

DEFORMATION HISTORY AND CORRELATION OF PAIKON AND TZENA TERRANES (AXIOS ZONE, CENTRAL MACEDONIA, GREECE)

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Abstract

Paikon and Tzena terranes are situated in the centre part of Axios zone, between Almopia and Paionia ophiolitic belts. Tectonostratigraphic data reveal that both have been affected by the same polyphase deformation and metamorphism, as well that they have the same lithostratigraphic column. The first deformation phase took place during the Middle to Late Jurassic and is associated with ophiolite obduction, nappe - stacking, terrane accretion and crustal thickening (D_1). Metamorphism does not exceed greenschist facies (M_1). Relict HP-LT metamorphic assemblages predating M_1 metamorphism are possibly developed during subduction processes and overloading of the obducted ophiolites on the continental margin, characterized the initial stages of deformation. Compressional tectonics and intense thrusting with the same kinematics continued in Lower Cretaceous time, affected all pre-Upper Cretaceous units and the obducted ophiolites (D_2). This phase is associated with low-greenschist metamorphism (M_2). The first main extensional event occurs in the Late Cretaceous, related to basin formation and sedimentation (D_3). During Paleocene to Eocene, D_4 intense imbrication of all tectonic units towards mainly SW takes place again. Nappes collapse and finally crustal exhumation taken place during Oligocene to Miocene, associated with low - angle normal faults, with a main top to the SW sense of movement (D_5). In Miocene to recent times, high - angle normal and strike-slip faults are formed in an extensional to transtensional strain regime (D_6), associated with Neogene to Quaternary basin formation and terrane dispersion. The basement rocks of both terranes are of Pelagonian origin, exhumed as a multiple tectonic window.

Keywords: kinematics, tectonic nappe, tectonic window.

Περίληψη

Τα πεδία Πάικου και Τζένας βρίσκονται στο κεντρικό τμήμα της ζώνης Αξιού, μεταξύ των οφιολιθικών λωρίδων Αλμωπίας και Παιονίας. Τεκτονοστρωματογραφικά δεδομένα φανερώνουν ότι έχουν υποστεί την ίδια πολυφασική παραμόρφωση και μεταμόρφωση, καθώς επίσης και ότι έχουν την ίδια λιθοστρωματογραφική στήλη. Η πρώτη παραμόρφωση έλαβε χώρα στο Μέσο - Άνω Ιουρασικό και συνδέεται με την τεκτονική τοποθέτηση των οφιολίθων, τη συσσώρευση των καλυμμάτων, την προσαύξηση των πεδίων και την πάχυνση του φλοιού (D_1). Η μεταμόρφωση δεν ξεπερνά την πρασινοσχιστολιθική φάση (M_1). Η ύπαρξη μιας υπολειμματικής μεταμόρφωσης HP/LT, προγενέστερης της M_1 , οφείλεται πιθανότατα στις συνθήκες υποβύθισης και στην υπερφόρτωση των επωθημένων οφιολίθων πάνω στο ηπειρωτικό περιθώριο, συνθήκες που χαρακτηρίζουν τα αρχικά στάδια της παραμόρφωσης. Η συμπιεστική τεκτονική και η

έντονη λεπίωση με την ίδια κινηματική συνεχίζονται στο Κάτω Κρητιδικό, επηρεάζοντας όλες τις ενότητες πριν το Άνω Κρητιδικό, καθώς και τους επωθημένους οφιόλιθους και συνδέονται με χαμηλή πρασινοσχιστολιθική μεταμόρφωση (M_2). Η πρώτη κύρια εφελκυστική φάση συμβαίνει στο Άνω Κρητιδικό και συνδέεται με το σχηματισμό λεκανών και ιζηματογένεση (D_3). Κατά το Παλαιόκαινο-Ηώκαινο, συνέβη έντονη λεπίωση όλων των ενοτήτων κυρίως προς τα ΝΔ (D_4). Η κατάρρευση των καλυμμάτων και τελικά η εκταφή του φλοιού συνέβη κατά το Ολιγόκαινο - Μειόκαινο, συνδεδεμένη με κανονικά ρήγματα μικρής γωνίας κλίσης και κύρια κινηματική προς τα ΝΔ (D_5). Μετά το Μειόκαινο, λαμβάνει χώρα η νεοτεκτονική δράση σε εφελκυστικό έως διεφελκυστικό πεδίο (D_6), συνδεδεμένη με το σχηματισμό των Νεογενών και Τεταρτογενών λεκανών και τη διασπορά των πεδίων. Το υπόβαθρο και των δύο πεδίων είναι Πελαγονικής προέλευσης, αποκαλυπτόμενο ως πολλαπλό τεκτονικό παράθυρο.
Λέξεις κλειδιά: κινηματική, τεκτονικό κάλυμμα, τεκτονικό παράθυρο.

1. Introduction

Paikon and Tzena terranes are situated in the centre part of Axios zone, between the Pelagonian nappe and the Serbomacedonian/Rhodope metamorphic province. Axios zone comprises the ophiolite-bearing Almopia Subzone in the West, the Paikon and Tzena terranes (Paikon Subzone) in the Middle, and the also ophiolite-bearing Paionia Subzone in the East (Fig. 1) (Mercier, 1968; Ricou and Godfriaux, 1995; Mercier and Vergely, 2001; Brown and Robertson, 1994, 2003 and Robertson *et al.*, 2013). In terms of the Hellenides classification into tectonostratigraphic terranes H1-H9 as proposed by Papanikolaou (2009, 2013) Paikon and Tzena terranes are considered to belong to H5 continental terrane, while both Almopia Subzone to the west and Paionia Subzone to the east are considered to belong to oceanic terranes (H4 and H6, respectively).

It is clear that the structural evolution and geotectonic position of both Paikon and Tzena terranes have long been a matter of controversy between researchers, with several questions remaining unanswered. Which is the sense of ophiolite obduction and when did this obduction happen? How many ocean basins existed within the Axios zone? Do Paikon and Tzena terranes form a single tectonostratigraphic terrane or they are two discrete terranes with different geological history? Are Paikon and Tzena terranes closely related to the Pelagonian Nappe (or even more to the External Hellenides), or they are of Serbomacedonian/Rhodope nappe stack origin?

The main target of this work is to study the geological structure and the relation of Paikon and Tzena terranes, as well as to reconstruct the evolution of deformation from Jurassic till recent times. We carried out geological mapping and detailed structural investigations, as well as thorough study of geological contacts, combined with all available geochronological and stratigraphic data. Shear criteria such as S-C fabrics, shear bands, asymmetric boudins as well as σ - and δ - clasts, were used in order to study the geometry and the kinematics of deformation (Hanmer and Passchier, 1991 and Passchier and Trouw, 2005).

2. Description of tectonostratigraphic units

2.1. Paikon terrane

Paikon terrane consists mainly of the units given below, described from the top to the bottom of the tectonostratigraphic column (Fig. 2, 3) (Mercier, 1968; Mavrides *et al.*, 1982; Mercier and Vergely, 1984; Godfriaux and Ricou, 1991; Bonneaux *et al.*, 1994; Ferriere *et al.*, 2001; Brown and Robertson, 2003 and Katrivanos *et al.*, 2013).

2.1.1. Ophiolites

At the western margin of this terrane, the Almopia ophiolites rest along tectonic contacts on the Maestrichtian Tchouka flysch and in places directly on the Upper Cretaceous Theodoraki carbonates.

Serpentinites, dolerites and basic lavas form an ophiolitic sequence of Triassic - Jurassic age. At the eastern margin, the Guevgeli/Paionia Ophiolites rest tectonically on the Upper Jurassic to Lower Cretaceous Griva-Khromni carbonates. Near the contact, gabbros dominate, while progressively towards the east the upper levels of an ophiolitic sequence crop out, i.e. sheeted dike complex and pillow-lavas of Jurassic age. Into this series, the Fanos Granite intruded during the Late Jurassic, 160 Ma (Soldatos *et al.*, 1993 and Anders *et al.*, 2005). In both Almopia and Paionia ophiolitic sequences, red, deep-sea sediments are deformed together with the ophiolitic rocks.

2.1.2. Tchouka Flysch

Sandstones alternating with siltstones, calcarenites and schists, form a typical flysch series, where carbonate olistoliths often appear. Tchouka Flysch was strongly deformed under brittle conditions and formed tectonic slices. Hence, the flysch rocks alternate tectonically with the underlying carbonate rocks. Tchouka Flysch is considered to be Maestrichtian in age.

2.1.3. Theodoraki Carbonates

It comprises mainly carbonate rocks deposited unconformably upon the lower units, beginning with the Cenomanian transgression. The series starts with dolomites, followed by neritic limestones and intercalations of limestones with sandstones and carbonate conglomerates. In the upper part, pelagic limestones dominate and the rocks show a deepening of the basin, until the deposition of Tchouka flysch. Their age is Late Cretaceous (Cenomanian to Maestrichtian).

2.1.4. Grammos Metaflysch

Metasandstones alternate with metapelites, metaconglomerates and a few limestones. The red sandstone bed intercalated with clastic material of volcanic origin characterizes the series. Grammos Metaflysch is considered of Early Cretaceous age (post-Kimmeridgian and pre-Albian).

2.1.5. Griva-Khromni Carbonates

It consists mainly of recrystallized carbonate rocks, dolomitic in places, intercalated with phyllites and calcareous, as well as sericite schists. Grey marbles dominate in the lower levels of this series. This unit is considered to be of Late Jurassic to Early Cretaceous age.

2.1.6. Kastaneri-Khromni Volcanosedimentary (VS) Series

It consists mainly of acidic volcanic rocks (fine grained tuffs, ignimbrites, sericite and quartz porphyry and metarhyolites), intercalated with clastic sediments (metaarkoses, metaconglomerates, pyroclastic sandstones) and with lenses/horizons or olistoliths of recrystallized limestones. In the western part of Paikon Mt., this volcano-sedimentary series contains both volcanic rocks of acidic to intermediate composition (keratophyres), and of basic composition (spilites and diabases). The age of this series is considered to be Middle to Late Jurassic.

2.1.7. Gkola Tchouka-Gropi Carbonates

This unit is formed mainly of white to grey calcitic and dolomitic marbles and calc schists. The carbonate rocks are strongly mylonitized, especially near the contact with the tectonically overlying volcano-sedimentary formation of Kastaneri-Khromni. The mineral paragenesis comprises calcite, quartz, white mica, sericite and chlorite. White mica is sericitized and calcite dynamically recrystallized. The age of this series should be Late Jurassic to Early Cretaceous.

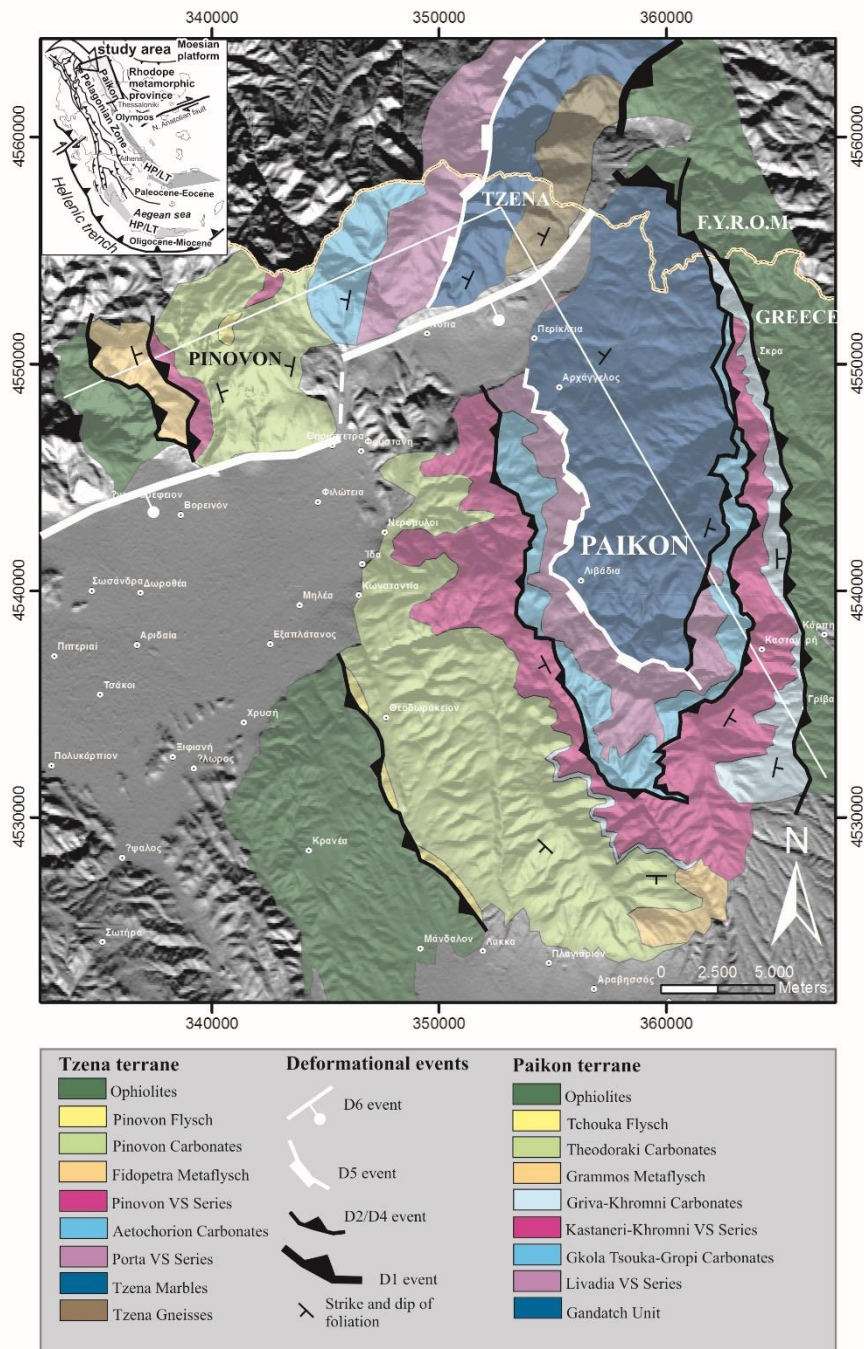


Figure 1- Geological map of Paikon and Tzena terranes (modified from Federal Geological Institute of Serj, 1970; Mavrides *et al.*, 1982; Mercier and Vergely, 1984; Godfriaux and Ricou, 1991; Brown and Robertson, 2003; Galeos *et al.*, 2003; Katrivanos *et al.*, 2001, 2013). (Co-ordinates system: Greek metric grid). Inset: Geological units of Hellenides with the position of the study area (square).

2.1.8. Livadia VS Series

This volcano-sedimentary series of Middle to Upper Jurassic age consists of chlorite-sericite schists, recrystallized limestones, quartz schists, and calcareous schists, intercalated with volcanic rocks: tuffs, metarhyolites, sericitised porphyry and metabasic rocks. Baroz *et al.* (1987) describe also for the Livadia Formation medium- to high-Si phengite.

2.1.9. Gandatch Unit

It is composed of intercalations of calcareous, chlorite, sericite and epidotic phyllites and schists with white or dark marbles and finely laminated marbles (Fig. 2, 3). White or grey, mostly thick-bedded marbles and locally dolomitic marbles exhumed as the deepest rocks in the core of the Gandatch Unit. The Gandatch Unit is not directly dated, as no determinable fossils have been found because of strong recrystallization. It is considered as Triassic to Early-Middle Jurassic age. Medium to high-Si phengite, chlorite and Na-amphibole were recognized by Baroz *et al.* (1987) in schists of the formation.

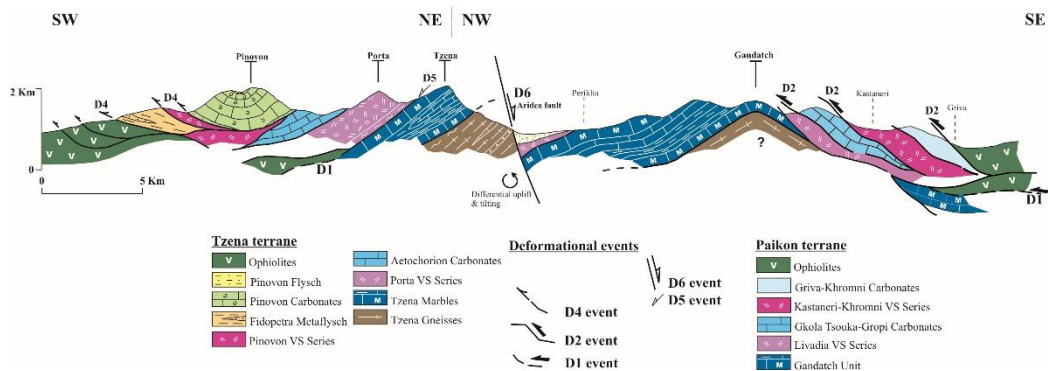


Figure 2 – Schematic geological cross - section, illustrating the geometry of deformation and the geological structure of Paikon and Tzena terranes.

2.2. Tzena terrane

Tzena terrane comprised mainly from the units given below (Quaternary volcanics, i.e. andesitic lavas and tuffs, are not described here but shown only on the map), described from the top to the bottom of the tectonostratigraphic column (Fig. 2, 3) (Mercier, 1968; Migiros and Galeos, 1990; Katrianos *et al.*, 2001 and Galeos *et al.*, 2003).

2.2.1. Ophiolites

West of Pinovon Mt., Garefi ophiolites form a tectonic pile of ultrabasic thrust sheets, consisting of serpentized dunites and hartzburgite tectonites. Diabase veins occur only locally. The age of this unit is considered to be as Jurassic. We consider this ophiolitic sequence as similar to Almopia ophiolites in Paikon column.

2.2.2. Pinovon Flysch

Pinovon nappe consists mainly of transgressive limestones that carry over a flysch series. Phyllites and sandstones intercalations, together with schists and siltstones constitute this typical flysch of Maestrichtian age. This flysch is analogous to Tchouka Flysch in Paikon tectonostratigraphic column.

2.2.3. Pinovon Carbonates

The transgressive limestones of Pinovon nappe consist mainly of alternations of dolomites and limestones. White crystalline neritic limestones become dark grey pelagic limestones to the upper levels of this series, which is analogous to Theodoraki carbonates in Paikon column and considered to be of Late Cretaceous age.

2.2.4. Fidopetra Metaflysch

This series is located to the west of Pinovon Mountain, below Pinovon syncline nappe and consists mainly of calcareous phyllites and metasandstones, with intercalations of limestones, conglomerates, shales and schists. It is analogous to Upper Albian Grammos Metaflysch in Paikon column.

2.2.5. Pinovon VS Series

It is a sequence of mainly volcanic rocks, such as spilites, metaandesites and keratophyres, together with a few pyroclastic and carbonate rocks. This unit is analogous to Kastaneri-Khromni VS series in Paikon column and its age is Upper Jurassic.

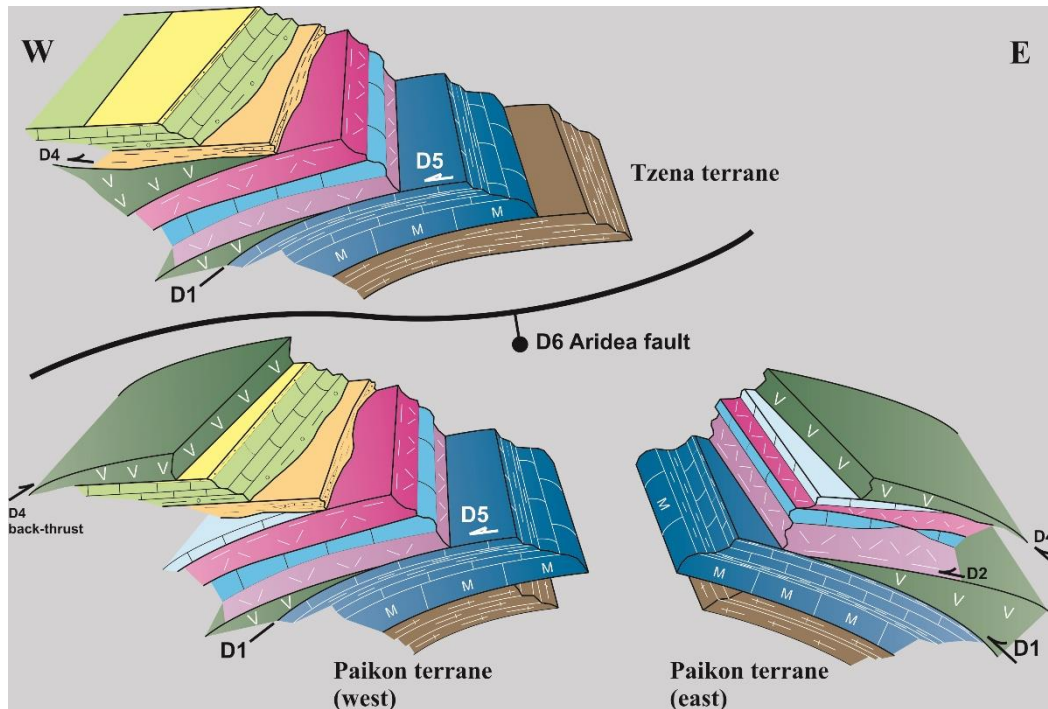


Figure 3 – 3-D tectonostratigraphic blocks of Paikon and Tzena terranes (symbols and colors as in Fig. 1, 2).

2.2.6. Aetochorion Carbonates

It consists of crystalline limestones and cipolins, alternated with chloritic schists and phyllites. This series is analogous to the other Upper Jurassic-Lower Cretaceous carbonate rocks in Paikon column.

2.2.7. Porta VS Series

Acid mylonitised metarhyolites alternates with basic porphyroids and prasinites, with few marbles, greenschists and quartzites that complete the series. Black-coloured chloritic-calcitic schists and phyllites are developed as a thin layer in the base of Porta VS Series. The whole is metamorphosed in greenschist facies, while the age of this unit is Middle to Upper Jurassic. Porta VS Series is analogous to Livadia VS Series of Paikon tectonostratigraphic column.

2.2.8. Tzena Marbles

It consists of white, thick-bedded marbles, intercalated with calc schists and cipolinic marbles. This unit is analogous to Gandatch Unit of Paikon column, considered to be as Triassic age.

2.2.9. Tzena Gneisses

A composite unit consisted of albitic and chloritic gneisses, cipolines, amphibolites and piemontitic schists. The age of this unit is considered to be as Paleozoic - Lower Triassic. This unit is not exposed to Paikon terrane, which forms the hangingwall part of Aridea fault, supposed to be buried beneath Gandatch unit.

3. Deformation History

Both Paikon as well as Tzena tectonostratigraphic terranes that described above have undergone the same polyphase deformation and metamorphism (D_1 - D_6), from Mid-Jurassic to recent times. Shortening alternated with extension and the deformation conditions evolved from ductile to brittle. Compressional events are related to nappe stacking, terrane accretion and crustal thickening, while extensional ones are related to orogenic collapse, terrane dispersion, isostatic rebound, unroofing and crustal thinning (Kilias *et al.*, 2010 and Katrivanos *et al.*, 2013).

3.1. D_1 event

The structures of the first deformational event (D_1) are penetrative and affect clearly the lower units of Triassic age, as well as the Mid- to Late Jurassic volcano-sedimentary series.

A penetrative synmetamorphic foliation (S_1) is parallel to the axial planes of well-preserved isoclinal folds (F_1) that deform a pre-existing S_0 foliation. Usually, fold axes are parallel to sub-parallel to an E-W to NE-SW trending, mineral stretching lineation (L_1). No clear kinematic indicators have been preserved due to the strong overprinting by subsequent tectonics. Elongated grains and aggregates of quartz, white mica, chlorite and rarely aktinolitite or biotite mainly define the mineral stretching lineation (L_1). According to syn- D_1 mineral assemblages, metamorphic conditions did not exceed the greenschist facies (M_1). Baroz *et al.* (1987) suggest that metamorphic conditions range from the lawsonite-chlorite-albite-facies through transitional Na-amphibole-greenschist facies to the chlorite sub-zone of the greenschist facies.

In this study, we assume that D_1 is of Late Jurassic age and responsible for the strong synmetamorphic deformation and internal imbrication of the Triassic basement units and the Mid-Late Jurassic volcano-sedimentary series (Fig. 2, 3).

A high pressure metamorphism (HP-LT) of Mid- to Late Jurassic age is also suspected by Baroz *et al.* (1987), related to a subduction zone, i.e. a subduction during the closure of the Axios Ocean (=Neotethys) and the Late Jurassic plate convergence, or to a tectonic overpressure caused by thrusting. In any case, this HP-LT metamorphism (M_0) predates M_1 metamorphism, because the syn- S_1 mineral assemblages are always related to greenschist facies metamorphic conditions and the HP/LT minerals occur only as remnants. Parts of the lower Paikon units (Gandatch and volcano-sedimentary units) were detached and buried in a depth of at least 20km beneath an emplacing part of oceanic lithosphere in response to continental margin-trench collision and collision of the Paikon continental margin with the oceanic lithosphere of the Axios Ocean. Most *et al.* (2001) and Kilias *et al.* (2010) in the eastern margin of the Pelagonian nappe described similar geotectonic conditions. During D_1 the HP/LT metamorphic rocks, came back to shallower crustal levels and were strongly deformed and imbricated. Unroofing of the metamorphic rocks formed during D_1 took place prior to or during the early stages of the accumulation of the overlying Late Jurassic-Early Cretaceous shallow water sediments.

3.2. D_2 event

D_1 structures are strongly overprinted by a later, deformational event D_2 , recognized in the Triassic units, the volcano-sedimentary series and the Late Jurassic - Early Cretaceous sedimentary units.

Asymmetric, recumbent to overturned, tight to isoclinal folds (F_2) refold both the S_1 foliation, as well as the isoclinal F_1 folds. A new foliation S_2 is parallel to F_2 axial planes. F_1 and F_2 folds axes

are mostly parallel, although in some places a scattering of F_2 folds from NW-SE to NE-SW is observed. S_1 is usually rotated into parallelism with the S_2 foliation, so that in some places only one foliation is recognized. D_2 is associated with an E-W to NE-SW (210° - 260°) trending mineral stretching lineation (L_2), defined mainly by M_2 sericite and chlorite, as well as quartz aggregates. L_2 is developed parallel to F_2 fold axes. The sense of shear during (D_2) is top-to-the-WSW. Opposite sense of movement is observed in some cases, showing the existence of an important coaxial component of deformation during D_2 .

Metamorphic conditions lie in the lower greenschist facies (M_2). Replacement of biotite by chlorite and of green amphibole by actinolite, as well as fine grained sericitisation of white mica, taken place during M_2 .

During D_2 in the Early Cretaceous, W- to SW-vergent imbrication and folding took place again, now affecting the Upper Jurassic - Lower Cretaceous sedimentary series, the Jurassic volcano-sedimentary series, the Triassic ones, as well as the ophiolitic bodies. The ophiolites continued to advance westwards during that time, overthrusting the Upper Jurassic-Lower Cretaceous sediments (Fig. 2, 3).

3.3. D_3 event

Structures of D_3 event are discrete, narrow mylonitic shear zones related to a mylonitic foliation (S_3) and a SW-NE to SSW-NNE trending mineral stretching lineation (L_3). The main sense of shear is top to the SW to SSW (200° - 210°). Rarely, kinematic indicators reveal the opposite sense towards NE. D_3 structures show a relatively constant geometry and affect the penetrative D_1 and D_2 structures. Dynamic recrystallization of quartz, as well as sericitisation of white mica takes place along the D_3 shear zones, which show mostly a down-dip sense of movement, possibly indicating an extensional tectonic regime during D_3 .

D_3 event must be Late Cretaceous (Early Cenomanian) because it overprints clearly D_2 structures but does not affect the transgressive Upper Cretaceous carbonate sediments and flysch. Sharp and Robertson (1993) and Kiliyas *et al.* (2010) also describe a possible extensional event of Late Cretaceous age (Cenomanian-Turonian), related to basin subsidence and crustal unroofing, analogous to D_3 event.

Upper Cretaceous extension (D_3 event) and exhumation of deeper crustal rocks is associated with basin subsidence and deposition of the Upper Cretaceous limestones and flysch (Cenomanian to Maastrichtian), outcropping on the western flanks of Paikon and Pinovon mountains (Fig. 2, 3).

3.4. D_4 event

Structures of D_4 event are open to tight kink folds (F_4) associated with reverse faults, affecting all units, including the transgressive Upper Cretaceous limestones and flysch, as well as the ophiolites. D_4 contractional structures show a general vergence towards SW. An S_4 crenulation cleavage parallel to axial planes of D_4 folds without visible recrystallization is usually developed.

Thus, D_4 structures form a well developed, NW-SE trending fold and thrust belt, active from Paleocene to Eocene and resulting in renewed SW-directed imbrication of all units. In the western Paikon, Almopias ophiolites overthrust the Theodoraki Carbonate Formation and Tchouka flysch, along a NEward D_4 back-thrust (Fig. 1, 3; Mercier and Vergely, 2001; Brown and Robertson, 2003).

3.5. D_5 event

D_5 structures are large, low-angle, dip-slip to oblique normal faults, considered of Oligocene - Miocene age (Fig. 1, 2). They are brittle structures, mainly NW-SE striking, with a main sense of movement towards SW in the western and towards NE in the eastern flanks of Paikon and Tzena terranes. They clearly overprint all previously described structures including the Paleocene-Eocene fold and thrust belt. Some of the tectonic contacts in the eastern Paikon Massif are reworked by the extensional D_5 low angle faults, juxtaposing structurally higher against lower formations, through

omission of several intermediate formations (e.g. Griva-Khromni limestones are tectonically overlying directly the Gandatch unit).

The final exhumation of Paikon and Tzena tectonostratigraphic units, as well as crustal thinning occurred during the Oligocene-Miocene extensional event D_5 under brittle conditions. Simultaneously, unroofing and exhumation of the External Hellenides units, took place under ductile conditions at deeper structural levels of the Hellenic orogen (Kilias, 1995).

3.6. D_6 event

Transension tectonics characterizes the D_6 event. During Miocene-Pliocene, faulting overprinted all previously described structures. D_6 structures include high-angle normal, dip-slip to oblique faults, as well as strike-slip faults. A very important D_6 fault is the ENE-WSW striking and SSE-dipping Aridea fault zone, which is considered to be originally a dextral strike-slip fault, reactivated during the Pliocene-Quaternary until recent as a normal dip-slip fault (Pavlidis *et al.*, 1990). In the study area, this fault separates Tzena from Paikon terrane, due to differential uplift and tilting of the footwall Tzena terrane (Katrivanos *et al.*, 2001), forming the Neogene to Quaternary Notia-Periklia depression and leading to terrane dispersion (Fig. 1, 2). The omission of Paleozoic basement in the Paikon terrane, described above for the Tzena terrane, can be ascribed to this D_6 normal fault.

4. Discussion and Conclusion

Paikon and Tzena terranes constitute a complex tectonic nappe pile with several tectonostratigraphic units, including the obducted Neotethyan ophiolites, far-traveled westwards from their initial place (Fig. 3). According to their tectonostratigraphy and structural evolution, as presented here in detail, we suggest that Paikon and Tzena terranes form two identical tectonostratigraphic terranes, on the contrary to other previous approaches (Godfriaux and Ricou, 1991 and Ricou and Godfriaux, 1991, 1995).

Nappe stacking and deformation started during the Mid- to Upper Jurassic. The primary emplacement of ophiolites on the Triassic marbles was possibly associated with the overthrusting of the volcanoclastic series. Brown and Robertson (2003) assumed Jurassic, northeastward subduction that created an island arc within the Paikon Massif, coupled with back-arc rifting, generating the Guevgeli Ophiolites and related units behind the Paikon arc. They also propose that overthrusting of the Paionias Ophiolites on the Paikon Massif took place firstly during the Late Cretaceous to Early Tertiary.

Nevertheless, in both Paikon and Tzena terranes, feeds dykes of the overlying volcanic formations are not found inside the lower units. Therefore, we suggest that these volcanic rocks of calc-alkaline composition formed somewhere else, during an initial Jurassic intra-oceanic subduction in the Neotethys Ocean, as also assumed by Michard *et al.* (1998), Katrivanos *et al.* (2013) and Michail *et al.* (2014). Furthermore, Jurassic magmatic series (Chortiatis series; Mussalam, 1991) including reefal limestones of Late Jurassic age (Kimmeridgian-Tithonian) and clastic deposits with spilite, keratophyre, andesite and granodiorite elements (Mussalam, 1991 and Michard *et al.*, 1998), exposed along the western margin of the Serbomacedonian massif, can be correlated in lithology and age with the Paikon volcano-sedimentary formations. This Chortiatis magmatic series and the volcanoclastic series along the western Serbo-Macedonian margin was interpreted by Michard *et al.* (1998) as having developed in an intra-oceanic island arc setting related to an intra-oceanic subduction predating the obduction of the Axios (=Neotethyan) ophiolites. Such a tectonic setting and place may be assumed also for the Paikon and Tzena volcano-sedimentary units, prior their westwards emplacement onto the Triassic units, owing to the arc-continent collision.

Therefore, we suggest that ophiolites obduction upon the continental series of Paikon and Tzena terranes took place simultaneously with the ophiolite tectonic emplacement towards west upon the Triassic marbles of the eastern Pelagonian margin, described by several researches (Vergely, 1984; Brown and Robertson, 2003, 2004; Kilias *et al.*, 2010 and Katrivanos *et al.*, 2013).

Finally, the nappe pile evolved into a multiple tectonic window, where the lower units emerged under the Jurassic volcano-sedimentary series and the Upper Jurassic-Lower Cretaceous carbonate series and these again under the duplicated, ophiolitic nappe (Fig. 3). The tectonic window formed due to successive compressional and extensional events from Jurassic to Tertiary time. The final configuration of the tectonic window resulted from the Oligocene-Miocene extension (D_5). Considering that Paikon and Tzena terranes are identical, the lower units of both terranes, as it is assumed for the Paikon lower units by Katrivanos *et al.* (2013), are possibly of Pelagonian origin (i.e. the eastward prolongation of H3 terrane, according to Hellenides terrane classification given by Papanikolaou, 2009, 2013).

Godfriaux and Ricou (1991), Ricou and Godfriaux (1991, 1995) proposed also an overall westward overthrusting of Paikon units but of Tertiary age. In their approach, the Paikon Massif is considered as a multiple tectonic window of Tertiary age beneath the thrust slices of the Axios Zone ophiolites and the Pelagonian Nappe of metamorphic rocks. Additionally, Tzena Massif is considered as a Tertiary metamorphic nappe with an origin from the east (Rhodopic hinterland), that was placed tectonically upon both the ophiolites and the Paikon units. The lower unit of the Paikon Massif is correlated with the carbonate unit of Olympos-Ossa, while the overthrust volcanic rocks with the Ambelakia HP/LT unit. However, we do not share this view, because those two windows show a different structural evolution and tectonic position. The Olympos-Ossa window represents a deeper tectonic unit of Hellenides belonging to the External Hellenides below the Pelagonian nappe pile, exhumed first during the Tertiary.

In conclusion, we suggest:

- Both Paikon and Tzena tectonostratigraphic terranes were affected by six main Alpine deformational events. They started in Mid-Late Jurassic time with an intra-oceanic subduction in the Axios Ocean (=Neotethys) and continued progressively until today. Shortening alternated with extension and the deformation conditions evolved from ductile to brittle. Compressional events are related to ophiolite obduction, nappe stacking, terrane accretion and crustal thickening, while extensional ones are related to orogenic collapse, unroofing, terrane dispersion and crustal thinning.
- Paikon and Tzena terranes are tectonostratigraphically identical and each one of them is a composite terrane that formed by terrane accretion, i.e. a complicated tectonic nappe pile, including obducted ophiolites rooted in the Axios zone (=Neotethys), far-travelled westward from their initial place.
- The core of both terranes, i.e. gneisses and marbles, may be of Pelagonian origin, exhumed as a multiple tectonic window under the overthrust nappe pile.
- The two composite terranes are separated during D_6 event, along Arideas fault, which is responsible for terrane dispersion and related to Neogene-Quaternary basin formation.

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6. References

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