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Research article

Geodynamics of Continents and Oceans – A tribute to Jean Aubouin

The Main Pelagonian Detachment (MPD): extensional reactivation of the frontal thrust of the Internal Zones of the Hellenides (Greece)

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Abstract. During the orogenic development of the Hellenides, the "Frontal Thrust of Internal Zones" (FTIZ) localised tectonic superposition of the Internal Zones over the External Zones. The belt was subsequently subject to a major extensional deformation responsible for a negative tectonic inversion of the FTIZ, along a major detachment called here "Main Pelagonian Detachment" (MPD). The along-strike changes in the geometry and the kinematics of the MPD suggest different tectonic configurations largely inherited from the flat–ramp–flat initial geometry of the thrust. The distribution of the recent basins, mainly located within the Internal Zones, illustrates the major role of the FTIZ reactivation in the overall collapse of Internal Hellenides.

Keywords. Tectonic inversion, Inherited structures, Detachments, Pliocene-Quaternary extensional basins, Central Greece.

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1. Introduction

The Hellenides mountain belt in Greece is a part of the alpine Tethyan orogen developed in the Mediterranean domain [e.g., Aubouin, 1959, Ricou et al., 1986, Dewey, 1988, Jolivet and Faccenna, 2000]. It is limited to the south and southwest by the subduction front of the African plate (Adria) beneath the Anatolian–Aegean plate (Figure 1).

The Hellenides present a contrasted morphology (Figure 2A) with a western mountainous external part displaying high relief (elevations up to ~2600 m) and a general topographical continuity from the NW to the SE, and an eastern, more segmented, internal part characterised by alternating ranges and troughs. The troughs correspond to post-orogenic intermontane rift basins. Such a "basin-and-range" type morphology, as well as the development of the Aegean Sea in the core of the arcuate Hellenides orogenic domain, basically results from the extensional collapse of the internal zones of the belt. This collapse is interpreted as the result of the southward retreat of the underlying subducted slab of the Africa plate margin and of the associated upwelling of asthenospheric mantle into the subduction corner

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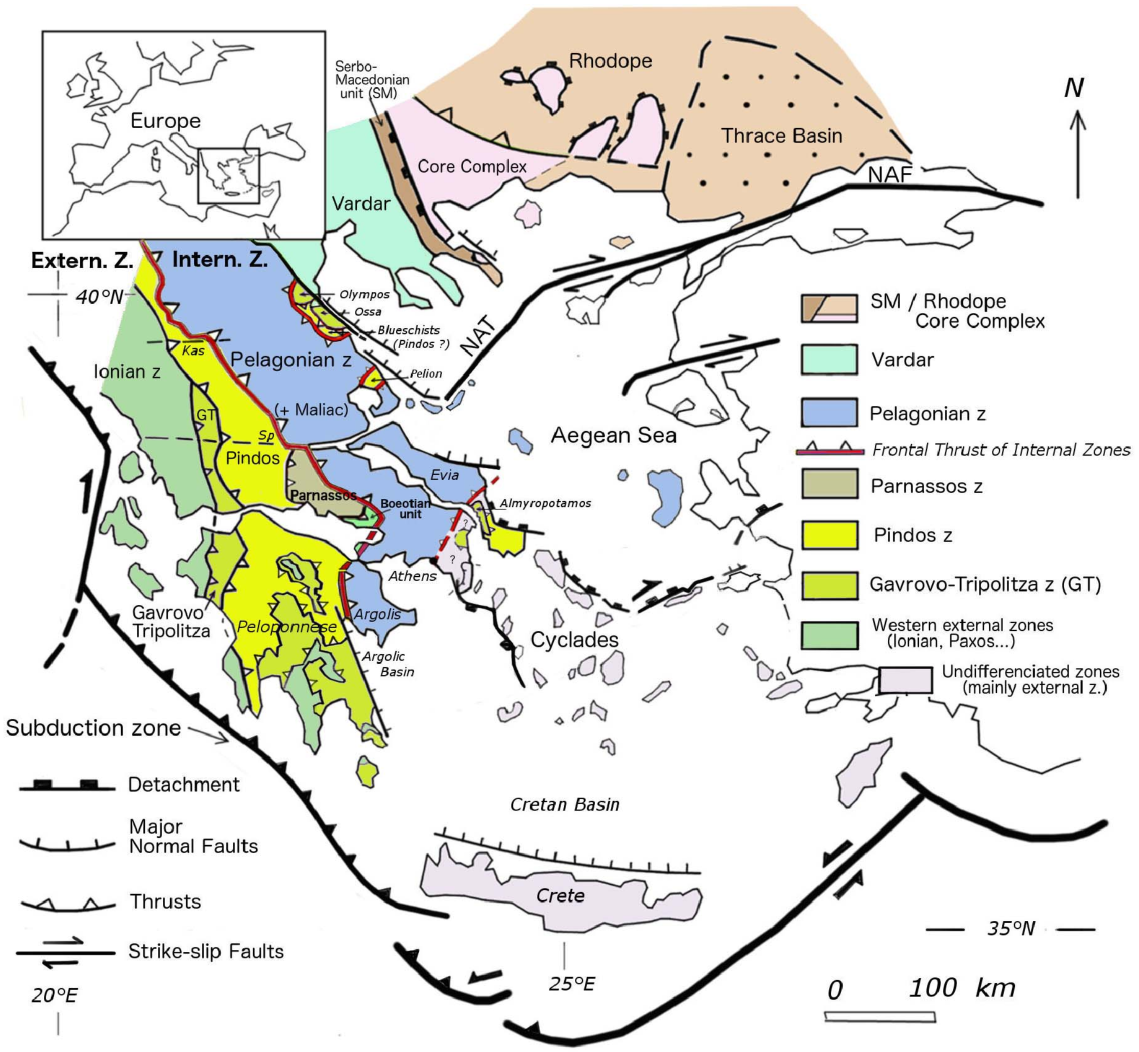

Figure 1. Simplified geologic map of the Aegean Domain. NAF: North Anatolian Fault; NAT: North Anatolian Trough [modified from Brun et al., 2016].

[Brun et al., 2016, Van Hinsbergen et al., 2005, Jolivet and Brun, 2010, Jolivet et al., 2021, Menant et al., 2016].

The transition zone between the two morphological parts of the Hellenic belt is narrow (bold dotted line on Figure 2A) and broadly follows a major compressional structure of the mountain belt, the Frontal Thrust of the Internal Zones (FTIZ), which separates the internal and external tectonic units (Figure 2B). Such a first-order geometrical pattern suggests that the FTIZ has been reactivated during the extensional collapse phase thereby representing a major detachment system within the Aegean rifted domain. However, the way this topographic collapse and the negative tectonic inversion process have operated remains poorly documented. It was only described at a local scale, at the transition between the Parnassos and Pelagonian domains in the Amphiklia area (Figure 3), where a low-angle contact between the uplifted unit (Parnassos mountains) and the collapsed unit (Pelagonian internal units) is interpreted as an extensional detachment, which reactivated the former thrust between the two units [Kranis and Papanikolaou, 2001].

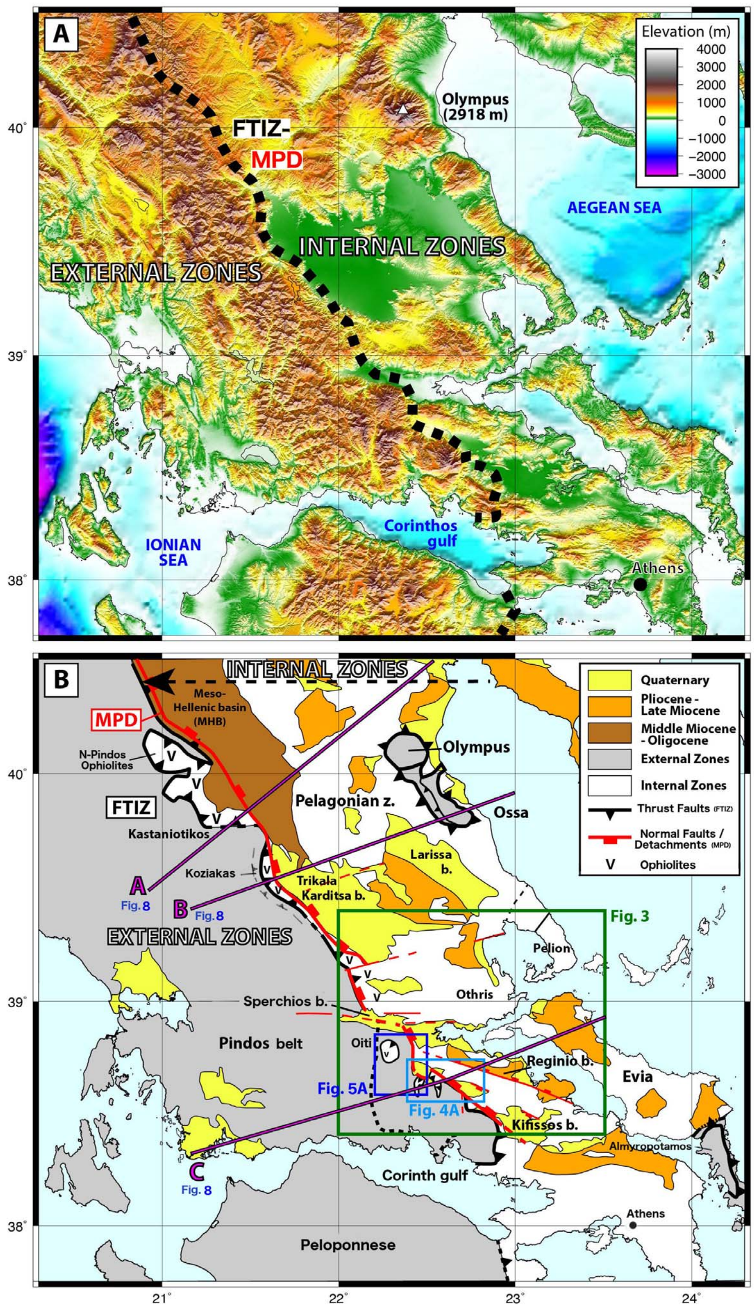

Figure 2. Main characteristics of the Hellenides in Continental Greece. (A) Topography from Digital Elevation Model (SRTM-DEM) showing the contrasting elevations from both the External Zones and the Internal Zones. The latter clearly shows alternating ridges and basins. Topography from Shuttle Radar Topography Mission [SRTM, Farr et al., 2007] and bathymetry from Smith and Sandwell [1997]. (B) Simplified geological map of continental Greece outlining the locations of detailed maps, sections across the Hellenic belt (A, B, C, Figure 8) and the occurrence of the main recent basins; e.g., Trikala, Larissa, Kifissos (Quaternary) and Reginio (Neogene) basins. The Frontal Thrust of Internal Zones (FTIZ) has been widely re-activated along a main extensional faulted structure (MPD: red line). Abbr. b: basin; z: Zone.

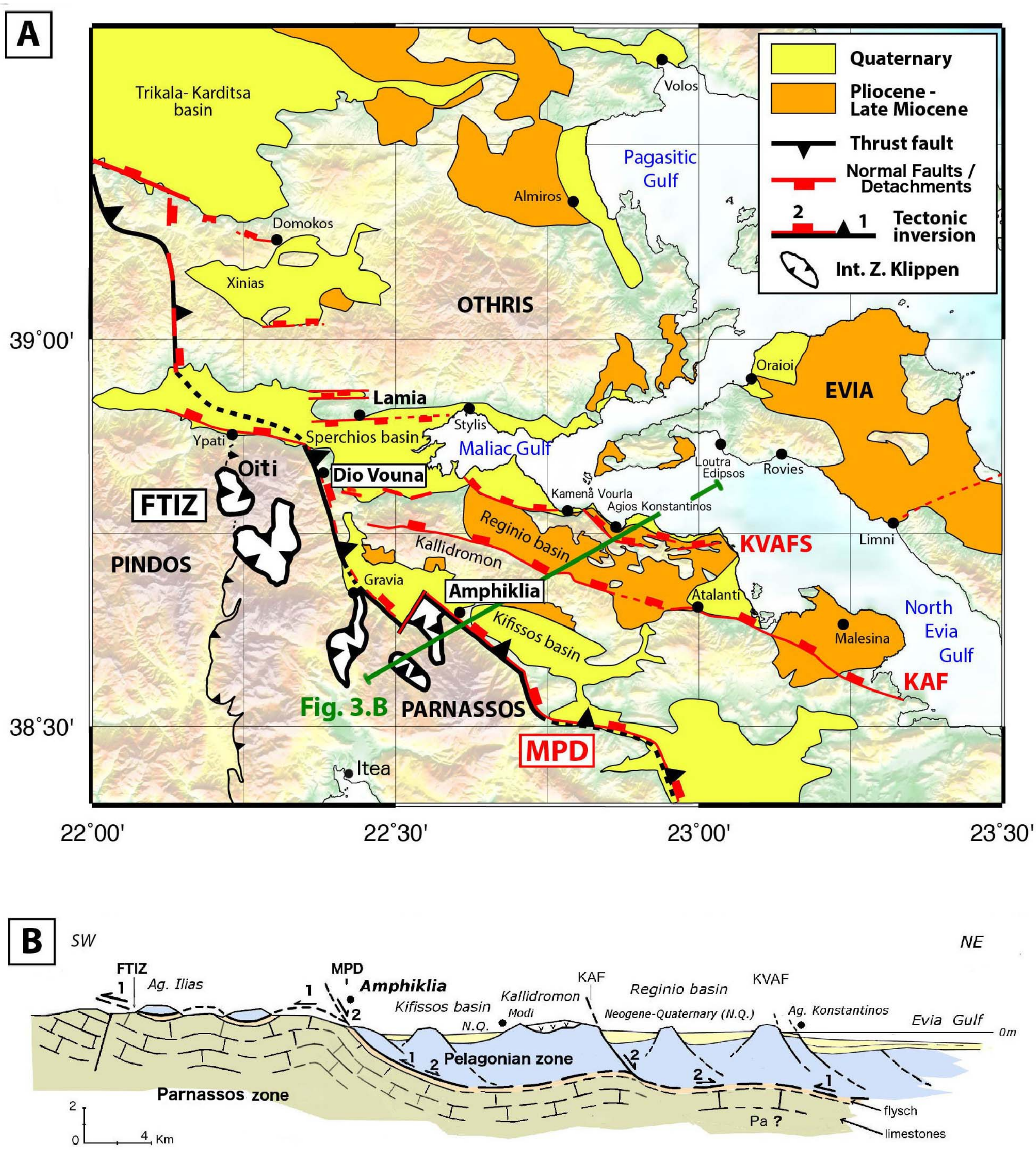

Figure 3. (A) Schematic geological map of the recent basins from the area of Othris and Parnassos mountains. (B): SW–NE cross-section from Parnassos unit to Maliac-North Evia Gulf across Amphiklia area (Location on A). Abbr. FTIZ: Frontal Thrust of Internal Zones; MPD: Main Pelagonian Detachment; KAF: Kallidromon-Atalanti Fault; KVAFS: Kamena Vourla-Arkitsa Fault System; 1: Eocene thrust; 2: Plio-Quaternary extensional deformation.

In this study, we propose to address this inversion tectonics mechanism and the related structural geometries by reassessing the geometry and kinematics of the FTIZ in the Hellenides north of the Corinth Gulf. Our study considers firstly, regional scale mapping and cross-sections to analyse spatial relationships between compressional and subsequent extensional structures and, secondly, outcrop description to better constrain the kinematics of deformation. As the observed rifted structures appear as highly segmented laterally, we examine the variation in structural geometries along strike of the FTIZ trace and document the 3D heterogeneity of the structural pattern of the inversion process. We investigate in detail the Dio Vouna–Amphiklia area (east of Mount Oiti, Figure 3A) where the complex geometry of the FTIZ provides a unique opportunity to decipher the tectonic inversion mechanisms along this major tectonic boundary.

2. Geological setting

The Hellenic alpine belt is the result of the early Tertiary convergence between Africa–Adria and Eurasia plates. The major collisional phase started by the Eocene but the involved rifted continental margins were affected by earlier compressional events. Indeed, during the Middle–Late Jurassic, the distal parts of the Adria–Africa continental margin (Pelagonia) underwent an obduction event implying ophiolitic nappes emplacement from the Maliac (Vardar) oceanic seaway [e.g., Ferrière et al., 2012, 2015, 2016]. The Internal Zones (IZ) correspond to the areas that were covered by the ophiolitic nappes during the Jurassic obduction [Brunn, 1956], while the External Zones (EZ) were deformed only during Tertiary times (Figure 2B). The boundary between these two sectors is the Frontal Thrust of the Internal Zones (FTIZ), whose importance is demonstrated by the occurrence of tectonic windows showing external series underthrust below the internal zones [e.g., Olympus window, Godfriaux, 1968]. By the end of the collisional period, a large basin, the Mesohellenic Basin (Figure 2B), developed in a piggy-back position on top of the main internal unit (Pelagonian basement) from early Oligocene to Middle Miocene times [Brunn, 1956, Ferrière et al., 2004, 2013]. This basin is slightly folded and elongated parallel to the fold-and-thrust belt.

During the Neogene, most of the Hellenides were subject to the extension that led to the development of deep intra-mountainous sedimentary basins. In continental Greece, these extensional basins are observed in the IZ (e.g., Trikala–Karditsa Basin; Larissa–Ptolemais Basin; Figures 2B and 3A), between the elevated Pindos fold-and-thrust belt (part of the EZ) to the west, and the Aegean Sea domain to the east. The Gulf of Corinth is the main extensional basin developed across both the IZ and EZ [Armijo et al., 1996, Jolivet et al., 2010a], but the whole Aegean Sea Domain is also affected by widespread brittle extensional deformation from Late Miocene times to present-day [Goldsworthy and Jackson, 2001, Jolivet and Faccenna, 2000, Jolivet et al., 2013, Brun et al., 2016].

The extension direction varied from NE–SW during the Pliocene and early Quaternary period to NNE–SSW and N–S during the late Quaternary [Caputo, 1995, Caputo and Pavlides, 1993, Doutsos and Kokkalas, 2001, Faucher et al., 2021, Kilias et al., 2008, Kranis, 2002, 2007, Mercier et al., 1979]. Most focal mechanisms consistently reveal a N–S direction of extension [Kilias et al., 2008, Papazachos et al., 1998], which is confirmed by GPS geodetic studies [e.g., Müller et al., 2013]. From both seismological and GPS data, the N–S extension appears to be the prevailing active deformation style in the studied area, especially in western Thessaly and in the northern Gulf of Evia. In the Aegean Domain, active deformation is locally dominated by strike-slip tectonics along the North Anatolian Fault (Figure 1) and its westward extension into the northern Aegean Sea [Hatzfeld et al., 1999, Jackson, 1994, Sakellariou and Tsampouraki-Kraounaki, 2019].

Among the extensional basins in the studied region, the Reginio Basin (or Lokris Basin) is a narrow uplifted and emerged basin located between the Kallidromon ridge and the North Evia Gulf (Figure 3A). It is one of the oldest basins associated to the post-orogenic extension in this domain as it developed from the latest Miocene to early Pliocene times [André and Pavlopoulos, 2004, Celet and Delcourt, 1960, Ioakim and Rondoyanni, 1988, Kranis, 2007]. Its sedimentary filling is mainly composed of lacustrine and fluvial deposits [Dermitzakis and Papanikolaou, 1981, Kranis, 2007] that are controlled by the development of large normal fault systems on both sides: the Kallidromon–Atalanti Fault to the south (KAF, Figure 3) and the Kamena Vourla–Arkitsa Fault System to the north (KVAFS, Figure 3). Both fault systems express an Uppermost Miocene to Early Pliocene extensional regime along the NNE–SSW direction [Caroir et al., 2024, Kranis, 2007].

Further west, the Sperchios Basin forms an asymmetric half-graben controlled by north-dipping normal faults belonging to the Sperchios Fault System [Kilias et al., 2008] (Figure 3A). These major normal faults on the southern border of the Sperchios Basin also coincide with the FTIZ, between the Parnassos external units to the south and the internal units to the north [Apostolopoulos, 2005, Caroir et al., 2021, 2024, Celet, 1962, Chanier et al., 2017, Eliet and Gawthorpe, 1995, Ferrière, 1982, Kilias et al., 2008, Marinos et al., 1967]. Extension probably initiated during the Pliocene but the basin is mainly filled by Pleistocene and Holocene sediments [Apostolopoulos, 2005, Pechlivanidou et al., 2014, 2018]. The Sperchios Basin connects to the North Evia Gulf toward the east, which also corresponds to a major rift system characterised by a succession of Pliocene and Quaternary subbasins that subsided during the Pliocene and the Quaternary [Caroir et al., 2021, 2024, Chanier et al., 2021, Sakellariou et al., 2007].

North of the Sperchios rift, the FTIZ corresponds to the western boundary of ophiolitic units detached from their Triassic–Jurassic Internal Zones basement during the Tertiary compressional episodes [e.g., Aubouin, 1959, Ferrière, 1982, Ferrière et al., 2024]. This is particularly the case in the northernmost Hellenic domain, where important ophiolitic units (N-Pindos ophiolites) are present over the Pindos Eocene flysch (Figure 2B). Further south, from the Koziakas area and southeastward, these units are present at much lower elevation, below the Trikala plain (Figure 2B).

South of the Sperchios rift, the allochthonous units belonging to the Internal Zones are represented by Pelagonian units, locally covered by ophiolites. These units are thrust over the Beotian and Parnassos units from the External Zones [Figures 3A and B; Celet, 1962, Celet et al., 1976, Nirta et al., 2018, Papastamatiou et al., 1962].

At the scale of the Hellenides, the FTIZ is well recognised as the crustal thrust of the Pelagonian Domain over the EZ [e.g., Ferrière et al., 2024, and references therein]. It was reactivated during the Miocene exhumation of the Cycladic metamorphic core complexes [Jolivet et al., 2010b, 2021, and references therein]. Such an extensional reactivation occurred as early as ca. 35 Ma, during early exhumation, as evidenced in the Sporades Islands [Porkoláb et al., 2020]. However, few studies investigated in detail the Plio-Quaternary reactivation of major thrust faults and their relationship with recent extensional features. In the literature [Kranis, 2002, 2007, Kranis and Papanikolaou, 2001], extensional structures associated with the reactivation as a detachment fault of the main thrust at the base of the Pelagonian nappe were evidenced near Amphiklia (Figure 4A).

3. Geometry and kinematics of the FTIZ/MPD at the boundary between Pelagonian and Parnassos units

In both the Dio Vouna–Oiti and Amphiklia areas, the observed tectonic pattern shows the superposition of Pelagonian nappes (IZ) over the units of the Parnassos zone (EZ) with locally the occurrence of some Beotian thrust sheets (EZ) in between (Figures 3B and 4A). The main lineament between EZ and IZ (FTIZ) is overprinted by several extensional faults and the structural geometries along this inverted contact are different in the Amphiklia and Dio Vouna–Oiti areas, as described below.

3.1. *The Amphiklia area*

The structural analysis of the Amphiklia area is based on the construction of three cross-sections to document the present relationships between the Pelagonian and the Parnassos units, and the southwestern boundary of the Kifissos Basin (Figure 4). These cross-sections are constrained by geological maps and field investigations. To our knowledge, neither deep boreholes nor seismic data exist to constrain the subsurface structures.

Near Amphiklia locality (Figures 4A, B-2), the Triassic–Jurassic limestones of the Pelagonian nappe are thrust over the Eocene flysch, lying itself over the Parnassos limestones. In map view, the major boundary between the two units corresponds to the SW border of the recent Kifissos Basin (Figure 4A). Close to the Amphiklia locality (Figure 4A), some klippes of Pelagonian series forming the high-elevated landforms [Celet, 1962, Papastamatiou et al., 1962] are still connected to the main Pelagonian unit

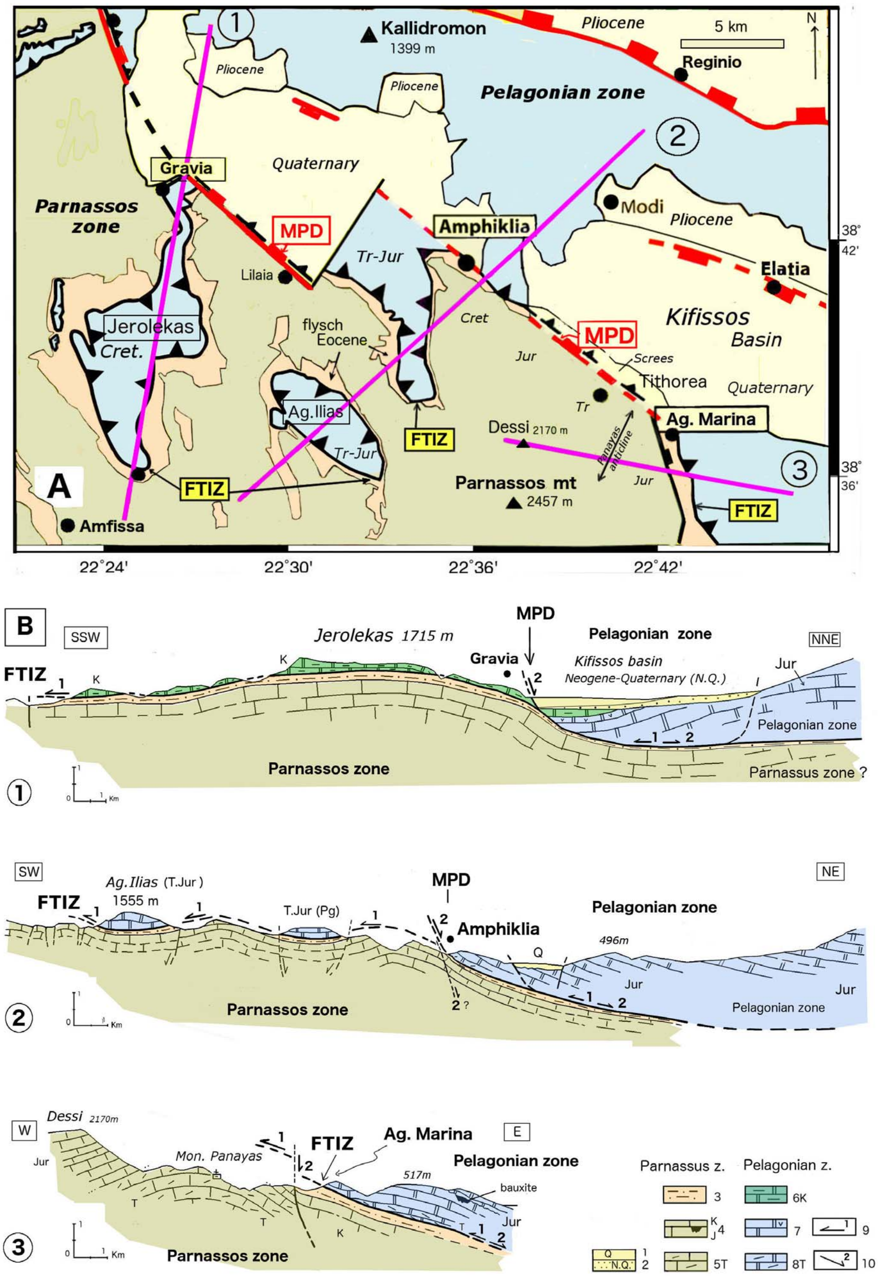

Figure 4. (A) Schematic geological map of the Amphiklia area. Purple lines 1, 2 and 3: location of cross-sections on (B); Tr–Jur: Triassic–Jurassic; Cret: Cretaceous. (B) Cross-sections 1 to 3 in the Amphiklia area located on (A). 1: Quaternary (Q); 2: Neogene-Quaternary (N.Q.); 3 to 5: Parnassos zone; 3: Flysch Paleocene–Eocene; 4: Cretaceous (K) and Jurassic (J) massive limestones; 5: Triassic (T) dolomitic limestones; 6 to 8, Pelagonian zone, 6: (K) Cretaceous limestones; 7: Jurassic limestones locally with ophiolites (v: section 1); 8: Triassic (T) limestones; 9: arrows with (1): Tertiary Thrust SW verging; 10: arrows with (2): tectonic inversion on the previous thrust during recent extensional deformation. Abbr. T: Triassic; Jur: Jurassic, K: Cretaceous; Pg: Pelagonian; MPD and FTIZ: Main Pelagonian Detachment and Frontal Thrust of the Internal Zones.

on the SW border of the Kifissos Basin. West of Amphiklia, in the Jerolekas unit (Figure 4B-1), the Pelagonian Cretaceous series directly overlie the Eocene flysch of the Parnassos unit.

At the transition from the Parnassos mountains and the Kifissos plain, the Parnassos series and the overlying tectonic contact with the Pelagonian unit (Figure 4B) are affected by a large bulge, and locally by a significant NE-facing flexure parallel to the Kifissos basin (Figures 4A, B-1 and B-2). Consequently, the basal thrust of the Pelagonian klippes was slightly steepened on the SW border of the Kifissos Basin, particularly SE of Gravia and SE of Amphiklia (Figures 4A and B).

On the SW border of the Kifissos Basin, i.e., SE of Amphiklia (Figures 4A and B-3), the Parnassos unit forms a wide anticline (Panayas anticline), whose NE–SW-directed axis is not parallel to the Kifissos Basin and cannot therefore be associated to the flexural deformation described above. The deformations of these Parnassos levels along the SW boundary of the Kifissos basin show that the Panayas anticline is older than the flexural event (Figure 4A). Moreover, some high-angle NW–SE-directed normal faults also cross-cut the SW border of the Kifissos Basin as it can be seen SE of Amphiklia (Figures 4B and C).

In the area of Agia Marina (Figure 4A), there are no preserved Pelagonian klippes over the Parnassos series. A major normal fault offsets downward the Pelagonian allochthonous units relative to the Parnassos series. Unlike the Amphiklia sector, this steeply dipping normal fault does not coincide in its location with the major thrust contact between Pelagonian and Parnassos series (Figures 4A and B-3).

In summary, from our mapping and structural analysis in the Amphiklia area, we show that the extensional reactivation of the FTIZ is localised on the low-dipping thrust thereby resulting in a major basin-bounding low-angle normal fault, i.e., the Main Pelagonian Detachment. This tectonic pattern is well expressed along the Gravia and Amphiklia segments (Figure 4A). The reactivation did not generate any modifications on the initial superposition of the internal units over the External Zones.

3.2. *The Dio Vouna area*

In the Oiti mountains (Figures 2 and 5), the basal contact of the IZ klippes upon the Parnassos units (FTIZ) is exposed at a high elevation (ca. 1000 to 2000 m-high, Figure 5B), while the crustal-rooted thrust in front of the Internal Zones is exposed next to Dio Vouna locality at an elevation of only 500 m. In this area of Frantzi–Dio Vouna (Figure 5A), the tectonic contact between the EZ and IZ units displays the most recent series from the IZ (Cretaceous or Late Jurassic in age) over the older series of the Parnassos domain, Jurassic in age (Figures 5A and B). The allochthonous units are mostly typical Pelagonian series, but some Cretaceous formations could locally belong to Beotian sedimentary units, forming tectonic slices transported at the base of the FTIZ [Nirta et al., 2018]. The tectonic contact between the EZ and IZ units is sub-horizontal at the base of the klippes and roots northeastward below the IZ (and the overlying Neogene-Quaternary basins) along a low-angle surface, which is generally dipping about 30°NE (Figures 5B and 6A–D).

In the klippe area on top of the Parnassos mountains (i.e., the Oiti massif; Figures 5A and B), the Pelagonian thrust sheets lay sub-horizontally onto the Eocene flysch. The klippes show some complex internal structures with multiple repetitions of some stratigraphic units, which appear locally inverted (Figure 5B-3).

In contrast, along the NE-dipping rooting zone of the FTIZ (Dio Vouna–Frantzi–Kostalexis area on Figure 5A) stratigraphic surfaces on both sides of the main tectonic contact are not parallel to it. The bedding planes are dipping about 20°SW in the Parnassos limestones and are almost horizontal next to the fault surface within the internal units (Figure 5B). The mean direction of the MPD is about N150°E with striations on the surface indicating a general top to the NE normal slip (Figures 5A and 6A–D). Here, the overall direction is slightly different from the other main fault contacts between the IZ and EZ, mainly N125°E to N135°E, for instance in the Amphiklia region (Figures 3A and 4A). However, this moderate change of direction is not significant at the scale of the Hellenic range and has no impact in the style of deformation that depends at first order on the changes in dip angles.

In the Dio Vouna area, the most recent normal faults, such as those exposed in the Ano-Vardates area, are E–W directed with striations indicating a N–S extension (Figures 6E–I). The

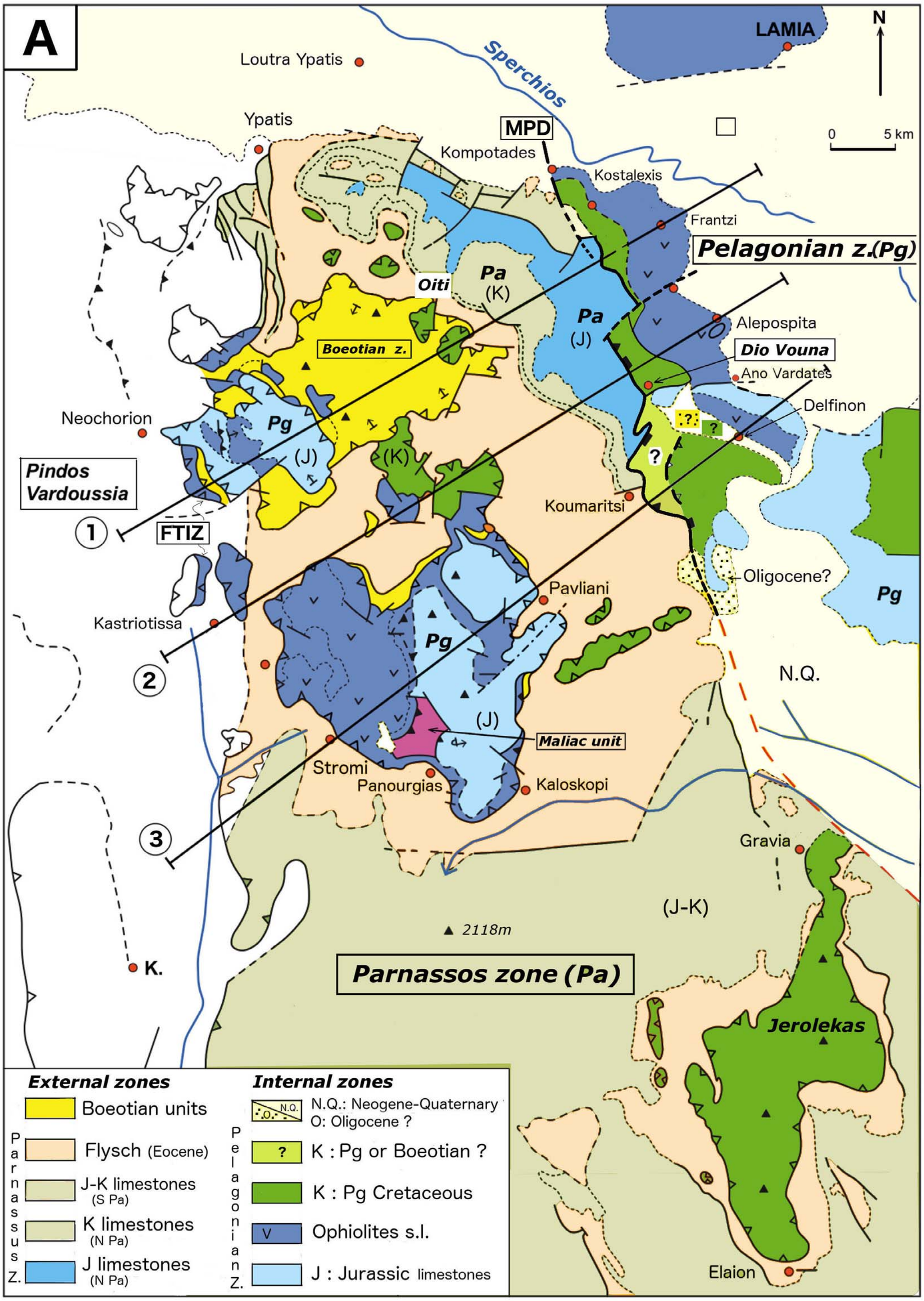

Figure 5. Continued on next page.

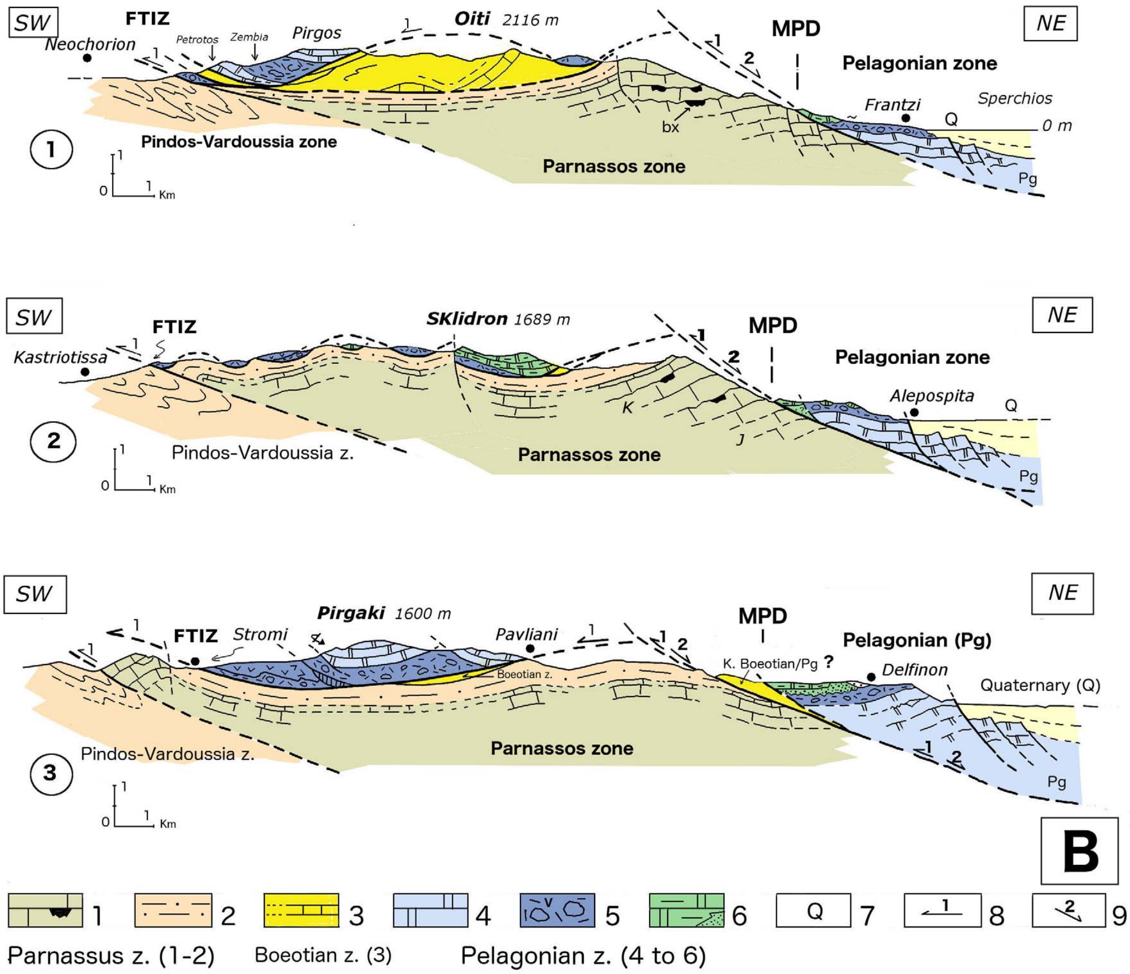

Figure 5 (cont.). (A) Schematic geological map of the Dio Vouna–Oiti area (location on Figure 2B). 1, 2 and 3: location of cross-sections from B. Abbr: J: Jurassic; K: Cretaceous; N.Q.: Neogene-Quaternary; N: North; S: South. Tectonic units: Pa: Parnassos; Pg: Pelagonian. (B) Cross-sections 1, 2 and 3 from the Dio Vouna–Oiti area (location on A). 1: massive limestones (K: Cretaceous, J: Jurassic) with bauxites (bx) from Parnassos zone (Pa); 2: Early Tertiary flysch from Parnassos zone; 3: Early Tertiary flysch, Late Cretaceous pelagic limestones and detrital Cretaceous formations from Beotian unit; 4: Jurassic limestones (Pelagonian Zone, Pg); 5: mélange with blocks and ophiolitic units (Pg); 6: Late Cretaceous limestones and detrital terrigenous beds (Pg); 7: Quaternary (Q); 8: Tertiary Thrust SW-verging; 9: negative tectonic inversion on the pre-existing thrust.

variations in the strike of the fault surfaces and in the directions of movement are likely to represent the complex accommodation of the evolving Aegean extension, from NE–SW extension during the Pliocene and early Quaternary period to N–S extension during the Late Quaternary, by a non-cylindrical initial shape of the FTIZ thrust complex.

3.3. *The inverted FTIZ in central Greece: the main Pelagonian detachment*

Field mapping and structural data from the southern side of the Sperchios Rift suggest that the Late Miocene to Quaternary extensional reactivation of the FTIZ gave rise to a new extensional structure: the Main Pelagonian Detachment (MPD).

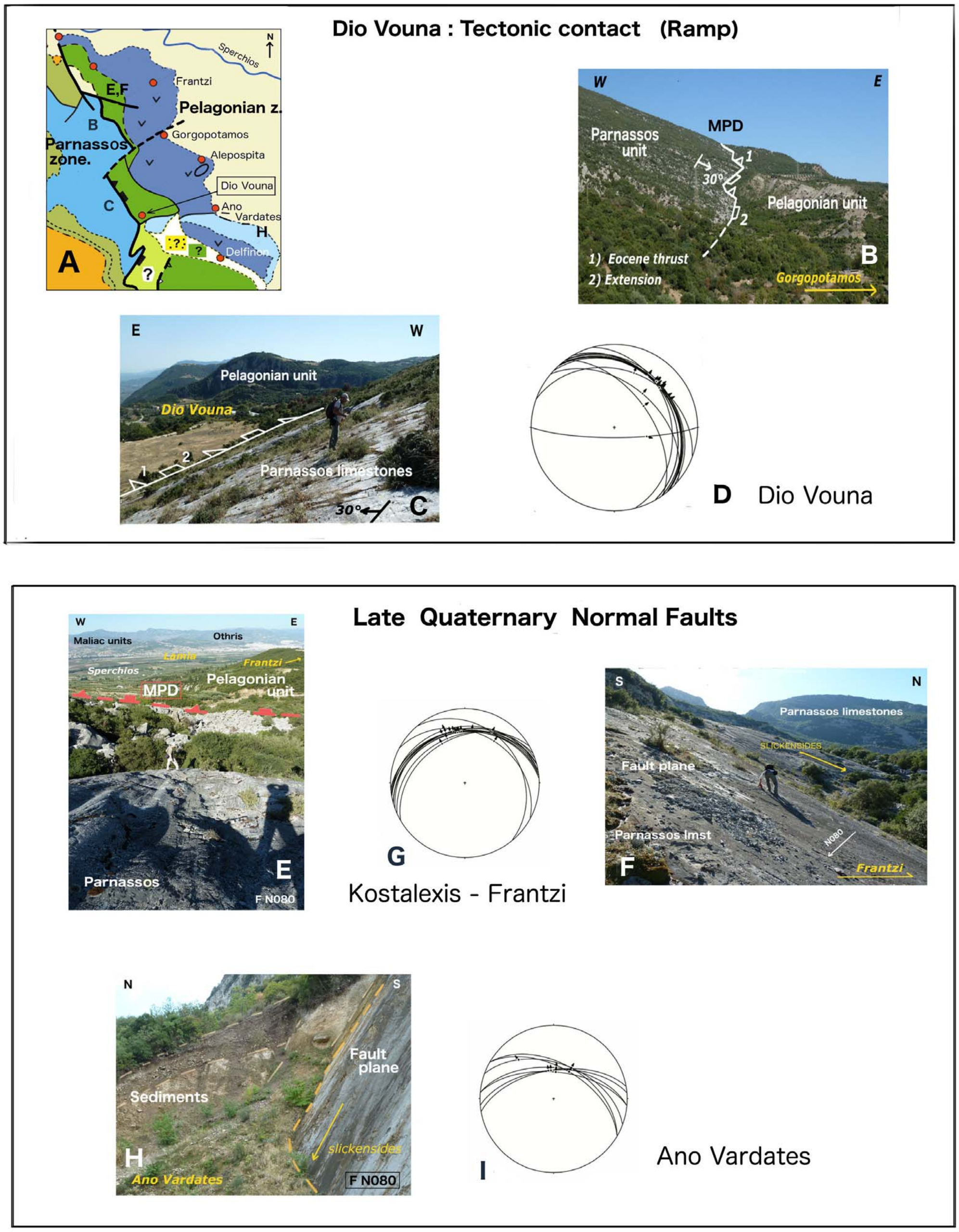

Figure 6. Normal faulting from the Dio Vouna area. (A) Map extract of the Dio Vouna area with the location of photographs from this (B, C, E, F, H). (B) General view from the south towards the low-angle MPD in the Dio Vouna area. (C) Closer view of the MPD dipping 30° towards Dio Vouna locality. (D) Stereoplot (Schmidt, lower hemisphere) showing faults and striations along the MPD in the Dio Vouna area. Solid lines are projections of fault planes with slicken-slide lineations as dots with arrows (outward for normal motion). (E) Downward view on a Late Quaternary normal fault near Frantzi with the Pelagonian zone on the hanging wall. (F) Closer view on the fault surface. (G) Stereoplot (Schmidt, lower hemisphere) showing faults and striations of the fault zone in Kostalexis–Frantzi area. (H) Normal fault west of Dio Vouna, and related stereoplot. (I) Next to Ano Vardates village.

From a geomechanical point of view, inherited crustal thrust zones, such as the FTIZ, are largely documented as weak zones likely to be reactivated in an extensional setting, provided they display substantial dip and relative low strength [Ivins et al., 1990, Lecomte et al., 2011, Le Pourhiet et al., 2004, 2006, Mattioni et al., 2006]. Considering the classical flat–ramp–flat geometry of thrust structures within the crust, extensional reactivation rarely affects the entire thrust surface. The footwall ramp, that exhibits the highest dip along the thrust, is a preferential site for reactivation [e.g., Averbuch et al., 1992, Mohapatra and Johnson, 1998, Ouzgaït et al., 2010, Powell and Williams, 1989, Smith and Bruhn, 1984, Tari et al., 2023, Williams et al., 1989]. These mechanical constraints lead to post- or late orogenic surface normal faults short-cutting the footwall flats and rooting down in the thrust ramps at depth [D'Agostino et al., 1998, Legrand et al., 1991, Minguely et al., 2010, Mohapatra and Johnson, 1998, Roure et al., 1994, Stein and Blundell, 1990, Tari et al., 2023, Tavarnelli, 1999]. Hence, exhumation of the deep geometry of the reactivating fault system (the initial thrust ramps) may lead to the observation of anomalously low angle normal faults [e.g., Ratcliffe et al., 1986, Morley, 2009] like in the Corinth Gulf region [Flotte et al., 2005, Jolivet et al., 2010a, Lecomte et al., 2012, Papanikolaou and Royden, 2007, Papanikolaou et al., 2009, Sorel, 2000].

In the studied region, the extensional reactivation of the initial crustal-scale thrust (FTIZ) developed in two types of configurations, in two separate areas (Amphiklia and Dio Vouna areas).

3.3.1. *Amphiklia area*

In the Amphiklia area, the reactivation of the Tertiary Pelagonian thrust (FTIZ) was previously considered as a "detachment fault" from the analysis of the thrust surface nearby this locality [Kranis and Papanikolaou, 2001]. Thus, from Gravia to the SE of Amphiklia (Figure 4), the observed "negative tectonic inversion" structure shows the following characteristics. Firstly, the basal contact of the Pelagonian nappe is always over the Eocene Parnassos flysch, which corresponds to the most recent stratigraphic series from the underlying unit. Secondly, the series of the Pelagonian nappe overriding this Eocene flysch are among the oldest series of the Pelagonian platform, Triassic or Jurassic in age (SW Amphiklia), or Cretaceous in some klippes further west (e.g., Mount Jerolekas, south of Gravia locality, Figure 4). Such a geometry implies an upper flat configuration for this particular FTIZ segment.

Our interpretation of this configuration is that the inversion of the FTIZ gave rise to the MPD where the upper flat of the FTIZ displays the highest dip. This increase in dip could be due to an anticline flexure of the footwall (Parnassos border) and hanging wall of the thrust (Figures 7A and C), subparallel to the Kifissos basin and to the general orogenic strike in the area. The extensional reactivation of such a thrust upper flat is relatively uncommon because reactivation generally requires substantial dips to be reactivated [e.g., Le Pourhiet et al., 2004, 2006, Mattioni et al., 2006, Ouzgaït et al., 2010, Lecomte et al., 2011, 2012]. However, the local tilt of the thrust associated with this flexure is likely to form an initial instability prone to control the inversion process.

Thus, the crustal rooting of the FTIZ in this specific area does not occur in relation to a major ramp as usually observed in orogenic systems, but is due to the backward flexure. Some secondary normal faults (Figure 4B-2) developed along the flank of the flexure in the footwall layers. The offsets along these second-order normal faults account for the geometry and the variability of the age of the Parnassos series on the southwestern border of the Kifissos Basin between Gravia, Amphiklia and Tithorea localities (Figure 4A). It is sometimes difficult to differentiate, within this sector, the recent normal fault planes from the inverted thrust contact, which displays also some extension markers.

A common origin of the inversion of the FTIZ (MPD) and the flexure of the footwall with associated normal faults during the same Pliocene-Quaternary extensional tectonic event is conceivable. However, as it probably has some direct control on the reactivation of the FTIZ, it is more likely that the flexure appeared earlier, by the end of the Tertiary compressional tectonic episode. In this hypothesis, some locking of the motion along the main thrust surface (FTIZ) could have triggered the development of incipient back thrusts of the Parnassos series northeastwards (Figure 7A—stage "d"). Despite these different second-order deformations, the tectonic contact between the Pelagonian nappe and the Parnassos unit generally remains parallel to the layers involved in the thrusting events in the Amphiklia area (Figure 4B).

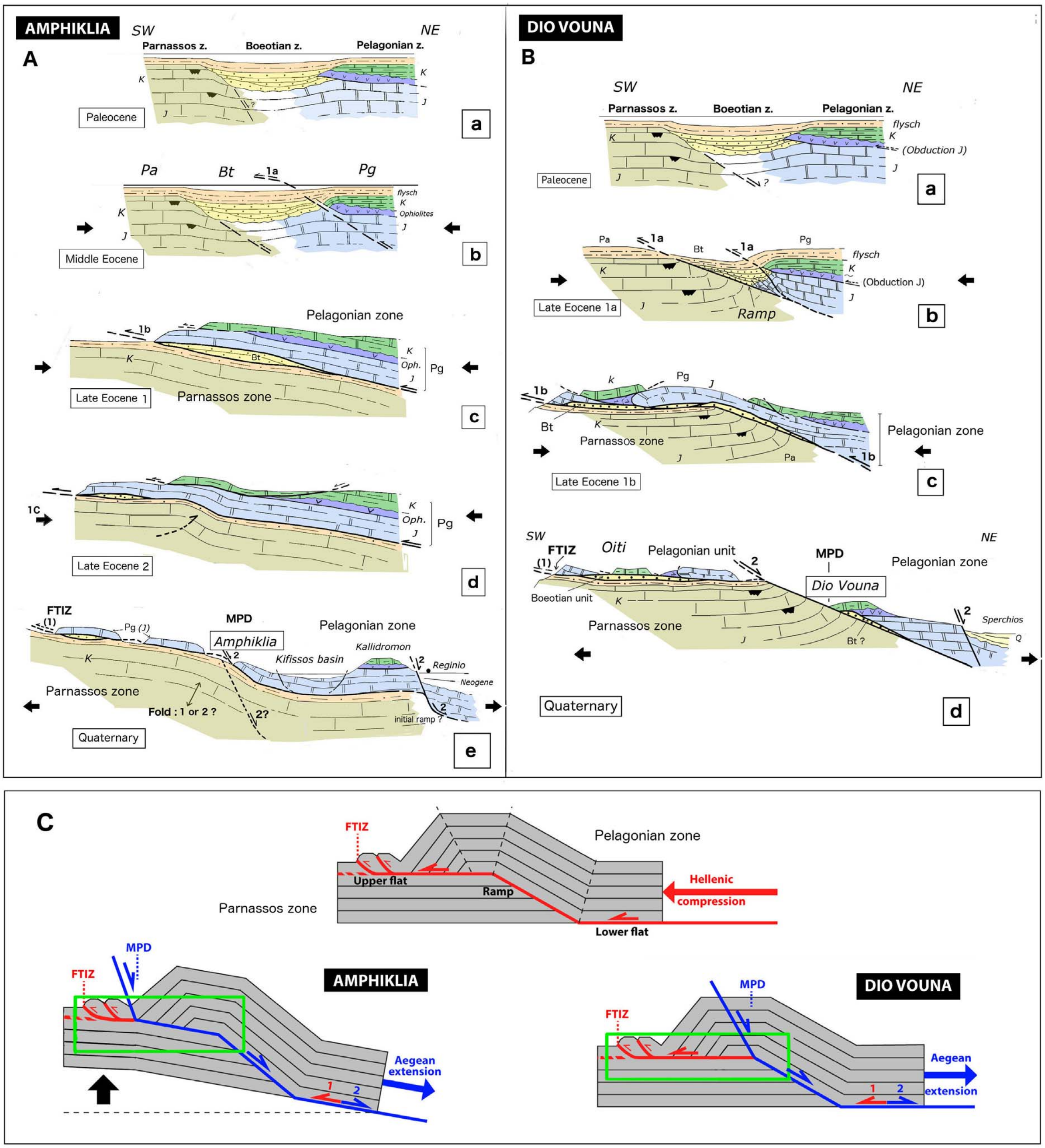

Figure 7. Early Tertiary to Quaternary tectonic evolution of the boundary between external (Parnassos) and internal zones (Pelagonian): (A) in Amphiklia area, and (B) in Dio Vouna–Oiti area. See text for detailed explanations. (C) Sketch cross-section illustrating the two different mechanisms giving rise to the negative tectonic inversion in both areas. (1): Paleocene–Eocene compressional phase; (2) Neogene-Quaternary extensional phase. Abbr. J: Jurassic; K: Cretaceous; Q: Quaternary; Bt: Beotian zone; Pa: Parnassos zone; Pg: Pelagonian zone.

3.3.2. *Dio Vouna–Oiti area*

Similarly to what was observed in the Amphiklia area, the Dio Vouna–Oiti structural pattern (Figure 5) is characterised by (i), the contact of the Pelagonian units over the Parnassos series, with local slivers of Beotian series, and (ii), the inversion of the structural topography acquired during the orogenic development, resulting in the hanging wall Pelagonian units to be at a much lower elevation than the underthrust Parnassos unit.

However, the tectonic inversion pattern observed in the Dio Vouna–Oiti area differs from that of the Amphiklia area, on several important points (Figure 7B). Firstly, the major tectonic contact involved in the negative tectonic inversion is a low-angle surface, dipping 30° or less, which is significantly less than the usual dips of most normal faults within the entire Central Greece region. Secondly, the series at the footwall and hanging wall of the FTIZ are truncated by the tectonic contact, so that the Jurassic Parnassos series and the Jurassic–Cretaceous Pelagonian units are often dipping opposite to the contact. Thirdly, the Pelagonian klippes exposed west of the main MPD in the Oiti mountains are affected by a complex deformation (tight folds, reverse series), much different from the regular stratal dips observed within the klippes near Amphiklia.

These observations lead us to consider that, in the Dio Vouna area, the inverted FTIZ here defined as the MPD corresponds to a large normal fault zone dissecting the upper flat of the FTIZ and reactivating at depth the thrust along a major footwall ramp (Figures 7B and C). This ramp, striking approximately N150°E, is almost perpendicular to the main Tertiary thrust movement of the IZ unit, and is dipping at about 30°, that is a classical dip for such type of structure. The peculiar geometry of the Pelagonian strata on the FTIZ hanging wall implies that these series were tilted after the thrust activation, i.e., during the negative tectonic inversion of the thrust and the coeval MPD development. Such cut-off relationships along the surface clearly indicate a roll-over type of folding associated with the normal fault displacement along the MPD (Figure 5B).

The complex internal structures in the klippes overriding the thick Parnassos platform series could be possibly the result of lithological weaknesses and particularly high basal shear conditions along the ramp and the upper flat of the FTIZ during nappes emplacements in this area.

In summary, the Dio Vouna–Oiti structural geometry is consistent with the classical views suggesting that, due to their weakness and optimal dip, the footwall ramps are the preferential zones to localise extensional reactivation along pre-existing thrusts [e.g., Averbuch et al., 1992, Mohapatra and Johnson, 1998, Minguely et al., 2010, Ouzgaït et al., 2010, Powell and Williams, 1989, Smith and Bruhn, 1984, Williams et al., 1989].

In the Amphiklia area, where the upper flat of the thrust has been inverted, the structural pattern is different. It has been driven by the late tilting of the thrust upper flat in response to the development of an anticline that folded the FTIZ thrust structure after its original emplacement (Figure 7A, Stage "d").

There is no clear evidence for the precise location of a major ramp of the FTIZ at depth across the Amphiklia cross-section. As shown in Figure 7A, the major normal fault zone bounding to the SW the large Pliocene Reginio basin (i.e., the Kallidromon Fault) could be the superficial expression of such a deeply seated ramp of the FTIZ, reactivated with normal motion during the Late Neogene.

4. Integration within the Hellenides–Aegean domain

4.1. *The MPD: a major detachment at the scale of the Hellenides?*

North of the Sperchios rift basin (Figures 8A and B), as there is no more exposure of the Parnassos units, the FTIZ corresponds to the contact surface between the Pindos–Beotian external zones and the ophiolitic units [e.g., Ferrière et al., 2012]. Immediately below the main thrust fault (FTIZ), the Pindos and Beotian zones are represented by the Eocene flysch that corresponds to their younger series.

The FTIZ locally includes several IZ klippes preserved over the Pindos zone, but the main thrust corresponding to the rooting of the FTIZ is relatively linear between internal and external zones (Figures 2A and B). This main deep-seated thrust, locally very steeply dipping and reactivated in extension, is associated with the collapse of the internal zones with respect to the external zones. Accordingly, this thrust can be considered as the prolongation of the MPD

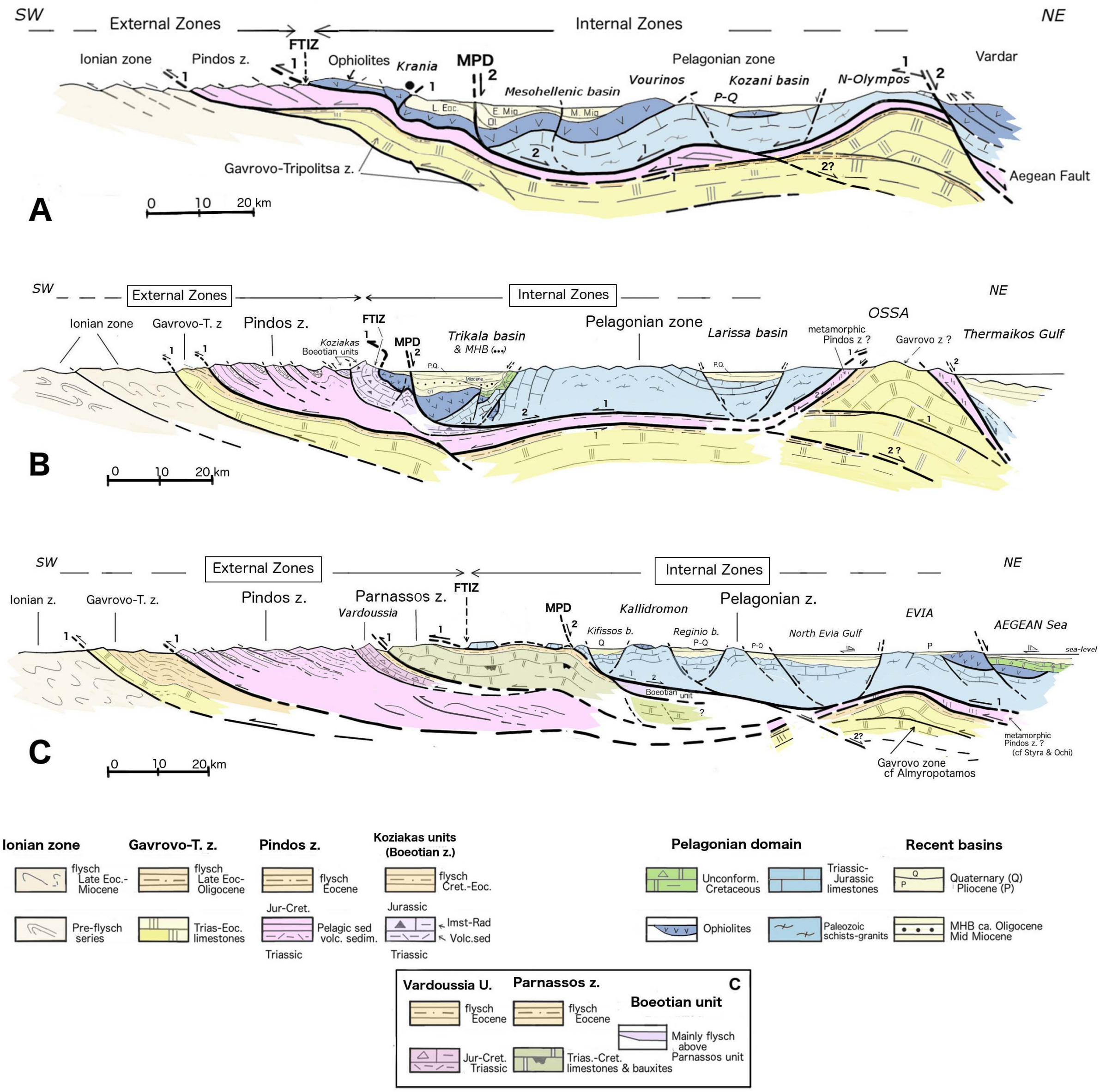

Figure 8. A, B and C: Cross-sections from north to south across the Hellenides. Location on Figure 2B. (A) From the Ionian and Pindos external zones to the Olympus window and Vardar Domain (Internal Zones). (B) From External Zones bounded by the Koziakas range, the Trikala and Larissa recent Basins, the Ossa window and up to the Thermaikos Gulf. (C) Cross-section further south, exposing the Parnassos zone against the Pelagonian zone, up to North Evia Gulf and the Aegean Sea.

that we define further south. The amount of extensional reactivation on this NW segment of the MPD seems much reduced compared to the Dio Vouna–Amphiklia segment, but it can be easily explained by the fact that the total amount of extensional deformation of the Aegean domain vanishes significantly westwards (NW of the Sperchios Basin, see Figure 1).

In this NW area, north of the Sperchios Basin, two different segments of the FTIZ show various overall geometries:

- North of the Kastaniotikos transverse structure (Figures 2B and 8A), important ophiolitic units (e.g., "North Pindos nappe") are preserved west of the relatively linear and continuous MPD. There, the internal zones appear at a much lower elevation than the North Pindos nappe that is over the external zones. The MPD also marks the steeply dipping western boundary of the Oligo-Miocene Mesohellenic Basin (MHB, Figures 2B and 8A) that developed originally as a large piggy-back basin [Ferrière et al., 2004, 2013].
- Between the Kastaniokos transverse structures to the north and the Sperchios Basin to the south, no main ophiolitic klippes are preserved over the external zones. In western Othris (Figure 2B), the FTIZ is very steep and corresponds to the western termination of the ophiolitic front. It is there considered as the MPD as it coincides with the downthrow of the internal zones (to the east) relative to the external zones exposed on the western side of the FTIZ. Along this segment, between western Othris and Kastaniotikos areas, the ophiolitic units are covering the Triassic–Jurassic Koziakas series at high elevation, the basal contact of the ophiolitic nappe appearing at 600 m-high (Figure 8B). On the eastern side of the MPD, this upper ophiolitic basal contact appears at a much lower elevation below the Trikala plain. Such an important offset from both sides of the MPD sub-vertical lineament suggests some significant normal motion between the Koziakas ophiolitic units and the Trikala plain (Figure 8B).

Despite some differences in geometry and amplitude of extension with the Amphiklia-Dio Vouna area, the flat–ramp–flat thrust model applied to the northern Hellenides (north of the Sperchios rift) allows us to propose that the MPD developed on the main ramp of the thrust system and that the upper flat of the FTIZ is mainly appearing in the northernmost Hellenides as the N-Pindos ophiolitic nappes.

South of the Amphiklia area (Central Greece), where the Corinth Rift cross-cuts the Hellenic structural pattern, the FTIZ is much less defined and its lateral extension is unclear. Further south, in the Peloponnese region, the IZ are only represented in the Argolis area, while the rest is constituted by a complex structural pattern of external zones, including many detachments intra-EZ [e.g., Itea–Amfissa detachment; Papanikolaou et al., 2009, Papanikolaou, 2021]. Some deep subsiding basins developed also along this boundary zone between EZ and IZ such as the Argolic Basin, south of Argolis Peninsula (Figure 1). This elongated basin, running parallel to the EZ-IZ boundary (FTIZ), on top of the internal zones could be very likely the surface expression of the overall collapse of the IZ relative to the EZ in this area. This large basement offset along the FTIZ on the eastern coast of southern Peloponnese (Figure 1), with a major collapse of the internal zones, is supporting the reactivation of the FTIZ as the MPD in this area also.

In summary, despite variations in amplitude and style of deformation due to the lateral crustal heterogeneities of the external zones (e.g., occurrence or absence of the thick Parnassos series), the MPD shows: (i) a similar tectonic and geomorphologic pattern along-strike, north and south of the Sperchios basin (Figure 2), and (ii) that this structural development resulted from negative tectonic inversion of the major thrust zone between Internal and External domains.

4.2. *The MPD versus other detachments in the Hellenides and Aegean Sea*

Many large low-dipping detachments linked to Cenozoic extensions have been described in the Hellenides and the Aegean Sea [see Papanikolaou, 2021, Figure 11.6].

These detachments notably known in the Rhodope, the Aegean region and the Peloponnese, affect the EZ and/or the IZ. However, no large detachments have been listed in the northern continental Hellenides beyond the Sperchios rift.

We consider that the FTIZ–MPD exposed between the EZ and IZ in the northern Hellenides represents the lateral continuation of the large detachment described here in the Dio Vouna–Amphiklia area as: (i) the vertical shifts of the Hellenic zones along the

MPD in this sector are similar in nature (collapse of the IZ relative to the EZ; Figure 2B); (ii) the major late Neogene to Quaternary sedimentary basins are widely located above the MPD within the IZ and northeastward of the MPD.

Within the Hellenides, most detachments affect either a single zone [i.e., the Parnassos zone for the Itea–Amfissa detachment; Papanikolaou et al., 2009] or several zones within the IZ or the EZ such as in the Peloponnese or in the Aegean Sea [Papanikolaou, 2021]. The normal motion along the MPD is not necessarily larger than other major detachments in the Aegean region, but the main particularity of the FTIZ–MPD is that it corresponds to the reactivation of a very important crustal thrust at the scale of the Hellenides. The initial geometry of this thrust system (flat–ramp geometry at crustal scale) has significative consequences on the extensional pattern of the upper crust during the negative inversion.

4.3. *The FTIZ/MPD and the Neogene basins within the Hellenides*

The main recent basins of the continental Hellenides, late Miocene to Quaternary in age, mainly appear over the internal Zones. The E–W directed Sperchios Basin prolongates slightly westwards within the EZ but is especially developed in the IZ, while the Trikala and Larissa basins to the north, and the Kifissos and Reginio basins to the south are exclusively over the IZ. Moreover, it is clear that the western boundary of the IZ (the FTIZ/MDP) coincides with the western boundaries of the Trikala and Kifissos basins.

The EZ, and specifically the inner EZ, show a thick crust, exceeding 40 km along the Pindos range [Makris et al., 2013]. Such a crustal thickness is related to the important stack of EZ tectonic units during the Tertiary collision. In contrast, the IZ present a much thinner crust (approx. 34 to 28 km-thick), gradually thinning further east towards the Aegean Sea where the crust reaches 22 to 18 km-thick approximately [Makris et al., 2001, 2013]. These IZ have a much more complex structural pattern as they underwent polyphase development since late Jurassic times, including crustal thickening with obduction of the Maliac Ocean and underthrusting of EZ such as the Gavrovo and Pindos zones [Ferrière et al., 2012, 2015, 2016]. The existence of underthrust units from the EZ below the Pelagonian crust is clearly demonstrated by their occurrence at exposure in the Olympus and Ossa windows (see Figure 8B). We have therefore to consider that these IZ, with overthrusted Maliac oceanic crust and underthrust EZ, had a much thicker crust by the end of the orogenic processes of the Hellenides belt, before the Tertiary post-orogenic thinning.

Even if the post-orogenic thinning of the Aegean crust is essentially related to the slab retreat beneath the Aegean Sea, corresponding to the main driving mechanism for extension [e.g., Jolivet et al., 2013], the inception of crustal thinning in continental Greece appears to be at least partly localised along the boundary between EZ and IZ, i.e., along the MPD. The development of the Neogene extensional sedimentary basins, preferentially on top of the IZ, represents the surface manifestation of crustal thinning in this part of the Hellenic-Aegean domain. Consequently, we suggest that most of the major normal faults bordering all these basins are very likely connected to the MPD surface at depth (Figure 8).

5. Conclusions

Our structural analyses in central continental Greece led us to characterise the tectonic boundary between Internal and External Zones in the Hellenides mountain belt. Two main geomorphological domains form the Hellenides in central continental Greece: (1) the western domain, composed of a high relief fold-and-thrust-belt settled over a relatively thick crust, and (2), the eastern domain, composed of alternating elongated ca. NW–SE basins and ranges settled over a thinner crust. The transition between these two domains is not gradual but localised along a major tectonic structure, the Frontal Thrust of Internal Zones (FTIZ). The FTIZ corresponds to the thrust contact of the Pelagonian zone (IZ) over the Pindos and Parnassos zones (EZ). We describe the structural development along this major tectonic boundary reactivated as an important detachment during negative tectonic inversion, and refer to it as the “Main Pelagonian Detachment” (MPD).

In Central Greece and northern Hellenides, the MPD forms a rather straight and continuous fault zone, with a N130°E average direction. It often coincides with the western boundaries of some of the main Plio-Quaternary basins, such as the Trikala and the Kifissos Basins.

Structural analysis based on new field mapping, regional cross-sections, and fault-slip data, allows to characterise the along-strike geometrical variations of the MPD and to describe the relationships between this inverted tectonic structure and the collapsed eastern domain hosting extensional basins. We show that the diversity of crustal structures that developed in relation to the MPD development is significantly controlled by the initial geometry of the FTIZ, i.e., the initial crustal thrust.

In two key areas of central Greece, we document two types of structural pattern triggered by the development of negative tectonic inversion along the FTIZ/MPD.

Firstly, in the Amphiklia area, the oldest series of the Pelagonian nappe (IZ) are thrust over the youngest formations of Parnassos Zone (EZ). The FTIZ appears parallel to bedding from both the hanging wall and the footwall. Reframed in a classical flat–ramp–flat geometry of crustal thrust emplacement, this configuration suggests that the structure observed in the Amphiklia region corresponds to an upper flat tectonic setting subsequently inverted. Its present-day geometry is the result of extensional reactivation of the gently NE-dipping upper flat of the FTIZ, presumably tilted in response to backfolding or backthrusting by the end of the Paleogene compressional episode.

Secondly, in the Dio Vouna area, the youngest series of the Pelagonian nappe are adjacent to old Parnassos formations, and the series are truncated by the major fault responsible for the downward shift of the Pelagonian units. There, the contact appears as a low-angle normal fault (~30° dip) and its direction (N150°E) is slightly different from the average direction of the MPD throughout the Hellenides (N130°E). According to the classical flat–ramp–flat geometry of thrust systems, this configuration suggests that the main thrust ramp was directly reactivated during the negative inversion.

From the analysis of Amphiklia and Dio Vouna areas, we propose that the thrust system initiated during the early Tertiary collision had initially a “flat–ramp” geometry, that controlled the structural development during the Late Miocene to Quaternary inversion and the development of Neogene basins. At the scale of the Hellenides, the locations and orientations of the Neogene basins highlight the importance of the MPD in the upper crust deformation of the Internal Zones. As most of the Neogene extensional basins developed in the IZ above the MPD, it appears that most of the major normal faults bordering these basins are likely connected at depth to the MPD. Consequently, we propose that most of the major normal faults responsible for the formation of the recent basins, mainly late Miocene to Quaternary in age, branch onto the MPD, i.e., the former FTIZ, at the base of the Pelagonian crustal unit.

Declaration of interests

The authors do not work for, advise, own shares in, or receive funds from any organization that could benefit from this article, and have declared no affiliations other than their research organizations.

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