exhumation in the upper crust. The Cyclades have been extensively studied from this point of view with a clear middle to late Miocene cluster in age (Hejl et al., 2002, 2008; Ring et al., 2003, 2007; Brichau et al., 2006, 2008; Seward et al., 2009; Berger et al., 2013; Soukis and Stockli, 2013; Seman, 2016; Grasemann et al., 2018; Schneider et al., 2018) highlighting important exhumation/extensional events at that time, related to detachment faulting (Brichau et al., 2008; Jolivet et al., 2010a; Krohe et al., 2010; Iglseder et al., 2011; Grasemann et al., 2018) and/or the coeval activity of high-angle normal faulting and strike-slip faulting during block rotation (Philippon et al., 2012; Brun et al., 2016). In contrast to the Cyclades, the absence of low temperature data in Central Greece (Fig. 1) obscures the timing and tectonics context of its exhumation and a comparison with the Cyclades.

The objective of this study is to provide new structural and geochronological constraints in Central Greece in order to characterize the role of both normal faults and NE-striking dextral faults (Pelagonian Fault, Fig. 1) during the formation of two middle Miocene basins inside the island of Evvia and Attica (Fig. 1). Furthermore, new low-temperature apatite fission-track (AFT) data acquired from the Pelagonian rocks will allow a quantification of their exhumation history and hence a possible comparison to the Cyclades.

2. Geological setting

Central Greece is formed by the stacking of Pelagonia-derived rocks on top of Adria-derived rocks, separated by Pindos and Parnassos flysch and/or ophiolites (remnants of the Pindos ocean/deep basin - Figs 1 and 2 - Papanikolaou, 2013). Pelagonian rocks mainly crop out in the north-west of Attica and in the island of Evvia while Adria (some fragments of Pindos ophiolites) rocks are exposed in Western Central Greece, in the South of Evvia and in all the Cyclades (Figures 1 and 2). The Pelagonian Fault (PF - also called South Evvia North Attica fault, Bradley, 2012 - orange line in Fig. 2) limits the Pelagonian and Adria/Pindos terranes in both Evvia and Attica (Xypolias et al., 2003).

Pelagonia is composed of two main units from bottom to top: 1/ Crystalline basement composed of a para- and orthogneiss with Cambrian ages (Yarwood et al; 1976, orange in Fig. 2); 2/ (Meta)-Sedimentary cover (pink, Fig. 2) with Permian metasediments and metavolcanics, Triassic to Jurassic marbles, and limestone (Doutsos et al., 1993; Ross & Zimmerman, 1996). These units are thrusted on top of the Mesozoic to Lower Tertiary Beotian and Parnassos Flysch (Faupl et al., 2007; Nirta et al., 2015). They have undergone greenschist facies metamorphism during the Early Cretaceous and locally underlie ophiolites (dark green, Fig. 2).

The Pindos unit (between Pelagonia and Adria rocks) mainly crops out in western Central Greece and is composed of Paleocene to Eocene flysch (Faupl et al., 2007).

Adria rocks are typical of continental rifted margin with contrasting deformation histories from west to east (and from bottom to top): 1/ deformed sediment plateform with a fold and thrust belt defining the External Hellenides locally named Ionian, Plattenkalk, Phylitte and Gavrovo tripolitza units (Aubouin, 1959; Bonneau, 1984; Doutsos et al., 2006); and 2/ the Cyclades Blueschist Units which are composed of Adria/Pindos derived rocks with HP/LT metamorphism (CBU, Bonneau, 1984). The CBU can be subdivided in three main units (Bonneau, 1984; Trotet et al., 2001; Philippon et al., 2012): i/ basement (gneiss and pelitic shales), ii/ metasedimentary cover (Triassic marbles and Mesozoic sediments), and iii/ meta-ophiolitic rocks (serpentinite, meta-basalt, meta-chert, metagabbro) on top with well-preserved HP-LT assemblages (e.g Syros, Philippon et al., 2013). The basement and sedimentary cover correspond to the distal part of the Adria margin and the meta-ophiolite to the Pindos Ocean (Philippon et al., 2012). The CBU is also exposed south of Evvia and Attica (called Evvia Blueschist Unit – EBU - Katsikatsos et al., 1986; Katzir et al., 2000; Xypolias et al., 2003) and are thrust onto the autochthonous Almyropotamos unit, which is the lateral equivalent of the external Hellenides (Gavrovo, Shaked et al., 2000; Ring et al., 2007; Jolivet et al., 2013, Fig 2). The Almyropotamos unit consists of 1.5 km-thick of Eocene-Oligocene metaflysch above 2 km-thick of Triassic-middle Eocene marbles interspersed with shales.

Numerous Neogene basins cover this Aegean domain, with the majority being Pliocene-Quaternary in age. They are also coeval with plate re-organisation and the formation of the North Anatolian Fault and the Corinth and Evvia rift systems (see §Introduction and Figure 2 in Brun et al., 2016; see also Mascle and Martin, 1990). We will focus our study on middle Miocene basins (Figs. 1 and 2), cropping out in Central Greece. They are mainly filled with lacustrine and alluvial sediments (limestones and conglomerates) and dated at around 14 Ma through K-Ar ages from syn-sedimentary volcanism (Oxylithos unit in Kymi Basin in Evvia, Katsikatsos et al., 1981; Pe-Piper and Piper, 1994; Bradley, 2012). In the CBU, in the Peloponnese and in Crete, Miocene extensional tectonics is supposed to be mainly controlled by low-angle normal faults (detachments). In particular, three major detachment systems have been described in South Attica/Cyclades: the North Cycladic Detachment, the West Cycladic Detachment (Lavrion detachment in Attica) and the Naxos-Paros/Central Cycladic Detachment (Gautier et al., 1993; Jolivet et al., 2010a; Iglseder et al., 2011; Scheffer et al., 2016; Coleman et al., 2019). The Cretan detachment is mapped in Crete (Ring et al., 2001), while the Corinth-Patras detachment has been described (Sorel, 2000) and debated (Bell et al., 2009) north of the Peloponnese. Contrastingly, the Neogene basins (middle Miocene and Plio-Quaternary) in Central Greece are proposed to be controlled by high-angle faults (Papanikolaou & Royden, 2007; Royden & Papanikolaou, 2011). Plio-Quaternary basins are controlled by E-striking high-angle faults, defining the major rift shoulders in Evvia and Corinth (Moretti et al., 2003; Bell et al., 2009). NW-striking high-angle normal faults (Figs. 1 and 2), observed throughout Central Greece and the Peloponnese, are proposed to control the middle Miocene basins deposition by reactivation in extension of former thrust faults (e.g. Pindos/Adria limits or Pelagonia/Pindos limit, Fig. 1 and 2; Papanikolaou and Royden, 2007). These high-angle faults are seismically active today with dip-slip normal (E-striking faults) and oblique sinistral and normal (NW-striking faults) kinematics (Roberts and Jackson, 1991; Kiratzi and Louvari, 2003; Papanikolaou and Royden, 2007; Ganas et al., 2016). middle Miocene basins in Evvia and Attica are also observed close to the NE-striking Pelagonian Fault (Figs. 1 and 2), which is initially a thrust formed during subduction nappe stacking, separating Adria and Pelagonia (Papanikolaou, 2013). The age of the activity of the Pelagonian Fault is controversial, with a potential middle Miocene age (Kokkalas, 2001; Xypolias et al., 2003). The Pelagonian Fault was characterized as a normal fault because of differential exhumation in the footwall (CBU) and hangingwall (Pelagonia) (Shaked et al., 2000; Papanikolaou and Royden, 2007; Diamantopoulos et al., 2009) or even as an extensional transfer fault (Bradley, 2012).

Our objective is to constrain the tectonics history of Central Greece (Evvia and Attica) from the middle Miocene to the present. To achieve our purpose, we will:

1/ Constrain the potential strike-slip activity of the Pelagonian Fault during middle Miocene times and its relation with middle Miocene basin deposition. To this end, we study the tectonics context of two middle Miocene basins: Limni (North Evvia) and Kymi (South Evvia) basins (Fig. 2). The Kymi basin was chosen for its proximity with the Pelagonian Fault and it will be compared with the Limni basin, which has no NE-striking structures. In particular, we aim to constrain the link between the activity of NW-striking high-angle normal faults and NE-striking strike-slip faults in middle Miocene times.

2/ Characterize the link between NW-striking and E-striking normal faults to constrain the role of middle Miocene inherited structures in controlling Plio-Quaternary faulting.

3/ Acquire new Apatite Fission Track data (AFT) to constrain the exhumation history of Central Greece and its relationship to faults activity. This work will also provide the first AFT dataset in this region (Fig. 1).

3. Structural data

3.1. The Limni basin and NW-striking normal faults

The northern middle Miocene Limni basin is located in the central part of northern Evvia (Fig. 3) and contains lacustrine limestones, conglomerates and shales deposited on different units of Pelagonia: the basement (gneiss and Permo-Carboniferous sediment) in the southern rim, Triassic-Jurassic marble/schists and ophiolites to the north and east (see geological setting and Fig. 3).

We conducted a structural study with around 125 bedding measurements in the basin (stereonet of basin’s sediment beddings in Fig. 3B) and 83 faults measurements in the Pelagonian bedrock and Miocene basin fill (stereonets of total faults shown in Figure 3B).

The structural map in Figure 3 shows the major faults inferred from our field study. Two main strike directions are observed: NW-SE and E-W (map and stereonets of Fig. 3). Note that minor NE-striking faults with horizontal slickenlines suggesting strike-slip motion and N-S faults are observed (location III, Fig. 3A). At map scale, the basin is controlled in its southern rim by a major NW-striking high-angle normal fault (fault 1, Fig. 3A), locally defining a NW-striking faulted zone in highly deformed

Pelagonian rocks (stereonet in location I, Fig. 3B and right picture in Fig. 3D). Local observations of NW-striking normal faults with slickenlines show two families of slickenlines, one with dip slip and one with slightly oblique slip (location II, Fig. 3A, stereonet in location II, Fig. 3B and left picture, Fig. 3D). Local observation on a fault plane with the two slickenlines suggest first a dip slip activity on NW-striking normal fault and a more recent oblique slip on the same fault. The present-day seismic activity shows consistently oblique sinistral on NW-striking faults (Roberts and Jackson, 1991; Papanikolaou and Royden, 2007; Ganas et al., 2016). On these bases, we will define therefore two fault families: NW-striking with dip slip (supposed to be active in middle Miocene, see below) and NW-striking with oblique slip (supposed to be active in Plio-Quaternary as suggested by the present-day seismic activity – Ganas et al., 2016)

A NE-SW cross-section (orthogonal to the major normal fault 1, Fig. 3C) shows the relationship between NW-striking faults and the basin bedding. It highlights a major offset of the Pelagonian basement in the footwall by the NW-striking fault 1 and the Pelagonian marble and schist, covered by middle Miocene sediments in the hangingwall. This observation implies a minimum vertical offset of the thickness of the marble/schists and of the ophiolite unit of the Pelagonian which is at least 1 to 2 km thick (Xypolias et al., 2003). In the basin, minor NW-striking normal faults are observed with limited offset in the Pelagonian bedrock (faults 2, 3 and 4), as shown in cross-section Fig. 3C. Although the Limni basin is bordered and internally affected by NW-striking normal faults, the dip of the bedding is relatively flat (stereonet of basin's sediment beddings, Fig. 3B), with a mean dip value of around 30° and a mean strike of NW-SE. Furthermore, our bedding measurements suggest that the basin thickness slightly increases in the hangingwall of major faults (like fault 1, cross-section in Fig. 3C). This observation suggests that NW-striking faults are synchronous with basin deposition.

These NW-striking normal faults strongly affect the Evvia and Attica areas (Fig. 2 and 3) by controlling the mean strike of the Evvia Gulf. Locally NW-striking normal faults are cross-cut by E-striking normal faults (location I, Fig. 3A, stereonet in location I, Fig. 3B and right picture, Fig. 3D). At map scale, this observation is also validated. In the Northern part of Evvia, near Loutra Edipsou, the coastline evolves from a NW-SE strike in the South to an E-W strike to the North showing the interplay (observed at small scale at locations IV and V, Fig. 3A and stereonets in location IV and V, Fig. 3B) between NW-striking normal faults and E-striking normal faults.

3.2. Loutra Ypatis: E-striking and NW-striking normal faults

The western termination of the Evvia Gulf also shows remarkable interactions between NW- and E-striking fault structures.

The active Kamena Vourla fault (location I, Fig. 4A, stereonet in location I in Fig. 4B and pictures a-b in Fig. 4C - Cundy et al., 2010; Walker et al., 2010), defining the southern rim of the Evvia Gulf and visible from the Athena-Thessaloniki highway, shows a large fault plane with slickenlines (pictures a-b in Fig. 4C). Our data suggest two dominant strikes: E-W and NW-SE. NW-striking faults evolve

locally to an E-W strike with the same slickenlines (location I in Fig. 4A and stereonet in location I, Fig. 4B). Similar features have been observed south of the Limni basin (Loutra Edispou – locations IV and V, Fig. 3A, and see details in the above section 3.1). At map scale, the Kamena Vourla fault system is part of an E-W en-échelon-system inside a NW-striking zone, explaining these two strikes.
This en-échelon system is found at larger scale, with five main E-striking fault segments from East to West: Arkitsa (already characterized with high resolution data by Jackson and McKenzie, 1999; Kokkalas et al., 2007), Kamena Vourla (location I, Fig. 4A), Thermopyles (location III, Fig 4A and stereonet in location III, Fig. 4B), Loutra Ypatis (location V, Fig. 4A, stereonet in location V, Fig. 4B and picture c, Fig 4C) and Lefkada. These E-striking fault segments are connected by NW-striking normal faults mapped in location II and IV (stereonets in locations II and IV in Fig. 4B) and NW-striking fault in west of Arkitsa fault and Kamena Vourla fault (location I, Fig. 4A). This en-échelon system defines the southern rim of the Evvia Gulf which is therefore, a NW-SE oblique rift with active E-striking normal faults.

3.3. Normal faults and stress tensors in Limni and Loutra Ypati areas

3.3.a. Inversion method

We invert our measured fault and slip data for paleostress . The inversion seeks a stress tensor that yields a shear stress direction on each fault plane as close as possible to the measured slip direction (Wallace, 1951; Bott, 1959; Angelier, 1984). We use the Fsa software (Burg et al., 2005; Célérier, 2020) that implements the random search method proposed by Etchecopar et al. (1981). This method allows inverting either the whole dataset in the case of monophase data, or only a fraction of the dataset in the case of polyphase data. It yields the principal stress directions s_1, s_2, s_3, and stress tensor aspect ratio r0 $= (\sigma 1 - \sigma 2)/(\sigma 1 - \sigma 3)$, where $\sigma 1 \geq \sigma 2 \geq \sigma 3$ are the principal stress magnitudes corresponding to the directions s_1, s_2, s_3. We use the quality criterion proposed by Heuberger et al. (2010) to distinguish robust solutions from possible statistical artifacts. It is based on a comparison between the total number of data in the data set, *Ntotal,* the number of data with a rake misfit lower than 15°, *Nexp15*, and the number of data *N0exp15* that could be obtained below the same misfit threshold by inverting a random dataset of the same size *Ntotal*. The result of this comparison is summarized by an integer quality index, *InvQual*, that varies from -1, for solutions that could be artifacts, to 2 for robust estimates. Because each data set is partly heterogeneous, each inversion is carried out in two steps to cancel the influence of outliers on the solution. In a first step, all data are considered, and the proportion of data with acceptable angular misfit (below 15 or 30°, depending on cases) is determined. In a second step, the inversion is required to account only for that proportion of data. To facilitate the discussion of the results, we will call a fault slip datum compatible or incompatible with a stress tensor when the angular misfit between its slip vector and the predicted shear stress direction is less than 15° or more than 30° respectively. We will also distinguish the terminology for tectonics regimes, compressional, wrench, and extensional, following Célérier (1995), from that of fault types, reverse, strike-slip, and normal.

3.3.b. Dataset

Our structural data show that Limni and Loutra Ypatis areas are controlled by three families of faults: family 1/ E-striking normal faults, family 2/ NW-striking normal fault with oblique-slip (strike-slip faults), and family 3/ NW-striking normal faults (e.g. with dip slip). Families 2 and 3 having similar fault plane orientations with markedly different slip orientations suggests that they belong to distinct tectonics phases, which is further supported by occasional slickensline record of these different slips on the same fault. Families (1) and (2) are seismically active today (Roberts and Jackson, 1991; Papanikolaou and Royden, 2007; Ganas et al., 2016), Our structural data show that NW-striking faults (with dip slip, Family 3) are synchronous with middle Miocene basin deposition. Family 3 was therefore active in middle Miocene, at a different period of time compare with families 1 and 2. We combined families 1 and 2 and kept the family 3 separated for the inversions, to obtain, respectively, a Plio-Quaternary stress tensor and a middle Miocene stress tensor.

3.3.c. Results

The resulting stress tensors are labeled with a subscript that indicates the family combination they are calculated from: T_3 is computed from family 3, while T_{12} is computed from the combination of families 1 and 2. They are shown in stereographic projection with the data they are computed from in Fig. 5. Their parameters are listed in supplementary material Table ST1 while the inversion parameters and quality are documented in Table ST2. Detailed misfit distributions and Mohr's circles are shown in Appendix (Fig. S1 and S2).

The combination of the two first families yields 40 faults and slip data and reduced stress tensor T_{12} with nearly vertical maximum principal stress s_1, thus in the extensional regime (Fig. 5A and supplementary materials Tables ST1 and ST2). The minimum principal stress, s_3, is horizontal and oriented North-South. However, the aspect ratio, $r0 = 0.92$, places the regime close to radial extension and thus suggests that the orientations of the horizontal principal stress are not highly significant. This solution yields an average angular error of 8.1° for 75% of the data, and accounts for 25 faults with rake misfit below 15° (*Nexp15* = 25), which ensures a high statistical significance with *InvQual* = 2 (supplementary material Table ST2).

The third family contains 15 data and yields stress tensor T_3 also in the extensional tectonics regime with a horizontal minimum principal stress, s_3, oriented NE-SW (Fig. 5B). The aspect ratio, $r0 = 0.8$, places the regime into a typical extension, further away from radial extension than T_{12}. The average angular error is 7.7° for 100% of the data, and 12 faults have rake misfit below 15° (*Nexp15* = 12), but the small number of data results in a lower quality solution with *InvQual* = 1 (supplementary material Table ST2).

This inversion therefore suggests:

1/ Almost radial extension during Plio-Quaternary (tensor T_{12} with s_3 orientated N-S) associated with dip-slip motion on new-formed E-striking normal faults and oblique sinistral and normal motion on pre-existing NW-striking normal faults

2/ NE-SW extension along NW-striking normal faults during middle Miocene times

3.4. The Kymi basin: NW-striking normal faults and NE-striking dextral faults.

Our structural analysis on the middle Miocene Kymi basin (location on Figure 2 and local map in Fig. 6A) allows the identification of the key faults controlling the sediment deposition. From bottom upwards, the basin contains lacustrine and conglomerate deposits (Bradley, 2012). Oxylithos volcanics intruded the basin during sediment deposition at 14 Ma (Fig. 6A, Pe-Piper & Piper, 1994) allowing relative dating of the basin to be middle Miocene. The basement of the basin is composed of Pelagonian rocks (Paleozoic, Triassic-Jurassic marble and schists and Cretaceous sediments), forming large scale open folds: NE-SW Amarynthos antiform and synform below the basin (Fig. 6A, Xypolias et al., 2003; Bradley, 2012). Similar folds are observed in the Adria unit (EBU, Almyropotamos antiform, Kokkalas, 2001; Xypolias et al., 2003). At map scale, the Pelagonian Fault separates the Pelagonian (to the North) from the EBU (to the South) and marks the southern limit of the Kymi basin (orange line in Fig. 6). We extended our analysis to the Nea-Palatia middle Miocene basin in Central Greece (Fig. 6A) in order to constrain the southern continuity of the Pelagonian Fault. Our study yielded 185 fault measurements (Fig. 6B stereonet of total faults), mainly outside of the basin, and 354 bedding measurements (Fig. 6B stereonet with 44 basin's sediment beddings).

Two main fault directions with map-scale fault trace exposure were observed: NW-striking normal faults and NE-striking sub-vertical strike-slip faults parallel to the map scale strike of the Pelagonian Fault (stereonets in Fig. 6B). Minor E- and N- striking faults are observed, with no clear map-scale fault trace exposure (stereonets, Fig. 6B).

In the Kymi basin, NW-striking normal faults are found in the south-western part of the basin marking the contact between lacustrine sediments and Pelagonian rocks (location I in Fig. 6A and stereonet in location I, Fig. 6B). Similarly, the northern rim of the Kymi basin is mainly controlled by NW-striking normal faults (as already discussed in Bradley, 2012), a feature that is similar to our findings in the Limni basin. Associated with these normal faults, we found NE-striking vertical faults, with sub-horizontal slickenlines and a dextral shear sense, defining a NE-striking corridor that limits the Kymi basin (location II, Fig. 6A and stereonet in location II, Fig. 6B). The southern limit of the Kymi basin is mainly controlled by these NE-striking faults (e.g. Pelagonian Fault, PF).

The novelty of our data is to provide numerous fault data with vertical plane and horizontal slickenlines along the Pelagonian Fault (locations III-IV, Fig. 6A, stereonets in locations III-IV, Fig. 6B and picture in Fig. 6C) that will be used for the stress inversion (see below). At location III, the Pelagonian marbles are strongly deformed, forming either large breccias or defining a new sub-vertical NE-striking schistosity at high-angle to the regional schistosity of Pelagonian schists (picture in Fig. 6D). Even in this strongly faulted zone, NW- striking normal faults are always observed, with no cross-cutting relationships, suggesting a possible coeval activity of strike-slip and normal faults (Fig. 6B, stereonets in locations III-IV and V). At map scale, the Pelagonian Fault defines the southern rim of the basin (cross-section Fig. 6E) indicating activity of the fault after or during the deposition of the Kymi basin. In addition, sub-horizontal bedding of the basin, even close to the PF, suggests that the basin is not deformed by the Pelagonian Fault (stereonet of basin's sediment beddings in Fig. 6B and cross-section, in Fig. 6E), indicating basin deposition during the PF activity (as already suggested by Kokkalas, 2001; Xypolias et al., 2003).

Similar conclusions can be drawn in the Nea-Palatia basin in Attica. The southern/eastern rim of the middle Miocene basin is marked at map scale by NE-striking dextral strike-slip faults (locations VI in Fig. 6A and stereonet in location VI in Fig. 6B). Note again the existence of NW-striking normal faults inside or close to NE-striking strike-slip faults, suggesting a potential coeval activity of normal faults and strike-slip fault (location VII in Fig. 6A and stereonet on location VII in Fig. 6B). This dextral fault zone is not directly continuous from the Pelagonian Fault in Evvia, suggesting two branches: one northern branch in Evvia, one southern branch in Central Greece. The northern branch (the Pelagonian Fault in Evvia) most probably ends inside the Evvia Gulf and leads to limited deformation in Central Greece (northern location VI in Fig. 6A). These two branches define a strike-slip corridor at regional scale (Fig 6A).

3.5. Stress tensor for the NE-striking strike-slip faults.

The 25 NE-striking strike-slip faults from the Kimi area define our 4th family of faults. Inverting it yields a new stress tensor T_4, a good quality solution (Table ST2), with a nearly vertical intermediate principal stress, s_2, thus in the wrench tectonics regime, and with a horizontal minimum principal stress, s_3, oriented North-South (Fig. 7 and supplementary materials S3 and Table ST1). An average angular error of 4.5° for 76% of the data and 19 faults with rake misfit below 15° (*Nexp15* = 19) result in a good quality: *InvQual* = 2 (supplementary material Table ST2). This stress tensor is different from the stress tensors inferred from E-striking normal faults with NW-SE oblique sinistral faults (T_{12}) and NW-striking normal faults with dip-slip (T_3), due to the differences on the vertical principal stress axis: T_{12} and T_3 are in extensional regime (s_1 vertical) while T_4 is in wrench regime (s_2 vertical). In the discussion section, we will discuss the compatibilities between T_3 and T_4, since our field data suggest coeval activities of NE-SW strike-slip and NW-SE normal faults with dip slip.

For T_4 stress tensor, the maximum principal stress direction s_1 is horizontal and orientated E-W (Fig. 7). Large scale folds in the Pelagonian rocks and the EBU, orientated N-S, are consistent thus consistent with this inferred shortening direction and hence with dextral strike-slip activity of the Pelagonian Fault (Fig. 6A, Fig. 7C). Moreover, the parallelisation of the fold axes evolving from N-S to NE-SW towards the Pelagonian Fault supports coeval PF activity and folding (Xypolias et al., 2003). Kymi basin deposits in a NE-SW oriented syncline, suggesting deposition during strike-slip activity (Fig. 6E).

4. Low-temperature thermochronology data

4.1. Method

We conducted Apatite Fission Track (AFT) analysis to constrain the exhumation history of the Pelagonian rocks in Central Greece, since no data are presently available in this region (Fig. 1). Samples were selected along a transect perpendicular to the Pelagonian Fault to characterize its impact on rock exhumation (samples location on Fig. 2 and Figs. 3,4,6). This new dataset, together with previous zircon fission track (ZFT), AFT and (U-Th)/He ages from Central Greece, will permit a comparison to published ages in the Cyclades that cluster around 10-12Ma, potentially revealing the role of the Pelagonian Fault on regional exhumation (Fig. 1, and see our Introduction and Geological setting for further details).

The AFT thermochronology data provide thermal information within a 60°C to 120°C temperature range, allowing us to describe the exhumation or burial of rocks within the upper 2 to 5 km of the crust (Gleadow & Duddy, 1981). AFT data will therefore be used to identify the last stage of exhumation in the upper crust and the potential role of the faults. Some samples were chosen close to the identified NW-striking faults, to provide further constraints on their age.

Six key-samples were selected (location Fig. 2): CG03 (Pelagonian schists close to Pelagonian Fault), CG08 (metamorphic Pelagonian schists), CG11 and CG13 (Pelagonian metamorphic basement), CG14 and CG16 (Pindos Flysch). CG11, CG13, CG16 and CG14 are located on the footwall of NW-striking normal faults.

The apatite samples were mounted on glass slides using epoxy glue and polished. Samples were etched in 6.5% HNO3 (1.6 M) for 45 seconds at 20°C to reveal the spontaneous fission tracks (Seward et al., 2000), before being irradiated with a neutron fluence rate of 1.0 x 1016 neutrons/cm2 (Oregon State University, Oregon, U.S.A.). The micas used as external detector were etched in 40% HF for 40 minutes at 20°C in order to reveal the induced fission tracks. The ages were calculated following the method recommended by the Fission Track Working Group of the I.U.G.S. Subcommission on Geochronology (Hurford, 1990) using the zeta calibration method (Hurford & Green, 1982). CN5 glass was used as a dosimeter. Ages were calculated using an overall weighted mean zeta value of 313.2±11.96 a cm2, obtained on both Durango (McDowell et al., 2005) and Mount Dromedary apatite standards (Green, 1985; Tagami, 1987). Samples were analyzed at the University of Rennes 1 – Observatoire des Sciences de l'Univers de Rennes using the Autoscan© software (on manual mode) on a Zeiss M1 microscope, with a magnification of 1250 under dry objectives. All ages are central ages and errors are quoted at 2σ (e.g. Galbraith & Laslett, 1993 ; Galbraith, 2005). The Dpar kinetic parameter was measured on all analysed crystals for each sample and corrected following the method of Sobel & Seward (2010). Due to the generally poor quality of the apatite crystals, not enough confined track lengths could be measured in each sample to allow robust thermal modelling. Data are reported in Table 1.

4.2. Data

Samples selected for AFT analysis are from both metamorphic and detrital rocks.

4.2.a. Metamorphic samples

Sample CG03 comes from the shales of the Triassic-Jurassic marble-schist unit included in the Pelagonian Fault. Eleven grains give a central age of 38.8 ± 6.3Ma. Sample CG08 comes from the same unit further north and has a central age of 30.9 ± 4.7 Ma based on 22 crystals (Fig. 8A). Considering the high P(χ2) value (~100%), the individual apatite ages seem to be regrouped in one main age population ranging from Palaeocene to Oligocene. Three early/middle Miocene ages mark younger ages of this group in CG08 (Fig. 8B). The chlorite schists sample CG11 in the Pelagonian Paleozoic basement yields a central age of 19.3±2.0 Ma based on 19 analysed crystals. As suggested by the relatively low P(χ2) of 38%, this sample shows two distinct age groups, one Oligocene the other early to middle Miocene (grey and red arrow Fig. 8C). Sample CG13 is a gneiss from the Pelagonian basement, comparable with CG11 but with potentially higher metamorphic grade. Only seven apatite crystals could be dated. The individual ages range between 25 and 45 Ma with a central age of 30.8 ±7.2Ma (Fig. 8D).

4.2.b. Detrital apatite samples

These samples provided more apatite crystals compare to the metamorphic samples. CG14 was collected from the Pindos Flysch. The analysis of 50 crystals provided a central age of 36.4 ± 3.1 Ma. The individual ages are largely scattered between 90 and 12 Ma. The sample displays three age groups: 1/ an older group corresponding to Palaeocene-early Eocene times, 2/ a Mid-Eocene to Oligocene group and 3/ a younger early Miocene group (Fig. 8E). Sample CG16, also collected in the Pindos Flysch gives a younger central age of 30.7 ±4.7 Ma based on 23 crystals. Individual ages are scattered between 139 and 10Ma (Fig. 8F). However, two groups are distinguished with a respective age population ranging from Cretaceous to early Eocene and Oligocene to middle Miocene. The second group is mainly composed of Miocene ages.

4.3. AFT data interpretation

Samples CG03 and CG08 from the lower Mesozoic series have clearly been reset after the sediment deposition but the large spread in individual ages associated with late Eocene – Oligocene central ages suggests slow exhumation initiated during that period (Fig. 8). Sample CG11, collected in the same unit as CG13, also displays few Oligocene ages but the early Miocene central age suggests either a later exhumation or an exhumation from a deeper level. The second hypothesis would be consistent with the stratigraphic position of sample CG11 situated below sample CG13. The stratigraphic age of the sediments that formed samples CG14 and CG16 is assumed to be between 70 and 45 Ma (Faupl et al., 1998, 2007).

The occurrence of individual ages much older than the deposition age (especially in sample CG16) suggests, at most, partial post-depositional resetting within the apatite partial annealing zone (Fig. 8). The sediments were therefore buried to a depth of less than 4km, allowing sufficient annealing to rejuvenate some of the apatite crystals, the degree of annealing probably depending on chemical composition (Barbarand et al., 2003). The Oligocene central ages obtained for those two samples again suggest exhumation during that period, implying a regional event.

The youngest age groups observed in samples CG11, CG14, CG16 and possibly CG08 could be interpreted as a final exhumation phase dated at the minimum from the early Miocene (CG14) to middle Miocene (CG08, CG11 and CG16, red arrow - Fig. 8).

Our AFT data show, in the majority of samples, an Oligocene exhumation event and a second early to middle Miocene exhumation phase (arrows in Fig. 8 and Fig. 9). The associated large dispersion of the AFT individual ages suggests a phase of slow exhumation of the Pelagonian rocks in Central Greece during the Oligocene. The middle Miocene AFT ages recorded in our samples are strongly related to NW-striking high-angle normal faults. The locations of samples CG11, CG16 and potentially CG14 in the footwall of NW-striking normal faults (Fig. 9A), highlight local exhumation during a relatively fast middle Miocene event (compared to the Oligocene phase). This feature suggests a middle Miocene activity of the NW-striking normal faults, as already suggested by our structural analysis.

5. Discussion

5.1. Differential amount of exhumation across the Pelagonian fault

Our new AFT data allow, for the first time, a regional-scale comparison between the Cycladic unit and the Pelagonian unit (Fig. 9A). In Central Greece, our AFT data show a clustering in age around the Oligocene. Published AFT, zircon fission track (ZFT) and (U-Th)/He on zircon data in northern Greece (Hejl et al., 1999, 2008; Most, 2003; Thomson et al., 2009; Vamvaka et al., 2010; Coutand et al., 2014; Schenker et al., 2015) also presented numerous ages in the early-Miocene, Oligocene and older ages, suggesting a regional exhumation event at minimum before 16Ma (Fig. 9B). The Cyclades also recorded an Oligocene exhumation (with Ar/Ar ages, see synthesis of thermochronoloy in Philippon et al., 2012) inducing a widespread exhumation throughout the Aegean domain at this time. However, in the Cyclades, the low-temperature thermochronology ages (ZFT, AFT, U-Th/He on zircon and Apatite – Hejl et al., 2002, 2008; Ring et al., 2003, 2007; Brichau et al., 2006, 2008; Seward et al., 2009; Berger et al., 2013; Soukis and Stockli, 2013; Seman, 2016; Grasemann et al., 2018; Schneider et al., 2018) are much younger and concentrated in the late/middle Miocene, suggesting faster exhumation during this period (Fig. 9A and B). This Miocene cluster of low-temperature thermochronology ages marks the large amount of extension/exhumation recorded in the Cyclades, as exemplified by the activity of several low-angle normal fault/detachment systems (Avigad and Garfunkel, 1989; Gautier et al., 1993; Tschegg and Grasemann, 2009; Jolivet et al., 2010b; Krohe et al., 2010; Iglseder et al., 2011; Grasemann et al., 2012, 2018). In Central Greece, the young AFT ages are concentrated on samples close to some high-angle normal faults (see our data and data from Coutand et al., 2014 in the Sporades), contrastingly suggesting a limited amount of exhumation/extension during Miocene time. Furthermore, scattered AFT ages between the Paleogene/Oligocene to late-Miocene could suggest slow exhumation of the Pelagonian rocks or heterogenous amount of exhumation at regional scale. This highlights a major difference in the amount of exhumation and hence of crustal extension between Central Greece and the Cyclades during the Miocene. This feature is also exemplified at first order by the unroofing of the Cycladic unit, structurally below Pelagonia (see nappe stack discussion in our introduction and in Fig. 1). We suggest that the Pelagonian strike-slip fault accommodates lateral differences in the amount of extension during the Miocene. This is accompanied by a large amount of extension accommodated by detachment faults in the Cyclades, and much lower amount of extension in Central Greece mainly accommodated by high-angle normal faults (Figs. 2 and 9).

5.2. Central Greece faulting activity and middle Miocene basins

Our structural data show that in the middle Miocene, syn-tectonics basin sedimentation is coeval with NW-striking normal faults and NE-striking dextral strike-slip activities (Fig. 2). Limni basin deposition (North Evvia) is controlled by NW-striking normal faults (with dip slip motion). AFT data on samples in the footwall of these normal faults show local middle Miocene ages, suggesting middle Miocene cooling. Our structural data are consistent with the formation of the Limni basin during NE-SW extension (Fig. 5) in Miocene time controlled by NW-striking normal faults, as already suggested by Mettos et al. (1991), (1992). The Kymi basin deposition is mainly controlled by the dextral strike-slip Pelagonian Fault corridor (Fig. 2), locally associated with NW-striking normal faults. Previous studies have already suggested strike-slip activity along the Pelagonian Fault during the middle Miocene but in a transpressive context (Kokkalas, 2001; Xypolias et al., 2003; Kokkalas et al., 2006). Our stress tensor calculation on the Pelagonian fault implies an E-W direction of compression (Fig. 7) that is consistent with compressional structures described previously (Kokkalas, 2001; Xypolias et al., 2003) but does not require a transpressional context. The combination of our structural data from Limni and Kymi basins suggests coeval middle Miocene activity of the NW-striking normal faults and the NE-striking strike-slip faults, indicating instead a transtensive regime during Kymi basin deposition. At large scale, E-W shortening is also highlighted by the presence of large open folds (i.e. Almyropotamos fold – Evvia island, Penteli - North of Athens and Ymitos mountain – East of Athens, see map in Bradley, 2012) with the axis evolving from N-S to NE-SW close to the Pelagonian dextral strike-slip fault (Kokkalas, 2001; Xypolias et al., 2003). In summary, our structural data show that the middle Miocene tectonics of Central Greece is marked by the coeval activity of NE-striking dextral faults and NW-striking normal faults, with spatial strain partitioning: NE-striking faults mainly inside the Pelagonian fault strike-slip corridor, associated in its vicinity with N/NE-S/SW folds, and away from this corridor, extension with NW-striking normal faults (Fig. 2). At regional scale, the existence of strike-slip activity in middle Miocene times is also independently suggested by the presence of syn-kinematics structures in middle Miocene plutons in the Cyclades (Walcott and White, 1998; Kokkalas and Aydin, 2013), although their fault kinematics are still debated (van Hinsbergen and Schmid, 2012; Malandri et al., 2017).

Our structural data show that the Plio-Quaternary is marked by E-striking normal faults mainly developed inside pre-existing NW-striking faults. Kokkalas (2010) describes the consistently close link between NW-striking and E-striking normal faults, with E-W relay zones inside major NW fault zones. This interplay defines a complex fault zone growth and propagation, likely explaining the major fault striking NW in Central Greece. This likely explains NW-striking oblique rift systems in Central Greece (Evvia and Corinth, Fig 2) associated with E-striking normal faults. These tectonics structures control Plio-Quaternary basin formation.

5.3. Stress regimes in Mid Miocene and Plio Quaternary times.

Stress tensor calculations show that the Plio-Quaternary N-S extension is associated with E-striking normal faults and oblique reactivation of NW-striking normal faults (Fig. 5). These findings are consistent with present-day seismic activity and focal mechanisms showing coeval E-striking normal faulting, sinistral normal activity along these NW-striking faults (Kiratzi and Louvari, 2003; Ganas et al., 2016), as well as N-S strain rate directions inferred from GPS data (Davies et al., 1997; Reilinger et al., 2006; Hollenstein et al., 2008; Pérouse et al., 2012). Similar conclusions were proposed further North, close to the Olympus Mount (e.g. Kozani normal fault – Schenker et al., 2015).

Because the present-day seismic activity shows also coeval NE-striking dextral strike-slip (e.g. North Anatolian Fault to the North of the studied area) and E-striking normal faulting in Greece, (e.g. Corinth and Evvia rifts), we tested the compatibility between our measured NE-striking dextral faults (Pelagonian fault, family 4) and the combination of E-striking normal faults (family 1) and NW-striking strike-slip faults (family 2) by inverting them together. The combination of these three families yielded T_{124} stress tensor (supplementary materials Fig. S4, Table ST1) in the wrench tectonics regime (Fig. 10 and supplementary material Table ST2). Even though the solution quality is statistically good (Table ST2), it comes into sight that, whereas it accounts for most data from family 4, it poorly accounts for data from families 1 and 2 (supplementary material Fig. S7). It thus appears more like the result of extracting a phase, similar to T_4 from a multiphase family, rather than a phase explaining all three families 1, 2 and 4 together. The combination of family 4 with families and 1 and 2 thus fails to demonstrate compatibility and rather highlights heterogeneity. The poor compatibility of family 4 (dextral strike-slip) with the combination of families 1 and 2 (normal and sinistral faults) is, in fact, consistent with the total absence of dextral strike-slip faults in Central Greece, a region only characterized by Plio-Quaternary extension (Corinth and Evvia rifts, Stefatos et al., 2002; Lykousis et al., 2007; Bell et al., 2009). This suggests a Plio-Quaternary strain partitioning with normal faulting in Central Greece and dextral strike-slip faulting in Northern Greece (North Anatolian Trough and North Anatolian Fault). This furthermore suggests the absence of a clear link between the NAF and Corinth/Evvia rift systems, at variance with Armijo et al. (1996).

Our structural observations suggest in contrast a coeval activity of NW-striking normal faults (family 3) and NE-striking strike-slip faults (family 4) during middle Miocene. We thus tested the stress compatibility between these two families by inverting them together. This combination yields T_{34} stress tensor in the wrench tectonics regime with vertical s_2 and r0 = 0.14, thus close to the transition with the extensional regime (Figs. 10A and 10B and supplementary material Table ST1). This solution accounts for most data of families 3 and 4 (*Nexp15* = 27, supplementary materials Table ST2; Fig S5) with a quality equivalent to that of T_4, thus supporting compatibility between these two families. Therefore, T_{34} tensor suggests a wrench middle Miocene tectonics regime activating both normal and dextral faults (Figs. 10B and E).

Palaeomagnetic data support mean value of ~30° of rotation (Horner and Freeman, 1983; Kissel et al., 1986, 2003; Duermeijer, 2000; van Hinsbergen et al., 2005, 2006; Bradley et al., 2013) during Miocene times, with a rotation pole close to Scutari-Pec. NW-striking normal faults, formed before or during such rotation, were therefore rotated during Miocene times. In contrast, NE-striking dextral fault have undergone little if any rotation because they are sub-parallel to the small Eulerian circle. We, therefore, suggest that NE-striking faults accommodated the clockwise rotation, which is consistent with their dextral movement (inset of Fig. 11B). We, therefore, applied a 30° counter-clockwise vertical axis rotation to the NW-striking normal faults (family 3) to restore them in their Miocene original position (family 3r – after a backrotation of 30˚, Fig. 10C). We then combined this restored family 3r (became E-striking normal faults) with the NE strike-slip faults (family 4) and inverted this combination. This yielded T_{3r4} in the wrench tectonics regime (Figs. 10D and E and supplementary material S6). This solution is similar to T_{34}, with a similar quality, also with a horizontal maximum principal stress direction, s_1, that is now close to E-W (supplementary materials Table ST1 and ST2).

5.4. Central Greece tectonics since Miocene times

On these bases, we propose the following evolution of Central Greece tectonics since middle Miocene times. In the middle Miocene, the co-existence of NE-striking dextral strike-slip and E-striking normal faults (i.e. back-rotated present-day NW-striking faults – Fig. 11A) corresponds to a wrench tectonics regime with an almost N-S extension and E-W compression (T_{3r4} tensor – Fig. 11A). We propose that the E-W compression is related to westward extrusion of Anatolia that most probably started during the middle Miocene in a broad zone of deformation (North Anatolian Shear Zone, Şengör et al., 1979, 2005). Furthermore, the existence of calcite gouge in the NAF with middle Miocene ages supports this hypothesis (Nuriel et al., 2019). This E-W compression is furthermore consistent with middle Miocene transpressional structures affecting molasse basins and granitic intrusions (Kokkalas et al., 2006; Kokkalas and Aydin, 2013). The extensional direction is orthogonal to the middle/late Miocene position of the Hellenic trench, suggesting that extension was controlled by Aegean trench retreat (Papanikolaou & Royden, 2007; Royden & Papanikolaou, 2011). The observed spatial distribution of deformation, with strike-slip corridors localising shortening (with folds) and pure extensional structures away from these corridors, may be controlled by tectonics inheritance, as the Pelagonian strike-slip corridor is located in the main contact between Adria/Pindos and Pelagonia.

The progressive trench curvature during rollback implies block rotation, likely accommodated by the NE-striking dextral faults (Fig. 11B). Normal faults rotated together with s_3 which became NE-SW (T_{34} tensor – Fig. 11B). This progressive rotation can explain the widespread distribution of NW normal fault strikes, as shown in our data (Fig 6 with NW- normal faults striking from N110 to N150). Compression related to Anatolia extrusion remains EW during Miocene times and is accommodated in NE-striking dextral faults (tensor T_4 -Fig. 7; and Fig. 11A and B). Our AFT and structural data show that the Pelagonian fault acted as major dextral strike-slip fault during middle Miocene. The Pelagonian fault accommodated not only EW compression but also accomodated lateral different amounts and styles of continental extension during trench curvature and block rotation: a large and younger amount of extension in the Cyclades/South Evvia/Attica accommodated by detachment faulting (Avigad and Garfunkel, 1989; Gautier et al., 1993; Liati et al., 2009 ; Tschegg and Grasemann, 2009 ; Jolivet et al., 2010a; Krohe et al., 2010; Iglseder et al., 2011 ; Grasemann et al., 2012, 2018 ; Scheffer et al., 2016; Coleman et al., 2019) and less extension in Central Greece (north of the Pelagonian fault) mainly accommodated by high-angle normal faults (Fig. 11A and B).

During the Plio-Quaternary, Central Greece evolved into a pure extensional tectonics regime, with almost radial extension and no more E-W shortening (tensor T_{12} - Figs. 5 and 10E and 11C). This implies that westward extrusion of Anatolia became fully accommodated by the North Anatolian Fault (NAF, as also suggested by Armijo et al., 1996; Reilinger et al., 1997) leading to the formation of the Anatolia/Aegean microplate. The middle Miocene normal faults were used to define NW-striking oblique rifts, with newly formed E-striking normal faults (Fig. 11C).

Our study suggests therefore that the Corinth and Evvia rifts are not opening in response to westward propagation of the NAF (Armijo et al., 1996) but are instead related to progressive strain localisation at lithospheric scale controlled by both a change in the direction of extension and the presence of inherited structures. This change in the direction of extension from NE-SW to N-S during the Plio-Quaternary cannot be explained by the progressive trench curvature and block rotation during trench retreat. It can be more likely related to slab deformation at depth, as exemplified by the formation of the Kephalonia strike-slip fault (Evangelidis, 2017; Bocchini et al., 2018).

Conclusions

Based on new structural data, stress tensor analysis and AFT data in Central Greece, we draw the following conclusions

- middle Miocene basins in Central Greece are controlled by both NW-striking normal faults and NE-striking dextral strike-slip faults. The Pelagonian fault that limits Pelagonia-derived rocks to the north from Adria-derived rocks to the south is an example of such dextral strike-slip active during the middle Miocene.

- Apatite Fission Track data constrain middle Miocene local exhumation near NW-striking high-angle normal faults in Central Greece, confirming their middle Miocene activity.

- New Apatite Fission Track data for Central Greece suggest a significant difference in the amount of exhumation between Central Greece and the Cyclades. This difference in the amount of exhumation/exhumation is found to be accommodated by the Pelagonian dextral strike-slip fault.

-The co-existence of NE-striking dextral strike-slip and NW-striking normal faults during the middle Miocene is associated with an almost N-S extension related to trench retreat and an E-W compression related to westward extrusion of Anatolia.

-The progressive trench curvature during slab rollback implies a progressive rotation of NW-striking normal faults. This rotation is proposed to be accommodated in Central Greece by the Pelagonian fault.

- During the Plio-Quaternary, a change in extensional direction from NE-SW to N-S implies the formation of E-W normal faults inside NW-striking fault zone, defining oblique rift systems.

Acknowledgements

This work was initiated by fruit-full discussion in the field with Jean-Pierre Brun in October 2017. Cyprien Astoury (Géosciences Montpellier) is thanked for his help in preparing samples (grinding and separation). Our work has received funding from the European Union's EU Framework Programme for Research and Innovation Horizon 2020 under Grant Agreement No. 674899. The Free GMT software (Wessel and Smith, 1991) was used for some illustrations. Additional datasets for this research were acquired from the literature, included datasets for Pelagonian dating: Hejl et al., 1999, 2008; Most, 2003; Thomson et al., 2009; Vamvaka et al., 2010; Coutand et al., 2014; Schenker et al., 2015; for the Cyclades/South Evvia/ Attica datation: Hejl et al., 2002, 2008; Ring et al., 2003, 2007; Brichau et al., 2006, 2008; Seward et al., 2009; Berger et al., 2013; Soukis and Stockli, 2013; Seman, 2016; Grasemann et al., 2018; Schneider et al., 2018 and for GPS data (Hollenstein et al., 2008). Readers can access our structural and thermochronology data from the text, tables and figures, as well as our complete dataset on https://hal.archives-ouvertes.fr/hal-03175867 .

References

Anderson, E. M. (1905). The dynamics of faulting, Transactions of the Edinburgh Geological Society, 8, 387–402.

Angelier, J. (1984). Tectonic analysis of fault slip data sets, J. Geophys. Res., 89(B7), 5835–5848, doi:10.1029/JB089iB07p05835.

Armijo, R., Carey, E., and Cisternas, A. (1982). The inverse problem in microtectonics and the separation of tectonic phases, Tectonophysics, 82, 145–160.

Armijo, R., Meyer, B., King, G.C.P., Rigo, A., Papanastassiou, D. (1996). Quaternary evolution of the Corinth Rift and its implications for the Late Cenozoic evolution of the Aegean. Geophys. J. Int. 126, 11–53. https://doi.org/10.1111/j.1365-246X.1996.tb05264.x

Armijo, R., Meyer, B., Hubert, A., Barka, A. (1999). Westward propagation of the North Anatolian fault into the northern Aegean: Timing and kinematics. Geology 27, 267. https://doi.org/10.1130/0091-7613(1999)027<0267:WPOTNA>2.3.CO;2

Armijo, R., Flerit, F., King, G., Meyer, B. (2004). Linear elastic fracture mechanics explains the past and present evolution of the Aegean. Earth Planet. Sci. Lett. 217, 85–95. https://doi.org/10.1016/S0012-821X(03)00590-9

Aubouin, J. (1959). Contribution à l'étude géologique de la Grèce septentrionale: les confins de l'Empire et de la Tessalie, (Doctoral dissertation). Retrieved from Annuaire Géologique des Pays Hellénique, 10, 1–483. Paris.

Aubouin, J., Dercourt, J. (1965). Sur la géologie de l'Egee; regard sur la Crete (Grèce). Bull. Société Géologique Fr. 7, 787–821.

Avigad, D., Garfunkel, Z. (1989). Low-angle faults above and below a blueschist belt?Tinos Island, Cyclades, Greece. Terra Nova 1, 182–187. https://doi.org/10.1111/j.1365-3121.1989.tb00350.x

Barbarand, J., Carter, A., Wood, I., Hurford, T. (2003). Compositional and structural control of fission-track annealing in apatite. Chem. Geol. 198, 107–137. https://doi.org/10.1016/S0009-2541(02)00424-2

Bell, R.E., McNeill, L.C., Bull, J.M., Henstock, T.J., Collier, R.E.L., Leeder, M.R. (2009). Fault architecture, basin structure and evolution of the Gulf of Corinth Rift, central Greece. Basin Res. 21, 824–855. https://doi.org/10.1111/j.1365-2117.2009.00401.x

Berger, A., Schneider, D.A., Grasemann, B., Stockli, D. (2013). Footwall mineralization during Late Miocene extension along the West Cycladic Detachment System, Lavrion, Greece. Terra Nova 25, 181–191. https://doi.org/10.1111/ter.12016

Bessiere, E., Rabillard, A., Précigout, J., Arbaret, L., Jolivet, L., Augier, R., Menant, A., Mansard, N. (2018). Strain Localization Within a Syntectonic Intrusion in a Back-Arc Extensional Context: The Naxos Monzogranite (Greece): STRAIN LOCALIZATION IN THE NAXOS PLUTON. Tectonics 37, 558–587. https://doi.org/10.1002/2017TC004801

Bocchini, G.M., Brüstle, A., Becker, D., Meier, T., van Keken, P.E., Ruscic, M., Papadopoulos, G.A., Rische, M., Friederich, W. (2018). Tearing, segmentation, and backstepping of subduction in the Aegean: New insights from seismicity. Tectonophysics 734–735, 96–118. https://doi.org/10.1016/j.tecto.2018.04.002

Bonneau, M. (1984). Correlation of the Hellenide nappes in the south-east Aegean and their tectonic reconstruction. Geol. Soc. Lond. Spec. Publ. 17, 517–527. https://doi.org/10.1144/GSL.SP.1984.017.01.38

Bono, A.D., Stampfli, G.M., Martini, R., Vachard, D. (1998). ANNALES GÉOLOGIQUES DES PAYS HELLÉNIQUES 17.
Bornovas, J., Rondogianni-Tsiambaou, T. (1983). Geological map of Greece, 1: 500 000.

Bott, M. H. P. (1959). The mechanics of oblique slip faulting, Geological Magazine, 96(2), 109–117, doi:10.1017/S0016756800059987.

Bradley, K.E. (2012). The roof of the Cyclades: A structural, stratigraphic, and paleomagnetic study of Neogene extensional tectonics in Central Greece (Doctoral dissertation). Massachusetts Institute of Technology.

Bradley, K.E., Vassilakis, E., Hosa, A., Weiss, B.P. (2013). Segmentation of the Hellenides recorded by Pliocene initiation of clockwise block rotation in Central Greece. Earth Planet. Sci. Lett. 362, 6–19. https://doi.org/10.1016/j.epsl.2012.11.043

Brichau, S., Ring, U., Ketcham, R. A., Carter, A., Stockli, D., & Brunel, M. (2006). Constraining the long-term evolution of the slip rate for a major extensional fault system in the central Aegean, Greece, using thermochronology. Earth and Planetary Science Letters, 241(1–2), 293–306. https://doi.org/10.1016/j.epsl.2005.09.065

Brichau, S., Ring, U., Carter, A., Bolhar, R., Monié, P., Stockli, D., Brunel, M. (2008). Timing, slip rate, displacement and cooling history of the Mykonos detachment footwall, Cyclades, Greece, and implications for the opening of the Aegean Sea basin. J. Geol. Soc. 165, 263–277. https://doi.org/10.1144/0016-76492006-145

Brun, J-P., Faccenna, C. (2008). Exhumation of high-pressure rocks driven by slab rollback. Earth Planet. Sci. Lett. 272, 1–7. https://doi.org/10.1016/j.epsl.2008.02.038

Brun, J-P., Sokoutis, D. (2018). Core Complex Segmentation in North Aegean, A Dynamic View. Tectonics 37, 1797–1830. https://doi.org/10.1029/2017TC004939

Brun, J-P., Faccenna, C., Gueydan, F., Sokoutis, D., Philippon, M., Kydonakis, K., Gorini, C. (2016). The two-stage Aegean extension, from localized to distributed, a result of slab rollback acceleration. Can. J. Earth Sci. 53, 1142–1157. https://doi.org/10.1139/cjes-2015-0203

Burg, J-P., B. Célérier, N. M. Chaudhry, M. Ghazanfar, F. Gnehm, Schnellmann, M. (2005), Fault analysis and paleostress evolution in large strain regions: methodological and geological discussion of the southeastern Himalayan fold-and-thrust belt in Pakistan, Journal of Asian Earth Sciences, 24(4), 445 – 467, doi:10.1016/j.jseaes.2003.12.008.

Célérier, B. (1995). Tectonic regime and slip orientation of reactivated faults, Geophysical Journal International, 121(1), 143–191, doi:10.1111/j.1365-246X.1995.tb03517.x & 10.1111/j.1365-246X.1995.tb07021.x.

Célérier, B. (2020). Fsa: Fault & Stress Analysis software, version 37.5, http://www.celerier.gm.univ-montp2.fr/software/dcmt/fsa/fsa.html.

Clift, P.D., Dixon, J.E. (1998). Jurassic ridge collapse, subduction initiation and ophiolite obduction in the southern Greek Tethys. Eclogae Geol. Helvetiae 123–138.

Coleman, M., et al. (2019). "Along-strike consistency of an extensional detachment system, West Cyclades, Greece." Terra Nova 31(3): 220-233.

Coutand, I., Walsh, M., Louis, B., Chanier, F., Ferrière, J., Reynaud, J.-Y. (2014). Neogene upper-crustal cooling of the Olympus range (northern Aegean): major role of Hellenic back-arc extension over propagation of the North Anatolia Fault Zone. Terra Nova 26, 287–297. https://doi.org/10.1111/ter.12099

Cundy, A.B., Gaki-Papanastassiou, K., Papanastassiou, D., Maroukian, H., Frogley, M.R., Cane, T. (2010). Geological and geomorphological evidence of recent coastal uplift along a major Hellenic normal fault system (the Kamena Vourla fault zone, NW Evoikos Gulf, Greece). Mar. Geol. 271, 156–164. https://doi.org/10.1016/j.margeo.2010.02.009

Davies, R., England, P., Parsons, B., Billiris, H., Paradissis, D., Veis, G. (1997). Geodetic strain of Greece in the interval 1892-1992. J. Geophys. Res. Solid Earth 102, 24571–24588. https://doi.org/10.1029/97JB01644

Diamantopoulos, A., Krohe, A., Mposkos, E. (2009). Kinematics of conjugate shear zones, displacement partitioning and fragmentation of the upper rigid crust during denudation of high-P rocks (Pelagonian and Sub-Pelagonian Zones, Greece). Tectonophysics 473, 84–98. https://doi.org/10.1016/j.tecto.2008.05.028

Doutsos, T., Pe-Piper, G., Boronkay, K., Koukouvelas, I. (1993). Kinematics of the central Hellenides. Tectonics 12, 936–953. https://doi.org/10.1029/93TC00108

Doutsos, T., Koukouvelas, I.K., Xypolias, P. (2006). A new orogenic model for the External Hellenides. Geol. Soc. Lond. Spec. Publ. 260, 507–520. https://doi.org/10.1144/GSL.SP.2006.260.01.21

Duermeijer, C. (2000). Neogene evolution of the Aegean arc: paleomagnetic and geodetic evidence for a rapid and young rotation phase. Earth Planet. Sci. Lett. 176, 509–525. https://doi.org/10.1016/S0012-821X(00)00023-6

Dunkl, I. (2002). Tracnkkey: a Windows program for calculation and graphical presentation of fission track data. Comput. Geosc. 28, 3–12. https://doi.org/10.1016/S0098-3004(01)00024-3

Etchecopar, A., G. Vasseur, Daignieres, M. (1981). An inverse problem in microtectonics for the determination of stress tensors from fault striation analysis, Journal of Structural Geology, 3(1), 51–65, doi:10.1016/0191-8141(81)90056-0.

Evangelidis, C.P. (2017). Seismic anisotropy in the Hellenic subduction zone: Effects of slab segmentation and subslab mantle flow. Earth Planet. Sci. Lett. 480, 97–106. https://doi.org/10.1016/j.epsl.2017.10.003

Faccenna, C., Jolivet, L., Piromallo, C., Morelli, A. (2003). Subduction and the depth of convection in the Mediterranean mantle: CONVECTION DEPTH IN THE MEDITERRANEAN MANTLE. J. Geophys. Res. Solid Earth 108. https://doi.org/10.1029/2001JB001690

Faupl, P., Pavlopoulos, A., Migiros, G. (1998). On the provenance of flysch deposits in the External Hellenides of mainland Greece: results from heavy mineral studies. Geol. Mag. 135, 421–442. https://doi.org/10.1017/S001675689800870X

Faupl, P., Pavlopoulos, A., Migiros, G. (2007). THE PALEOGENE HISTORY OF THE PELAGONIAN ZONE S. L. (HELLENIDES, GREECE): HEAVY MINERAL STUDY FROM TERRIGENOUS FLYSCH SEDIMENTS 10.

Flerit, F., Armijo, R., King, G., Meyer, B. (2004). The mechanical interaction between the propagating North Anatolian Fault and the back-arc extension in the Aegean. Earth Planet. Sci. Lett. 224, 347–362. https://doi.org/10.1016/j.epsl.2004.05.028

Forster, M.A., Lister, G.S. (1999). Detachment faults in the Aegean core complex of Ios, Cyclades, Greece. Geol. Soc. Lond. Spec. Publ. 154, 305–323. https://doi.org/10.1144/GSL.SP.1999.154.01.14

Galbraith, R.F. (1990). The radial plot: graphical assessment of spread in ages. Nucl. Tracks Radiat. Meas. 17, 207–214. https://doi.org/10.1016/1359-0189(90)90036-W

Galbraith, R.F. (2005). The Statistics for Fission Track Analysis. Boca Raton, Florida, Chapman & Hall/CRC, 240.

Galbraith, R.F., Laslett, G.M. (1993). Statistical models for mixed fission track ages. Nucl. Tracks Radiat. Meas. 21, 459–470. https://doi.org/10.1016/1359-0189(93)90185-C

Ganas, A., Mouzakiotis, E., Moshou, A., Karastathis, V. (2016). Left-lateral shear inside the North Gulf of Evia Rift, Central Greece, evidenced by relocated earthquake sequences and moment tensor inversion. Tectonophysics 682, 237–248. https://doi.org/10.1016/j.tecto.2016.05.031

Gautier, P., & Brun, J-P. (1994). Ductile crust exhumation and extensional detachments in the central

Aegean (Cyclades and Evvia Islands). Geodinamica, 7(2), 57–85.

Gautier, P., Brun, J-P., Jolivet, L. (1993). Structure and kinematics of Upper Cenozoic extensional detachment on Naxos and Paros (Cyclades Islands, Greece). Tectonics 12, 1180–1194. https://doi.org/10.1029/93TC01131

Gleadow, A.J.W., Duddy, I.R., 1981. A natural long-term track annealing experiment for apatite. Nucl. Tracks 5, 169–174. https://doi.org/10.1016/0191-278X(81)90039-1

Goldsworthy, M., Jackson, J., Haines, J. (2002). The continuity of active fault systems in Greece: Fault continuity in Greece. Geophys. J. Int. 148, 596–618. https://doi.org/10.1046/j.1365-246X.2002.01609.x

Grasemann, B., Schneider, D.A., Stöckli, D.F., Iglseder, C. (2012). Miocene bivergent crustal extension in the Aegean: Evidence from the western Cyclades (Greece). Lithosphere 4, 23–39. https://doi.org/10.1130/L164.1

Grasemann, B., Huet, B., Schneider, D.A., Rice, A.H.N., Lemonnier, N., Tschegg, C. (2018). Miocene postorogenic extension of the Eocene synorogenic imbricated Hellenic subduction channel: New constraints from Milos (Cyclades, Greece). GSA Bull. 130, 238–262. https://doi.org/10.1130/B31731.1

Green, P. F. (1985). Comparison of zeta calibration baselines for fission-track dating of apatite, zircon and sphene. Chemical Geology: Isotope Geoscience section, 58(1-2), 1-22. https://doi.org/10.1016/0168-9622(85)90023-5

Hejl, E., Riedl, H., Weingartner, H. (1999). Cretaceous palaeokarst and Cenozoic erosion of the North Sporades (Greece): Results from geomorphological studies and fission-track analysis. Mitteilungen Österr. Geol. Ges. Wien 90, 67–82.

Hejl, E., Riedl, H., Weingartner, H. (2002). Post-plutonic unroofing and morphogenesis of the Attic–Cycladic complex (Aegea, Greece). Tectonophysics 349, 37–56. https://doi.org/10.1016/S0040-1951(02)00045-8

Hejl, E., de Grave, J., Riedl, H., Weingartner, H., Van den haute, P. (2008). Fission-track thermochronology of the Middle Aegean Island Bridge implications for Neogene geomorphology and palaeogeography. Z. Dtsch. Ges. Für Geowiss. 159, 495–512. https://doi.org/10.1127/1860-1804/2008/0159-0495

Heuberger, S., B. Célérier, J. P. Burg, N. M. Chaudhry, H. Dawood, and Hussain, S. (2010), Paleostress regimes from brittle structures of the Karakoram-Kohistan suture zone and surrounding areas of NW Pakistan, Journal of Asian Earth Sciences, 38(6), 307–335, doi:10.1016/j.jseaes.2010.01.004.

Hollenstein, Ch., Müller, M.D., Geiger, A., Kahle, H.-G. (2008). Crustal motion and deformation in Greece from a decade of GPS measurements, 1993–2003. Tectonophysics 449, 17–40. https://doi.org/10.1016/j.tecto.2007.12.006

Horner, F., Freeman, R. (1983). Palaeomagnetic evidence from pelagic limestones for clockwise rotation of the Ionian zone, western Greece. Tectonophysics 98, 11–27. https://doi.org/10.1016/0040-1951(83)90208-1

Hubert-Ferrari, A., Armijo, R., King, G., Meyer, B., Barka, A. (2002). Morphology, displacement, and slip rates along the North Anatolian Fault, Turkey: THE NORTH ANATOLIAN FAULT. J. Geophys. Res. Solid Earth 107, ETG 9-1-ETG 9-33. https://doi.org/10.1029/2001JB000393

Hubert-Ferrari, A., King, G., Manighetti, I., Armijo, R., Meyer, B., Tapponnier, P. (2003). Long-term elasticity in the continental lithosphere; modelling the Aden Ridge propagation and the Anatolian extrusion process. Geophys. J. Int. 153, 111–132. https://doi.org/10.1046/j.1365-246X.2003.01872.x

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. Chem. Geol. Isot. Geosci. Sect. 80, 171–178. https://doi.org/10.1016/0168-9622(90)90025-8

Hurford, A.J., Green, P.F. (1982). A users' guide to fission track dating calibration. Earth Planet. Sci. Lett. 59, 343–354. https://doi.org/10.1016/0012-821X(82)90136-4

Iglseder, C., Grasemann, B., Rice, A.H.N., Petrakakis, K., Schneider, D.A. (2011). Miocene south directed low-angle normal fault evolution on Kea Island (West Cycladic Detachment System, Greece): WEST CYCLADIC DETACHMENT SYSTEM ON KEA. Tectonics 30. https://doi.org/10.1029/2010TC002802

Jackson, J., McKenzie, D. (1999). A hectare of fresh striations on the Arkitsa Fault, central Greece. J. Struct. Geol. 21, 1–6. https://doi.org/10.1016/S0191-8141(98)00091-1

Jolivet, L. (2003). Subduction tectonics and exhumation of high-pressure metamorphic rocks in the Mediterranean orogens. Am. J. Sci. 303, 353–409. https://doi.org/10.2475/ajs.303.5.353

Jolivet, L., Lecomte, E., Huet, B., Denèle, Y., Lacombe, O., Labrousse, L., Le Pourhiet, L., Mehl, C. (2010a). The North Cycladic Detachment System. Earth Planet. Sci. Lett. 289, 87–104. https://doi.org/10.1016/j.epsl.2009.10.032

Jolivet, L., Trotet, F., Monié, P., Vidal, O., Goffé, B., Labrousse, L., Agard, P., Ghorbal, B. (2010b). Along-strike variations of P–T conditions in accretionary wedges and syn-orogenic extension, the HP–LT Phyllite–Quartzite Nappe in Crete and the Peloponnese. Tectonophysics 480, 133–148. https://doi.org/10.1016/j.tecto.2009.10.002

Jolivet, L., Faccenna, C., Huet, B., Labrousse, L., Le Pourhiet, L., Lacombe, O., Lecomte, E., Burov, E., Denèle, Y., Brun, J-P., Philippon, M., Paul, A., Salaün, G., Karabulut, H., Piromallo, C., Monié, P., Gueydan, F., Okay, A.I., Oberhänsli, R., Pourteau, A., Augier, R., Gadenne, L., Driussi, O. (2013). Aegean tectonics: Strain localisation, slab tearing and trench retreat. Tectonophysics 597–598, 1–33. https://doi.org/10.1016/j.tecto.2012.06.011

Katsikatsos, G., Brujin, D., Van der Meulen, A.J. (1981). The Neogene of the island of Euboea (Evia). Geol. En Mijnb. 60, 509–516.

Katsikatsos, G., Migiros, G., Triantaphyllis, M., Mettos, A. (1986). Geological structure of internal Hellenides (E. Thessaly—SW. Macedonia, Euboea—Attica—Northern Cyclades islands and Lesvos). Geōlogikai Kai Geōfusikai Meletai 191–212.

Katzir, Y., Avigad, D., Matthews, A., Garfunkel, Z., Evans, B.W. (2000). Origin, HP/LT metamorphism and cooling of ophiolitic melanges in southern Evia (NW Cyclades), Greece. J. Metamorph. Geol. 18, 699–718. https://doi.org/10.1046/j.1525-1314.2000.00281.x

Kiratzi, A., Louvari, E. (2003). Focal mechanisms of shallow earthquakes in the Aegean Sea and the surrounding lands determined by waveform modelling: a new database. J. Geodyn. 36, 251–274. https://doi.org/10.1016/S0264-3707(03)00050-4

Kissel, C., Laj, C., Mazaud, A. (1986). First paleomagnetic results from Neocene Formations in Evia, Skyros and the Volos Region and the deformation of Central Aegea. Geophys. Res. Lett. 13, 1446–1449. https://doi.org/10.1029/GL013i013p01446

Kissel, C., Laj, C., Poisson, A., Görür, N. (2003). Paleomagnetic reconstruction of the Cenozoic evolution of the Eastern Mediterranean. Tectonophysics 362, 199–217. https://doi.org/10.1016/S0040-

1951(02)00638-8

Kokkalas, S. (2001). Tectonic evolution and stress field of the Kymi-Aliveri basin, Evia island, Greece. Bull. Geol. Soc. Greece 34, 243. https://doi.org/10.12681/bgsg.17019

Kokkalas, S. (2010). SEGMENTATION AND INTERACTION OF NORMAL FAULTS IN CENTRAL GREECE. Bull. Geol. Soc. Greece 43, 428. https://doi.org/10.12681/bgsg.11194

Kokkalas, S., Aydin, A. (2013). Is there a link between faulting and magmatism in the south-central Aegean Sea? Geol. Mag. 150, 193–224. https://doi.org/10.1017/S0016756812000453

Kokkalas, S., Xypolias, P., Koukouvelas, I., Doutsos, T. (2006). Postcollisional contractional and extensional deformation in the Aegean region, in: Postcollisional Tectonics and Magmatism in the Mediterranean Region and Asia. Geological Society of America. https://doi.org/10.1130/0-8137-2409-0.97

Kokkalas, S., Jones, R.R., McCaffrey, K.J.W., Clegg, P. (2007). Quantitative fault analysis at Arkitsa, Central Greece, using Terrestrial Laser- Scanning (“LIDAR”). Bull. Geol. Soc. Greece 40, 1959. https://doi.org/10.12681/bgsg.17237

Koukouvelas, I.K., Kokkalas, S. (2003). Emplacement of the Miocene west Naxos pluton (Aegean Sea, Greece): a structural study. Geol. Mag. 140, 45–61. https://doi.org/10.1017/S0016756802007094

Krohe, A., Mposkos, E., Diamantopoulos, A., Kaouras, G. (2010). Formation of basins and mountain ranges in Attica (Greece): The role of Miocene to Recent low-angle normal detachment faults. Earth-Sci. Rev. 98, 81–104. https://doi.org/10.1016/j.earscirev.2009.10.005

Liati, A., Skarpelis, N., Pe-Piper, G. (2009). Late Miocene magmatic activity in the Attic-Cycladic Belt of the Aegean (Lavrion, SE Attica, Greece): implications for the geodynamic evolution and timing of ore deposition. Geol. Mag. 146, 732–742. https://doi.org/10.1017/S0016756809006438

Lister, G.S., Banga, G., Feenstra, A. (1984). Metamorphic core complexes of Cordilleran type in the Cyclades, Aegean Sea, Greece 6.

Lykousis, V., Sakellariou, D., Moretti, I., & Kaberi, H. (2007). late Quaternary basin evolution of the Gulf of Corinth: Sequence stratigraphy, sedimentation, fault–slip and subsidence rates. Tectonophysics, 440(1–4), 29–51. https://doi.org/10.1016/j.tecto.2006.11.007

Malandri, C., Soukis, K., Maffione, M., Özkaptan, M., Vassilakis, E., Lozios, S., van Hinsbergen, D.J.J. (2017). Vertical-axis rotations accommodated along the Mid-Cycladic lineament on Paros Island in the extensional heart of the Aegean orocline (Greece). Lithosphere 9, 78–99. https://doi.org/10.1130/L575.1

Mascle, J., Martin, L. (1990). Shallow structure and recent evolution of the Aegean Sea: A synthesis based on continuous reflection profiles. Mar. Geol. 94, 271–299. https://doi.org/10.1016/0025-3227(90)90060-W

McClusky, S., Balassanian, S., Barka, A., Demir, C., Ergintav, S., Georgiev, I., Gurkan, O., Hamburger, M., Hurst, K., Kahle, H., Kastens, K., Kekelidze, G., King, R., Kotzev, V., Lenk, O., Mahmoud, S., Mishin, A., Nadariya, M., Ouzounis, A., Paradissis, D., Peter, Y., Prilepin, M., Reilinger, R., Sanli, I., Seeger, H., Tealeb, A., Toksöz, M.N., Veis, G. (2000). Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus. J. Geophys. Res. Solid Earth 105, 5695–5719. https://doi.org/10.1029/1999JB900351

McDowell, F.W., McIntosh, W.C., Farley, K.A. (2005). A precise 40Ar–39Ar reference age for the Durango apatite (U–Th)/He and fission-track dating standard. Chem. Geol. 214, 249–263. https://doi.org/10.1016/j.chemgeo.2004.10.002

Menant, A., Sternai, P., Jolivet, L., Guillou-Frottier, L., Gerya, T. (2016). 3D numerical modeling of mantle flow, crustal dynamics and magma genesis associated with slab roll-back and tearing: The eastern Mediterranean case. Earth Planet. Sci. Lett. 442, 93–107. https://doi.org/10.1016/j.epsl.2016.03.002

Mettos, A., Rondogianni, Th., Papadakis, G., Pashos, P., Georgiou, H. (1991). New data on the geology of the Neogene deposits of N. Evia. Bull. Geol. Soc. Greece 25, 71–83.

Mettos, A., Rondogianni, Th., Ioakim, Ch., Papadakis, I. (1992). Evolution geodynamique et reconstruction paleoenvironnementale des basins Neogenes–Quaternaires de la Grece centrale. Paleontol. Evolucio 24–25, 393–402.

Moretti, I., Sakellariou, D., Lykousis, V., Micarelli, L. (2003). The Gulf of Corinth: an active half graben? J. Geodyn. 36, 323–340. https://doi.org/10.1016/S0264-3707(03)00053-X

Most, T. (2003). Geodynamic evolution of the Eastern Pelagonian Zone in northwestern Greece and the

Republic of Macedonia. Implications from U/Pb, Rb/Sr, K/Ar, Ar/Ar, geochronology and fission track thermochronology. (Doctoral dissertation). Tubingen, Germany.

Nirta, G., Moratti, G., Piccardi, L., Montanari, D., Catanzariti, R., Carras, N., Papini, M. (2015). The Boeotian Flysch revisited: new constraints on ophiolite obduction in Central Greece. Ofioliti 40. https://doi.org/10.4454/ofioliti.v40i2.438

Nuriel, P., Craddock, J., Kylander-Clark, A.R.C., Uysal, I.T., Karabacak, V., Dirik, R.K., Hacker, B.R., Weinberger, R. (2019). Reactivation history of the North Anatolian fault zone based on calcite age-strain analyses. Geology 47, 465–469. https://doi.org/10.1130/G45727.1

Papanikolaou, D. (1997). The tectonostratigraphic terranes of the Hellenides. Ann. Geol. Pays Hell. 37, 495–514.

Papanikolaou, D. (2013). Tectonostratigraphic models of the Alpine terranes and subduction history of the Hellenides. Tectonophysics 595–596, 1–24. https://doi.org/10.1016/j.tecto.2012.08.008

Papanikolaou, D.J., Royden, L.H. (2007). Disruption of the Hellenic arc: Late Miocene extensional detachment faults and steep Pliocene-Quaternary normal faults-Or what happened at Corinth?: DISRUPTION OF THE HELLENIC ARC. Tectonics 26. https://doi.org/10.1029/2006TC002007

Pe-Piper, G., Piper, D.J.W. (1994). Miocene magnesian andesites and dacites, Evia, Greece: adakites associated with subducting slab detachment and extension. Lithos 31, 125–140. https://doi.org/10.1016/0024-4937(94)90004-3

Pérouse, E., Chamot-Rooke, N., Rabaute, A., Briole, P., Jouanne, F., Georgiev, I., Dimitrov, D. (2012). Bridging onshore and offshore present-day kinematics of central and eastern Mediterranean: Implications for crustal dynamics and mantle flow: CENTRAL TO EAST MEDITERRANEAN KINEMATICS. Geochem. Geophys. Geosystems 13. https://doi.org/10.1029/2012GC004289

Philip, H. (1987), Plio-Quaternary evolution of the stress field in Mediterranean zones of subduction and collision, Annales Geophysicae, 5B, 301–320.

Philippon, M., Brun, J-P., Gueydan, F. (2012). Deciphering subduction from exhumation in the segmented Cycladic Blueschist Unit (Central Aegean, Greece). Tectonophysics 524–525, 116–134. https://doi.org/10.1016/j.tecto.2011.12.025

Philippon, M., Gueydan, F., Pitra, P., Brun, J-P. (2013). Preservation of subduction-related prograde deformation in lawsonite pseudomorph-bearing rocks. J. Metamorph. Geol. 31, 571–583. https://doi.org/10.1111/jmg.12035

Rabillard, A., Arbaret, L., Jolivet, L., Le Breton, N., Gumiaux, C., Augier, R., Grasemann, B. (2015). Interactions between plutonism and detachments during metamorphic core complex formation, Serifos Island (Cyclades, Greece): PLUTONISM - STRAIN LOCALIZATION. Tectonics 34, 1080–1106. https://doi.org/10.1002/2014TC003650

Reilinger, R.E., McClusky, S.C., Oral, M.B., King, R.W., Toksoz, M.N., Barka, A.A., Kinik, I., Lenk, O., Sanli, I. (1997). Global Positioning System measurements of present-day crustal movements in the Arabia-Africa-Eurasia plate collision zone. J. Geophys. Res. Solid Earth 102, 9983–9999. https://doi.org/10.1029/96JB03736

Reilinger, R., McClusky, S., Vernant, P., Lawrence, S., Ergintav, S., Cakmak, R., Ozener, H., Kadirov, F., Guliev, I., Stepanyan, R., Nadariya, M., Hahubia, G., Mahmoud, S., Sakr, K., ArRajehi, A., Paradissis, D., Al-Aydrus, A., Prilepin, M., Guseva, T., Evren, E., Dmitrotsa, A., Filikov, S.V., Gomez, F., Al-Ghazzi, R., Karam, G. (2006). GPS constraints on continental deformation in the Africa-Arabia-Eurasia continental collision zone and implications for the dynamics of plate interactions: EASTERN MEDITERRANEAN ACTIVE TECTONICS. J. Geophys. Res. Solid Earth 111. https://doi.org/10.1029/2005JB004051

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 5.

Ring, U., Thomson, S.N., Bröcker, M. (2003). Fast extension but little exhumation: the Vari detachment in the Cyclades, Greece. Geol. Mag. 140, 245–252. https://doi.org/10.1017/S0016756803007799

Ring, U., Glodny, J., Will, T., Thomson, S. (2007). An Oligocene extrusion wedge of blueschist-facies nappes on Evia, Aegean Sea, Greece: implications for the early exhumation of high-pressure rocks. J. Geol. Soc. 164, 637–652. https://doi.org/10.1144/0016-76492006-041

Roberts, S., Jackson, J. (1991). Active normal faulting in central Greece: an overview. Geol. Soc. Lond. Spec. Publ. 56, 125–142. https://doi.org/10.1144/GSL.SP.1991.056.01.09

Ross, J.V., Zimmerman, J. (1996). Comparison of evolution and tectonic significance of the Pindos and

Vourinos ophiolite suites, northern Greece. Tectonophysics 256, 1–15. https://doi.org/10.1016/0040-1951(95)00160-3

Royden, L.H., Papanikolaou, D.J. (2011). Slab segmentation and late Cenozoic disruption of the Hellenic arc: DISRUPTION OF THE HELLENIC ARC. Geochem. Geophys. Geosystems 12. https://doi.org/10.1029/2010GC003280

Sakellariou, D., Tsampouraki-Kraounaki, K. (2019). Plio-Quaternary Extension and Strike-Slip Tectonics in the Aegean, in: Transform Plate Boundaries and Fracture Zones. Elsevier, pp. 339–374. https://doi.org/10.1016/B978-0-12-812064-4.00014-1

Sakellariou, D., Mascle, J., & Lykousis, V. (2013). Strike slip tectonics and transtensional deformation in the Aegean region and the Hellenic arc: Preliminary results. Bulletin of the Geological Society of Greece, 47(2), 647. https://doi.org/10.12681/bgsg.11098

Scheffer, C., Vanderhaeghe, O., Lanari, P., Tarantola, A., Ponthus, L., Photiades, A., France, L. (2016). Syn- to post-orogenic exhumation of metamorphic nappes: Structure and thermobarometry of the western Attic-Cycladic metamorphic complex (Lavrion, Greece). J. Geodyn. 96, 174–193. https://doi.org/10.1016/j.jog.2015.08.005

Schenker, F.L., Fellin, M.G., Burg, J.-P. (2015). Polyphase evolution of Pelagonia (northern Greece) revealed by geological and fission-track data. Solid Earth 6, 285–302. https://doi.org/10.5194/se-6-285-2015

Schneider, D.A., Grasemann, B., Lion, A., Soukis, K., Draganits, E. (2018). Geodynamic significance of the Santorini Detachment System (Cyclades, Greece). Terra Nova 30, 414–422. https://doi.org/10.1111/ter.12357

Seman, S.M., (2016). The tectonostratigraphy of the Cycladic Blueschist Unit and new garnet geo/thermochronology techniques (Doctoral dissertation). University of Texas, Austin.

Şengör, A.M.C. (1979). The North Anatolian transform fault: its age, offset and tectonic significance. Journal of the Geological Society, 136(3), 269-282. https://doi.org/10.1144/gsjgs.136.3.0269

Şengör, A.M.C., Tüysüz, O., İmren, C., Sakınç, M., Eyidoğan, H., Görür, N., Le Pichon, X., Rangin, C. (2005). THE NORTH ANATOLIAN FAULT: A NEW LOOK. Annu. Rev. Earth Planet. Sci. 33, 37–112. https://doi.org/10.1146/annurev.earth.32.101802.120415

Seward, D., Spikings, R., Viola, G., Kounov, A., Ruiz, G.M.H., Naeser, N. (2000). Etch times and operator variation for spontaneous track length measurements in apatites: an intra-laboratory check. OnTrack, 10 (21), 16–21.

Seward, D., Vanderhaeghe, O., Siebenaller, L., Thomson, S., Hibsch, C., Zingg, A., Holzner, P., Ring, U., Duchêne, S. (2009). Cenozoic tectonic evolution of Naxos Island through a multi-faceted approach of fission-track analysis. Geol. Soc. Lond. Spec. Publ. 321, 179–196. https://doi.org/10.1144/SP321.9

Shaked, Y., Avigad, D., Garfunkel, Z. (2000). Alpine high-pressure metamorphism at the Almyropotamos window (southern Evia, Greece). Geol. Mag. 137, 367–380. https://doi.org/10.1017/S001675680000426X

Sobel, E.R., Seward, D. (2010). Influence of etching conditions on apatite fission-track etch pit diameter. Chem. Geol. 271, 59–69. https://doi.org/10.1016/j.chemgeo.2009.12.012

Sorel, D. (2000). A Pleistocene and still-active detachment fault and the origin of the Corinth-Patras rift, Greece 4.

Soukis, K., Stockli, D.F. (2013). Structural and thermochronometric evidence for multi-stage exhumation of southern Syros, Cycladic islands, Greece. Tectonophysics 595–596, 148–164. https://doi.org/10.1016/j.tecto.2012.05.017

Speranza, F., Kissel, C., Islami, I., Hyseni, A., Laj, C. (1992). First paleomagnetic evidence for rotation of the Ionian Zone of Albania. Geophys. Res. Lett. 19, 697–700. https://doi.org/10.1029/92GL00575

Stefatos, A., Papatheodorou, G., Ferentinos, G., Leeder, M., & Collier, R. (2002). Seismic reflection imaging of active offshore faults in the Gulf of Corinth: their seismotectonic significance. Basin Research, 14(4), 487–502. https://doi.org/10.1046/j.1365-2117.2002.00176.x

Tagami, T. (1987). Determination of zeta calibration constant for fission track dating. Int. J. Radiat. Appl. Instrum. Part Nucl. Tracks Radiat. Meas. 13, 127–130. https://doi.org/10.1016/1359-0189(87)90023-9

Thomson, S. N., Ring, U., Brichau, S., Glodny, J., & Will, T. M. (2009). Timing and nature of formation of the Ios metamorphic core complex, southern Cyclades, Greece. Geological Society, London, Special Publications, 321(1), 139–167. https://doi.org/10.1144/SP321.7

Trotet, F., Vidal, O., Jolivet, L. (2001). Exhumation of Syros and Sifnos metamorphic rocks (Cyclades, Greece). New constraints on the P-T paths. Eur. J. Mineral. 13, 901–920. https://doi.org/10.1127/0935-1221/2001/0013/0901

Tschegg, C., Grasemann, B. (2009). Deformation and alteration of a granodiorite during low-angle normal faulting (Serifos, Greece). Lithosphere 1, 139–154. https://doi.org/10.1130/L33.1

Vamvaka, A., Spiegel, C., Frisch, W., Danišík, M., Kilias, A. (2010). Fission track data from the Mesohellenic Trough and the Pelagonian zone in NW Greece: Cenozoic tectonics and exhumation of source areas. Int. Geol. Rev. 52, 223–248. https://doi.org/10.1080/00206810802674402

Vandenberg, L.C., Lister, G.S. (1996). Structural analysis of basement tectonites from the Aegean metamorphic core complex of Ios, Cyclades, Greece. J. Struct. Geol. 18, 1437–1454. https://doi.org/10.1016/S0191-8141(96)00068-5

van Hinsbergen, D.J.J., Schmid, S.M. (2012). Map view restoration of Aegean-West Anatolian accretion and extension since the Eocene: RESTORATION OF THE AEGEAN REGION. Tectonics 31. https://doi.org/10.1029/2012TC003132

van Hinsbergen, D.J.J., Langereis, C.G., Meulenkamp, J.E. (2005). Revision of the timing, magnitude and distribution of Neogene rotations in the western Aegean region. Tectonophysics 396, 1–34. https://doi.org/10.1016/j.tecto.2004.10.001

van Hinsbergen, D.J.J., van der Meer, D.G., Zachariasse, W.J., Meulenkamp, J.E. (2006). Deformation of western Greece during Neogene clockwise rotation and collision with Apulia. Int. J. Earth Sci. 95, 463–490. https://doi.org/10.1007/s00531-005-0047-5

van Hinsbergen, D.J.J., Krijgsman, W., Langereis, C. G., Cornée, J.-J., Duermeijer, C. E., & van Vugt, N. (2007). Discrete Plio-Pleistocene phases of tilting and counterclockwise rotation in the southeastern Aegean arc (Rhodos, Greece): early Pliocene formation of the south Aegean left-lateral strike-slip system. Journal of the Geological Society, 164(6), 1133–1144. https://doi.org/10.1144/0016-76492006-061

van Hinsbergen, D.J.J., Dekkers, M. J., & Kroc, A. (2010). Testing Miocene Remagnetization of Bey Dağları: Timing and Amount of Neogene Rotations in SW Turkey. Turkish Journal of Earth Sciences, 19(2), 123–156.

Walcott, C.R., White, S.H. (1998). Constraints on the kinematics of post-orogenic extension imposed by stretching lineations in the Aegean region. Tectonophysics 298, 155–175. https://doi.org/10.1016/S0040-1951(98)00182-6

Wallace, R. E. (1951), Geometry of shearing stress and relation to faulting, The Journal of Geology, 59, 118–130.

Walker, R.T., Claisse, S., Telfer, M., Nissen, E., England, P., Bryant, C., Bailey, R. (2010). Preliminary estimate of Holocene slip rate on active normal faults bounding the southern coast of the Gulf of Evia, central Greece. Geosphere 6, 583–593. https://doi.org/10.1130/GES00542.1

Wessel, P. & Smith, W. H. (1991), Free software helps map and display data. Eos, Transactions American Geophysical Union, 72(41), 441–446.

Xypolias, P., Kokkalas, S., Skourlis, K. (2003). Upward extrusion and subsequent transpression as a possible mechanism for the exhumation of HP/LT rocks in Evia Island (Aegean Sea, Greece). J. Geodyn. 35, 303–332. https://doi.org/10.1016/S0264-3707(02)00131-X

Yarwood, G.A., Aftalion, M. (1976). Field relations and U-Pb geochronology of a granite from the Pelagonian Zone of the Hellenides (High Pieira, Greece). Bull. Société Géologique Fr. 7, 259–264. https://doi.org/7(2), 259-264. https://doi.org/10.2113/gssgfbull.S7-XVIII.2.259

Figure captions

Figure 1: *Simplified tectonics map of the Aegean with different continental terranes (Rhodope, Pelagonia, Adria; modified after Bradley et al., 2013; Papanikolaou, 2013; Brun et al., 2016), deep basins and/or oceans (Vardar, Pindos) and main faults or deformation zones: NAF: North Anatolian Fault; NAT: North Aegean Trough; CHSZ: Central Hellenic Shear Zone; MIF: Myrthes-Ikaria Fault, the Pelagonian Fault. middle Miocene basins in dark Orange and syn-tectonics Miocene plutons (Koukouvelas and Kokkalas, 2003; Kokkalas and Aydin, 2013) in red. Low-temperature data from Hejl et al., 1999, 2008; Most, 2003; Thomson et al., 2009; Vamvaka et al., 2010; Coutand et al., 2014; Schenker et al., 2015 for Pelagonia; Hejl et al., 2002, 2008; Ring et al., 2003, 2007; Brichau et al., 2006, 2008; Seward et al., 2009; Berger et al., 2013; Soukis and Stockli, 2013; Seman, 2016; Grasemann et al., 2018; Schneider et al., 2018 for the Cyclades. Curved arrow: North Aegean clockwise block rotation (Horner and Freeman, 1983; Kissel et al., 1986, 2003; Duermeijer, 2000; van Hinsbergen et al., 2005, 2006; Bradley et al., 2013) and counterclockwise rotation in south Aegean*

(van Hinsbergen et al., 2007, 2010; van Hinsbergen and Schmid, 2012). Black arrows: average directions of Anatolia westward extrusion and southward Hellenic trench retreat related to slab rollback (Reilinger et al., 2006). Dashed box: study area in Central Greece. Inset: present-day GPS velocity field (modified from Hollenstein et al., 2008).

Figure 2: *Tectonic map of Central Greece (location in Fig. 1) gathering our intrepretation (see text for details) and already published data (geology simplified from Bornovas and Rondogianni-Tsiambaou, 1983; Faupl et al., 2007; Nirta et al., 2015; and tectonics interpretation from Roberts and Jackson, 1991;Gautier and Brun, 1994; Jackson and McKenzie, 1999; Goldsworthy et al., 2002; Kokkalas et al., 2007; Lykousis et al., 2007; Bell et al., 2009; Kokkalas, 2010; Krohe et al., 2010; Walker et al., 2010) . Coexistence of NW-striking normal faults (red) and NE-striking dextral strike-slip faults (Pelagonian fault strike-slip corridor in orange) during middle Miocene basins deposition (in yellow); and younger E-W normal faulting (black) during Plio-Quaternary basins deposition (in light yellow). Grey diamonds: AFT samples. Dashed boxes: location of local studies (Limni basin shown in Fig. 3, Loutra Ypatis shown in Fig. 4 and Kymi basin shown in Fig. 6).*

Figure 3: *Structural features of the Limni basin (location in Fig. 2). A/ structural map (modified from Bornovas and Rondogianni-Tsiambaou, 1983; Bono et al., 1998) of the Limni basin with basin bedding, basement foliation and main inferred normal faults (NW-striking in red and E-striking in black). "I, II, IV, V": sites of measurements shown in B/. Grey diamonds: AFT samples. B/ Stereonets for measurements made in different key locations, shown in A/, with fault and basin bedding. Dip-slip slickenlines associated with NW-striking normal faults are represented by red circles and oblique slickenlines associated with NW-striking sinistral faults are represented by purple circles. Slickenlines with a rake ≤ 45° are considered as oblique. C/ NNE-SSW a''-a cross section (profile drawn in A/). Fault numbering shown also in map A/. D/ Outcrop pictures. Left: dip-slip slickenlines in NW-striking normal fault plane (location II shown in A/, B/ and C/); right: cross-cutting relation between NW-striking and E-striking normal fault (location I shown in A/, B/ and C/).*

Figure 4: *Structural features in the Loutra Ypatis area (location in Fig. 2). A/ Structural map (modified after Bornovas and Rondogianni-Tsiambaou, 1983; Faupl et al., 2007; Nirta et al., 2015) with main inferred normal faults (NW-striking in red and E-striking in black). "I, II, III, IV, V": key locations of measurements shown in B, "a,b,c": location of outcrop pictures shown in C/. Arkitsa fault geometry from Jackson and McKenzie, 1999; Kokkalas et al., 2007. Grey diamonds: AFT samples. B/ Stereonets for fault measurements made in different sites (shown in A/) with NW-striking normal faults in red and E-striking normal faults in black. Dip-slip slickenlines associated with NW-striking normal faults et E-W normal faults are respectively represented by red and black circles. Oblique slickenline associated with NW-striking sinistral fault is represented by purple circle. C/ Outcrop pictures: slickenlines in Kamena Vourla fault planes (locations a and b in A/) and E-striking fault plane (location c in A/).*

Figure 5: *Stress inversion results (Fault and Stress Analysis software) for Plio-Quaternary (A) and middle Miocene (B) fault families measured in Limni (Fig. 3) and Loutra Ypatis (Fig. 4) area. A/ Stress inversion tensor result T_{12} for E-striking normal faults (family 1) and NW-striking oblique (sinistral) faults (family 2): sub-vertical s_1, sub-horizontal and radial extension with N-S s_3. A-1: Left lower hemisphere Schmidt stereographic representation of the fault slip data. A-2: lower hemisphere Schmidt stereographic projection of the principal stress orientations. Circle, square and triangle correspond to s_1, s_2, s_3, respectively. A-3: Plio-Quaternary schematic tectonics map with N-S extension associated with E-striking normal fault and oblique slip on NW-striking faults and Plio-Quaternary basins. B/ Stress inversion tensor result T_3 for NW-striking normal faults (with dip slip motion, family 3) with NE-SW s_3. B-1 and B-2: same convention as in A/, B-3: middle Miocene schematic tectonics map with NE-SW extension with dip-slip motion on NW-striking normal faults and middle Miocene basin deposition.*

Figure 6: *Structural features of the Kymi basin area (location in Fig. 2). A/ Structural map (modified after Bornovas and Rondogianni-Tsiambaou, 1983; Bradley, 2012) of the Kymi basin with inferred main NW-striking normal faults (red) and NE-striking dextral strike-slip faults (orange), basin bedding and basement foliations. Large scale folds from West to East: Amarynthos antiform, Kymi syncline, Almyropotamos antiform (Xypolias et al., 2003). "I, II, III, IV, V, VI, VII": zones of measurements shown on stereonets in B/. Grey diamonds: AFT samples. B/ Stereonets for fault measurements and basin bedding conduced in several key locations (shown in A/). C/ Outcrop pictures showing sub-horizontal slickenlines on NE-striking fault plane (zone IV in A/). D/ Outcrop picture in location III showing new NE-striking shistosity inside a NE-striking sub-vertical fault zone. E/ The Kymi basin cross-section (profile drawn in A/) orthogonal to the NE-striking Pelagonian dextral strike-slip fault*

Figure 7: *Stress tensor inversion result T_4 for NE-striking dextral strike-slip faults (family 4, measured in Kymi area, Fig. 6). A/ Left lower hemisphere Schmidt stereographic representation of the fault slip data. B/ lower hemisphere Schmidt stereographic projection of the principal stress orientations. Circle, square and triangle correspond to s_1, s_2, s_3, respectively. C/ Schematic tectonics map of the Kymi basin deposition controlled by NE-striking strike-slip faults with N-S extension and E-W compression, compatible with observed large-scale open folds.*

Figure 8: *Single crystal apatite fission track age distribution of the samples presented in radial plots (Galbraith, 1990, 2005) and age spectra. Samples location in Fig. 2. Radial plots were made using the Trackkey software (Dunkl, 2002). The light-blue shade represents the estimated stratigraphic age of the sediment for each sample. The grey arrows point to the Oligocene cooling phase and the red arrows to the Miocene cooling phase, if present. Red vertical dashed line: Oligocene-Miocene boundary. A/*

Results for Sample CG03; B/ Results for Sample CG08; C/ Results for Sample CG11; D/ Results for Sample CG13; E/ Results for Sample CG14; F/ Results for Sample CG16.

Figure 9: *Synthesis of low-thermochronology data in Central Greece and the Cyclades, highlighting the major differences in exhumation history between the Cycladic Blueschist Unit (CBU, in blue) and the Pelagonian-derived rocks (in pink). A/ Simplified map (geology simplified from Papanikolaou, 2013; Brun et al., 2016) with a synthesis of low-temperature thermochronology ages from this study (circle for AFT) and from previous studies (diamond for AFT, triangle for Zircon Fission Track-ZFT, hexagon and square for (U-Th)/He age in respectively Zircon and Apatite) in both Central Greece and the Cyclades. Data from Hejl et al., 1999, 2008; Most, 2003; Thomson et al., 2009; Vamvaka et al., 2010; Coutand et al., 2014; Schenker et al., 2015; and Cyclades/South Evvia/Attica datation from Hejl et al., 2002, 2008; Ring et al., 2003, 2007; Brichau et al., 2006, 2008; Seward et al., 2009; Berger et al., 2013; Soukis and Stockli, 2013; Seman, 2016; Grasemann et al., 2018; Schneider et al., 2018). B/ Low-temperature thermochronology ages along a NE-SW transect (location as black line in A/) orthogonal to the Pelagonian fault. AFT, ZFT, and (U-Th)/He on Zircon and Apatites ages respectively as diamonds, triangles, stars and square. AFT data from this study as circle. Colors refer to different references (see A/). Thick pink and blue lines: mean low temperature age calculated in Pelagonian rocks and in the Cycladic rocks. Thick dashed line: Pelagonian fault. See text for further explanations. References: (a) Berger et al., 2013 - (b) Brichau et al., 2006 - (c) Brichau et al., 2008 - (d) Coutand et al., 2014 - (e) Grasemann et al., 2018 - (f) Hejl et al., 1999 - (g) Hejl et al., 2002 - (h) Hejl et al., 2008 – (i) Most, 2003 – (j) Ring et al., 2003 – (k) Ring et al., 2007 – (l) Schenker et al., 2015 – (m) Schneider et al., 2018 – (n) Seward et al., 2009 – (o) Soukis and Stockli, 2013 – (p)PhD of Seman, 2016 – (q) Thomson et al., 2009 – (r) Vamvaka et al., 2010.*

Figure 10: *Stress inversion and stress compatibilities between NE-striking dextral faults, NW-striking high-angle normal faults and E-striking high-angle normal faults. A/ Stress inversion results for the combination of NW-striking normal faults (with dip-slip, family 3) and NE-striking dextral strike-slip (family 4). B/ Inferred stress tensor solution T_{34}. Same conventions as Fig. 5. WNW s1 and NNE s3; C/ Stress inversion results for the combination of back-rotated NW-striking normal faults (with dip-slip, family 3r) and NE-striking dextral strike-slip (family 4). D/ Stress tensor solution T_{3r4}, with back-rotated NW-striking normal faults. N-S s3 and E-W s1. E/ Tectonic regime diagram (Armijo et al., 1982; Philip, 1987; Célérier, 1995). Left: each stress tensor is represented by an open circle. Center: the three tectonics regimes of Anderson (1905) are designated by the vertical principal stress Sv. Right: stress tensor aspect ratio $r_0 = (\sigma_1-\sigma_2)/(\sigma_1-\sigma_3)$.*

Figure 11: *Schematic tectonics reconstruction of Central Greece from middle Miocene to Present (simplified from Royden and Papanikolaou, 2011) and position of the Hellenic trench and emerged area in the Aegean domain in inset (right corners). A/ middle to late Miocene before block rotation*

(back-rotated position): with NE-striking dextral strike-slip faults and restored position of the NW-striking normal faults (almost E-striking after a 30° of back-rotation), respectively accommodating initiating westward Anatolia extrusion and ongoing Hellenic trench retreat. On the right: middle Miocene Stress Tensor before rotation (T_{3r4}, Fig. 10).B/ middle to late Miocene after block rotation(in present-day configuration): distributed deformation with coexistence of normal faults and dextral strike-slip fault. Block rotation, accommodated by dextral strike-slip faulting (see inset bottom left for clockwise rotation consistent with dextral faults) and subsequent rotation of normal faults (red). Extensional stress rotated subsequently from N-S (see A/) to NE-SW (stress tensor T_3 in red rectangle, from Fig. 5). Shortening direction are similar to A/ in the strike-slip corridors (stress tensor T_4 in orange rectangle, from Fig. 7) . C/ Plio-Quaternary: Formation of E-striking normal faults inside pre-existing NW-striking structures now associated to sinistral kinematics. Stress tensor T_{12} (from Fig. 7) : radial extensional.

Table. 1. *Position of each sample is given in columns coordinates. ρs, ρi and ρd correspond respectively to spontaneous, induced and dosimeter track densities (× 104 cm-2). Ns, Ni and Nd correspond respectively to the total number of spontaneous, induced and dosimeter tracks. U is the calculated Uranium density. P(χ2) is the probability in % of χ2 for ν degrees of freedom (where ν = number of crystals – 1). Dpar is the mean fission-track pit diameter in µm corrected following Sobel & Seward (2010) using a correction factor of 0.825. Central age calculated for each sample are given in the last column.*