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ORIGINAL PAPER

The Maliac Ocean: the origin of the Tethyan Hellenic ophiolites

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Abstract The Hellenides, part of the Alpine orogeny in Greece, are rich in ophiolitic units. These ophiolites and associated units emplaced during Jurassic obduction, testify for the existence of one, or several, Tethyan oceanic realms. The paleogeography of these oceanic areas has not been precisely described. However, all the authors now agree on the presence of a main Triassic–Jurassic ocean on the eastern side of the Pelagonian zone (Vardar Domain). We consider that this Maliac Ocean is the most important ocean in Greece and Albania. Here, we limit the detailed description of the Maliac Ocean to the pre-convergence period of approximately 70 Ma between the Middle Triassic rifting to the Middle Jurassic convergence period. A quick overview on the destiny of the different parts of the Maliac Ocean during the convergence period is also proposed. The studied exposures allow to reconstruct: (1) the Middle to Late Triassic Maliac oceanic lithosphere, corresponding to the early spreading activity at a Mid-Oceanic Ridge; (2) the Western Maliac Margin, widely exposed in the Othris and Argolis areas; (3) the Eastern-Maliac Margin in the eastern Vardar domain (Peonias and Paikon zones). We established the following main characteristics of the Maliac Ocean: (1) the Middle Triassic rifting marked by a rapid subsidence and volcanism seems to be short-lived (few My); (2) the Maliac Lithosphere is only represented by Middle to Late Triassic units, especially the Fourka unit, composed of WPB-OIB and MORB pillow-lavas, locally covered by a pelagic Middle Triassic to Middle Jurassic sedimentary cover; (3) the Western Margin is the most complete and our data allow to distinguish a proximal and a deeper distal margin; (4) the evolution of the Eastern Margin (Peonias and Paikon series) is similar to that of the W-Margin, except for its Jurassic terrigenous sediments, while the proximal W-Margin was dominated by calcarenites; (5) we show that the W- and E-margins are not Volcanic Passive Margins; and (6) during the Middle Jurassic convergence period, the Eastern Margin became an active margin and both margins were affected by obduction processes.

Keywords Tethys · Triassic–Jurassic · Maliac Ocean · Rifting · Spreading · Passive margins · Ophiolites · Hellenides · Greece

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Introduction

The Hellenides, an alpine-type orogen, are rich in ophiolites (Fig. 1) cropping out in the Pelagonian and Vardar domains of the eastern Hellenides. The Hellenic ophiolites were obducted during Jurassic times from Tethyan oceanic areas onto the Pelagonian microcontinent (see Celet and Ferriere 1978).

A long lasting controversy exists about the origin of the ophiolites (Bernoulli and Laubscher 1972). According to some authors, these ophiolites could have come from two

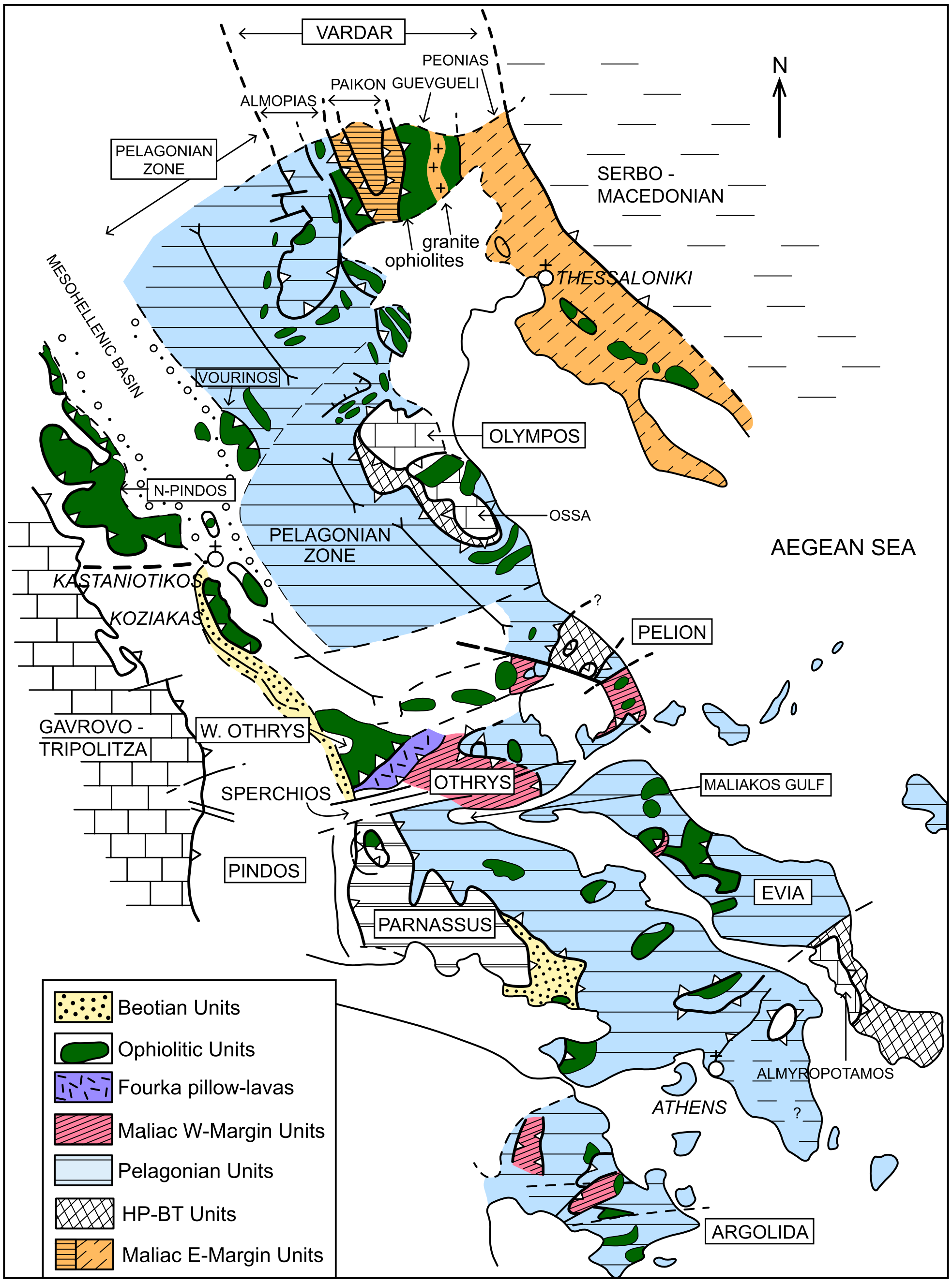

Fig. 1 Main Maliac oceanic units in the Hellenic Pelagonian and Vardar zones. Ophiolitic units with mafic and ultramafic rocks (*green*); Fourka pillow-lavas (*dashes*, *violet*); West Maliac margin (*oblique lines*, *pink*); East-Maliac margin (Peonias and Paikon: *orange*). W, western; HP-BT, blueschists units

oceans located on both sides of the Pelagonian domain, while a majority of authors favor a hypothesis in which all ophiolites were derived from a single ocean located to the east of the Pelagonian (cf discussion in Saccani et al. 2011; Ferriere et al. 2012; Robertson 2012; Bortolotti et al. 2013).

We consider that this eastern Pelagonian Ocean here named «Maliac Ocean» (Ferriere 1976a, 1982) is the major Hellenic Tethyan Ocean represented by the ophiolites.

Most of the remnants of this Maliac Ocean are the Supra-Pelagonian Ophiolites (SPO) and the underlying tectonic units formed during westward obduction along its western margin (W-Margin) in present-day coordinates.

Numerous ophiolitic bodies have been dated in the last years by the biochronology of radiolarians recovered from radiolarites stratigraphically associated with basalts (Bortolotti et al. 2004; Baumgartner and Bernoulli 2015), as well as by radioisotopic methods (Spray et al. 1984; Liati et al. 2004). Many ophiolitic bodies yielded Middle to Late Jurassic ages (e.g., most of the SPO and of the East-Almopias and Guevgueli ophiolites) (Fig. 1). Hence, these ages are thought to date the period of convergence and are not significant of the spreading evolution of the Maliac Ocean.

The only major ophiolite unit testifying for this spreading period is a Triassic unit (Fourka Unit) largely developed in western Othris (W-Othris). This unit is described with some detail in this paper (see also Ferriere et al. 2015).

Outcrops of good quality representing the Maliac margins are mainly known from the W-margin in the Othris and Argolis areas, whereas those of the eastern margin (E-margin), only known in the eastern Vardar domain (Peonias and Paikon) were affected by strong deformation and/or metamorphism.

Our synthesis about the development of the Maliac Ocean (rifting and spreading) is based on:

1. The experience of the authors who worked on the different W- and E-margin outcrops especially in Othris, Argolis and eastern Vardar areas (Ferriere 1974, 1982, 1985; Celet and Ferriere 1978; Baumgartner 1985; Stais and Ferriere 1991, 1994; Ferriere and Stais 1995; Ferriere et al. 2012);
2. Analytical works on the Hellenic ophiolites especially those concerning their geochemical affinities as these data permit to share between ophiolites developed during the divergence (spreading) or convergence (subduction–obduction) periods (Moores 1969; Celet et al. 1979; Capedri et al. 1980; Bebien et al. 1980; Bebien 1983; Beccaluva et al. 1984; Vergely 1984; Ross and Zimmermann 1996; Bortolotti et al. 2004; Saccani and Photiades 2004; Saccani et al. 2004, 2008b, 2011; Rassios and Moores 2006; Dilek et al. 2008; Barth et al. 2008; Barth and Gluhak 2009);
3. Data relative to the age of the different ophiolitic bodies allowing to follow the evolution of the ocean. Ages are based on radioisotopic (e.g., plagiogranites, metamorphic soles) and paleontological (radiolarite beds stratigraphically associated with lavas) analyses (Baumgartner and Bernoulli 1976; Spray and Roddick 1980; Spray et al. 1984; Jones and Robertson 1994; Baumgartner 1984, 1985, 1995; Baumgartner et al. 1993, 1995; Dimo-Lahitte et al. 2001; Danelian et al. 2000; Bortolotti et al. 2002a, 2008; Chiari et al. 2003, 2012; Liati et al. 2004; Ozsvart et al. 2011; Kukoc et al. 2015; Ferriere et al. 2015);
4. Works on the tectonostratigraphy of units representing the Maliac margins, including sedimentary and syn-rift igneous series (Hynes 1974; Ferriere 1982; Vrielynck 1982; Baumgartner 1985, Lefèvre et al. 1993; Bortolotti et al. 2002a; Saccani et al. 2003; Monjoie et al. 2008; see also Pe-Piper and Piper 2002, chapter "Triassic rifting and volcanism")

In short, new and literature data on the Hellenic ophiolitic domains allow us to propose:

1. A synthesis of the whole Maliac Ocean (oceanic lithosphere and margins) for the divergence period from the rifting (Middle Triassic, c. 235–240 Ma) to the beginning of subduction (Middle Jurassic, c. 170 Ma);
2. A short view on the evolution of the different parts of this ocean during the complex convergence setting (c. 170–150 Ma).

Greek and Albanian ophiolites correspond to the same ocean and show the same evolution (e.g., Bortolotti et al. 2004; Dilek et al. 2008); consequently, we use and compare data from the Albanian ophiolites and our results can be applied to the Albanian continuation of the Hellenic ophiolites.

Geological setting

The main elements allowing to reconstruct the Maliac Ocean are the ophiolitic nappes (oceanic lithosphere) and some associated syn-obduction sedimentary nappes (margins).

These units are located in the Pelagonian and Vardarian domains constituting the Internal Hellenides (Fig. 1).

The most complete and largely developed ophiolitic outcrops (some of them are "incomplete ophiolitic sequences" *sensu* Dilek and Furnes 2011) are the Supra-Pelagonian Ophiolites (SPO) especially those known as Vourinos, N-Pindos, W-Othris, and N-Evia (Fig. 1). On the Argolis Peninsula no ophiolite (pseudo)stratigraphy is preserved; Km-sized bodies of serpentinised ultramafic cumulates and Triassic MORB-type basalts, as well as minor occurrences of gabbros, are embedded in a Middle Jurassic siliceous ophiolitic breccia.

Among these SPO, those coming from the Maliac Oceanic Lithosphere (MOL) formed during the divergence period (e.g., Fourka unit in W-Othris, Ferriere et al. 2015) are less represented than those developed during the convergence step (e.g., Vourinos, Chiari et al. 2003).

Some other SPO (Aspropotamos unit of the N-Pindos area, Mega Isoma unit in W-Othris) are differently interpreted as Supra-Subduction Zone (SSZ) ophiolites (e.g., Dilek et al. 2008) or as resulting from two superimposed processes: the first one at the Mid-Oceanic Ridge (MOR), the second one in a SSZ area (Saccani and Photiades 2004; Barth et al. 2008).

The ophiolites located in the Vardarian domain correspond to different types:

1. The West-Almopias ophiolites are considered as SPO (Mercier 1968; Vergely 1984; Saccani et al. 2008a);
2. The Guevgueli ophiolites, the easternmost ones, are interpreted as a Middle-Late Jurassic back-arc basin (Mercier et al. 1975; Bebien et al. 1980; Ferriere and Stais 1995; Saccani et al. 2008b);
3. The East-Almopias ophiolites located between the previous ones (Mercier 1968; Bechon 1981; Bertrand et al. 1994; Stais and Ferriere 1991; Sharp and Robertson 1998) are not well enough dated (Late Jurassic-Early Cretaceous, maybe Tithonian according to Stais and Ferriere 1991) to be precisely interpreted.

The oceanic basements of Guevgueli, E-Almopias, and probably W-Almopias formed after the divergence period of the Maliac Ocean.

The sedimentary series representing the Maliac margins are not homogeneously preserved:

1. Along the W-Maliac margin remnants crop out, as syn-obduction tectonic units below the main SPO, especially in Othris, Argolis, and to a minor extent in Evia (Ferriere 1972; Hynes et al. 1972; Smith et al. 1975; Ferriere 1982; Baumgartner 1985; De Bono et al. 2002; Scherreiks et al. 2009);
2. Along the E-Maliac margin, small slivers of this margin became tectonically emplaced during the Late Jurassic and were further emplaced during Tertiary events (Mercier 1968; Ferriere and Stais 1995; Bonev and Stampfli 2008, 2011; Bonev et al. 2015). The Paikon series correspond probably to the distal part of this E-Maliac margin (Ferriere and Stais 1995).

The pre-convergence Maliac Oceanic Lithosphere

The Middle Triassic—Early Jurassic Maliac Oceanic Lithosphere (MOL) is only recorded in a few parts of the SPO. Many MORB-type lavas are dated as Triassic, but most of them occur in mélanges or in small tectonic slivers, lacking a relationship with any ultramafic or gabbroic basement (e.g., Ferriere et al. 1988; Photiades et al. 2003; Saccani et al. 2008a). It is important to determine in each unit if the mafic extrusives belong to the MORB suite of the Maliac oceanic lithosphere and not to other volcanic events, such as the syn-rift volcanism on the margins.

The oldest Maliac Oceanic Lithosphere (Middle and Late Triassic)

The oldest units corresponding to the MOL are only lavas, the ages of which are Middle and Late Triassic.

The Triassic Fourka unit (Othris): the main unit of pre-convergence Maliac oceanic crust

The Fourka unit is a major unit of 200–300 m thick covering a surface of about 35 km by 35 km in the Othris mountains (Fig. 2). This syn-obduction unit is sandwiched between peridotitic nappes, above, and sedimentary nappes of the W-margin below (Figs. 2, 3).

The Fourka unit is made of pillow-lavas showing mainly MOR, within plate (WPB) and ocean island (OIB) basalts (Hynes 1974; Ferriere 1982; Bortolotti et al. 2008; Barth and Gluhak 2009). Some other kinds of lavas have been cited but they could belong to units of the W-Maliac margin (some basalts mentioned in Ozsvart et al. 2011 or some low KT lavas described in Bortolotti et al. 2008).

The homogeneity of the geochemical affinities of the lavas (mainly MORB) added to the long life of the volcanism (minimum c. 240–210 Ma based on radiolarian dating) lead us to interpret this unit as the oldest part of the MOL rather than to the distal part of a possible Volcanic Rifted Margin (cf Geoffroy 2005).

The sediments covering the lavas are mainly radiolarites and siliceous shales. The radiolarites with a clear stratigraphic contact on the pillow-lavas are always Triassic in age (Ferriere et al. 2015). Two sets of datings have been evidenced: late Anisian-early Ladinien (Kalamakion, N-Moschokarya) and early Norian (E-Moschokarya) (Fig. 4).

The sedimentary cover of the Fourka pillow-lavas of the N-Moschokarya section (Fig. 4) could be a complete section deposited during the whole divergence period documented by Mid-Triassic and Mid-Jurassic radiolarite ages. The intercalated red shales could be Early Jurassic in age but no Radiolarians of that age have been recovered from the Othris sections.

The Triassic Maliac oceanic crust: other examples

The Fourka unit in Othris is by far the most important remain of the Triassic oceanic domain but some various Triassic lava bodies could be eventually also assigned to this large oceanic area:

- In the Koziakas area (Fig. 1), tectonic slivers of some MORB-WPB pillow-lavas, late Anisian to Norian in age, have been ascribed to the Fourka unit (Chiari et al. 2012).
- In the Argolis peninsula, small bodies of Late Triassic MORB pillow-lavas and Alkali basalts lead some authors to conclude to the possible «local existence of a minor oceanic basin during the Triassic» (Bortolotti et al. 2002a, Saccani et al. 2003). Since the Argolis ophiolites are tectonically dismembered and "reworked" in a prism, MOL-type blocks are juxtaposed with intraplate and SSZ-type blocks.

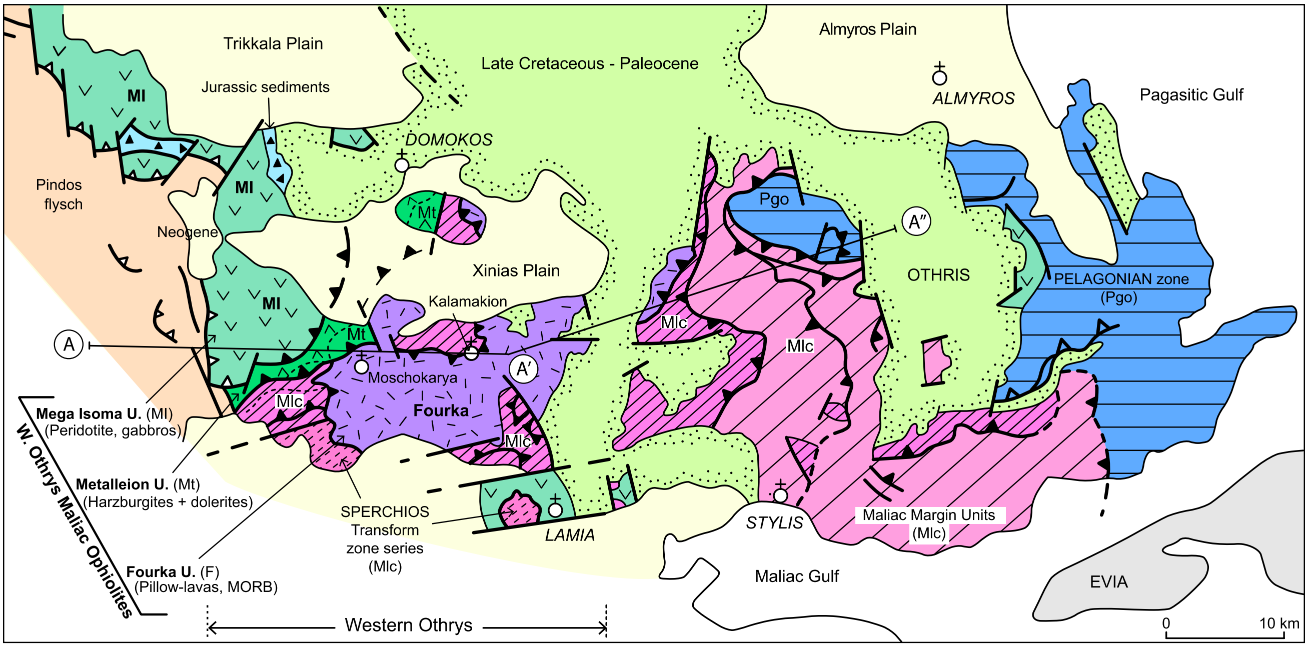

Fig. 2 Schematic geological *map* of Othris (modified from Ferriere 1982). AA′A″: location of cross section on Fig. 3. Mlc: Maliac margin series (*pink*); *closely spaced oblique lines*: distal margin; *spaced oblique lines*: proximal margin; *Light-green*: Cretaceous formations unconformably overlying the syn-obduction nappes; *light-yellow*: Neogene to quaternary deposits

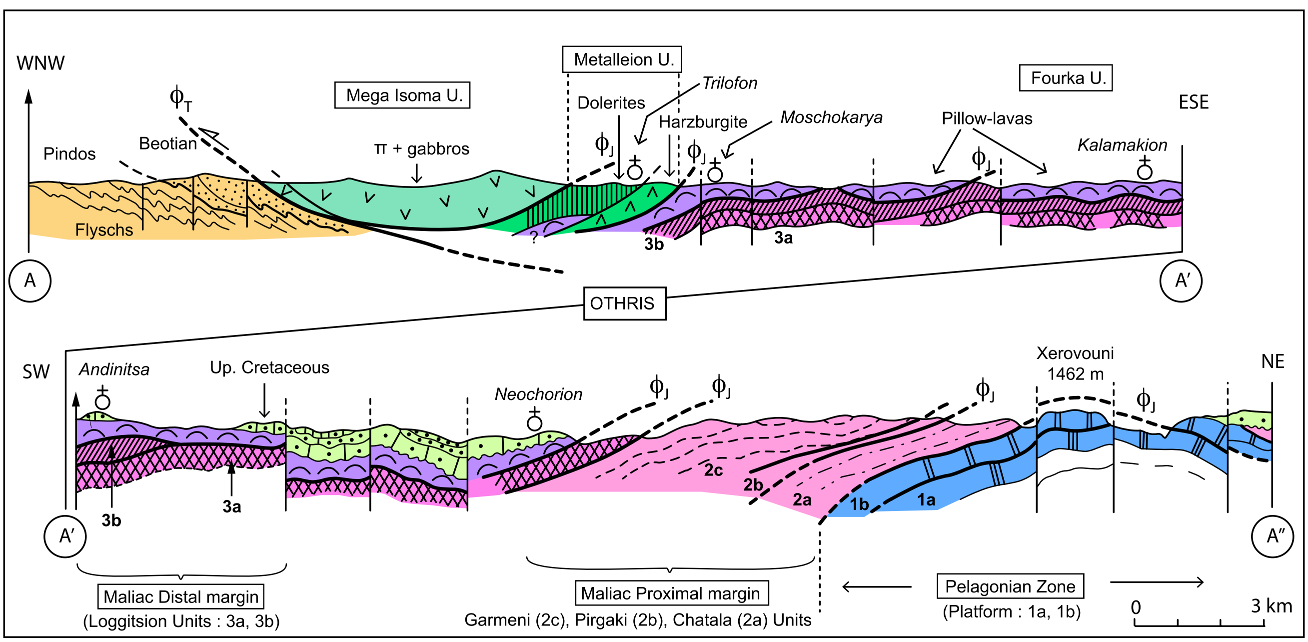

Fig. 3 Cross section AA′A″ across the Maliac syn-obduction tectonic units (location on Fig. 2). The *upper units* are the ophiolitic ones (Mega Isoma, Metalleion and Fourka). The *lower units*, above the Pelagonian series, correspond to the West Maliac margin. *The numbers* (*1a–3b*) refer to the different series appearing in Figs. 4 and 5

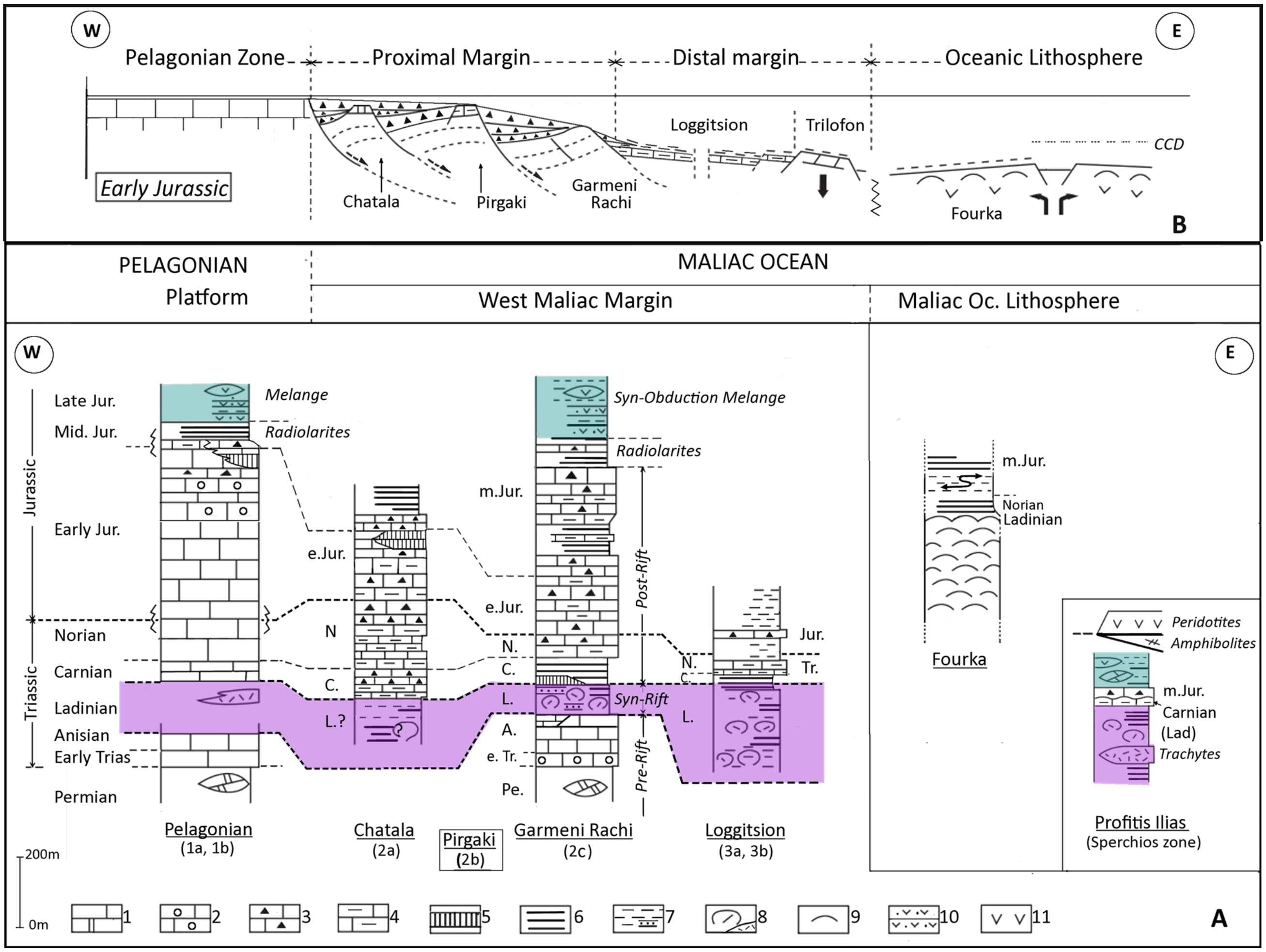

Fig. 4 *a* synthetic stratigraphic sections from the Othris area: W-Margin (*1a–3b*), Fourka (oceanic crust) and Sperchios transform zone (Profitis Ilias). *b* Interpretative cross section of the W-Margin during Early Jurassic times. (*1a*)–(*3b*) refer to the tectonic units (Fig. 3) and to reconstructed tectonic blocks in Fig. 5. *Violet*: Triassic rifting; *blue*: Jurassic syn-obduction formations. *1–5*: limestones. *1*: neritic (platform); *2*: oolitic; *3*: redeposited calcarenites; *4*: fine-grained and cherty; *5*: nodular; *6*: radiolarites; *7*: shales with few interbedded sandstones; *8* and *9*: Triassic lavas: *8*: pillow-lavas of the W-margin; *dashes*: tuffites (Pelagonian) or trachytes (Sperchios); *9*: pillow-lavas of the Fourka unit; *10*: graywackes; *11*: peridotites

- In Evia, small units of Late Triassic MORB pillow-lavas (Elias Complex) exist between some peridotitic nappes (Scherreiks et al. 2009). Due to their location and geochemical affinities, they can be ascribed to the Triassic MOL.
- In the central Almopias domain, there are some Late Triassic radiolarites in the Vrissi unit (Stais et al. 1990) which could cover MOR-type pillow-lavas (Sharp and Robertson 2006). These outcrops are of importance as they are the only Triassic pelagic sediments of the Almopias zone, but their belonging to the MOL or to the Maliac margins has to be established.
- In Albania, the Porava unit (Bortolotti et al. 2006) is very similar in nature, structural position, and age to the Fourka unit: (1) it is made of MOR-basalts; (2) this unit is located between the ophiolitic peridotitic units above and the margin units beneath.

The Jurassic Maliac pre-convergence Oceanic Lithosphere

Because of the continuous evolution of the Maliac margins during the Early Jurassic period, the MOL probably grew during this period. Surprisingly, no Liassic MOL is known.

Different hypotheses can explain this lack of dated Liassic ophiolites:

1. Outcrops of Liassic ophiolites does not exist because: (1) they disappeared in subduction zones, especially if the Mid-Jurassic subduction began at the mid-oceanic

ridge as it is often admitted (e.g., Barth et al. 2008; Moix et al. 2008); (2) Liassic sediments and crust were eroded and reworked in Middle—Late Jurassic mélanges (cf Fig. 4) or in younger flysch formations (e.g., Beotian flysch, Celet et al. 1976); (3) they have been transformed as metamorphic soles; (4) the spreading of the Maliac Ocean stopped at the end of the Late Triassic period, that is not supported by any sort of data.

2. Outcrops of Liassic ophiolites do exist, but they could not be clearly recognized for the following reasons:

   (a) Liassic radiolarian assemblages are almost never preserved, with one notable exception: the Mn-encrusted chert nodules of Angelokastron (N-Argolis), reworked in Mid-Late Jurassic orogenic sediments (Chiari et al. 2013). Baumgartner et al. (2015) give three arguments for the non-preservation of Liassic radiolarians: (1) low radiolarian productivity; (2) dilution by land-derived detrital input and (3) tectonic deformation and accelerated silica diagenesis of still unconsolidated clay-rich sediments during Middle-Late Jurassic emplacement.
   (b) Another possibility is that the Jurassic pre-convergence pillow-lavas of the MOL have been hidden by younger Mid-Jurassic SSZ-type lavas. Such a superposition is observed in the Aspropotamos unit of the N-Pindos ophiolites (Saccani and Photiades 2004) or in the Western belt of Albania (cf Bortolotti et al. 2002b, 2004) in which SSZ lavas and boninites are present above MORB lavas or, locally, alternate with them. Unfortunately, these MORB lavas are not well-dated. According to some recent works, all these lavas (MORB + SSZ) are thought to be born in SSZ areas (Dilek et al. 2008; see also Saccani et al. 2011).

The scarcity of Liassic radiolarites and the role of Middle Jurassic subduction processes seem to be the main processes leading to the lack of well-dated Liassic ophiolites.

Transform faults in the Maliac Ocean

On both sides of some transverse faulted zones (E–W to ENE–WSW), significant geological changes exist (e.g., across Sperchios, Kastaniotikos or Corinthos structures) (Fig. 1). As large peridotitic units are bounded by the transverse faults, the Sperchios zone has been compared to a transform zone (Aubouin and Dercourt 1975; Ferriere 1982).

The unconformity of the transgressive Cretaceous beds on these ENE–WSW faults of the Sperchios zone and the deposition of peculiar Triassic–Jurassic series along them prove that these faults were active during the spreading of the ocean (Ferriere 1982) and consequently support the hypothesis of an oceanic transform zone.

The Western pre-convergence Maliac Margin

The series of the Western Maliac margin (W-Margin) are well-exposed. They crop out as syn-obduction tectonic units between the ophiolitic nappes and the Pelagonian basement especially in Othris (Figs. 2, 3) and Argolis areas.

W-Margin type-series (Othris)

In Othris Mountains, the sedimentary series of the syn-obduction tectonic units allow to reconstruct the architecture of a complete passive margin. These nappes are regularly stacked from the most distal above (deeper margin) to the most proximal below. New dating with radiolarian assemblages allows us to precise the former descriptions (Ferriere 1974, 1982).

The proximal W-Margin

The Permian to Middle (Late?) Jurassic Chatala, Pirgaki and Garmeni Rachi series (Figs. 3, 4) represent the proximal W-margin.

Several pre-convergence formations can be distinguished (Figs. 4, 5):

1. Sandstone beds with lenses of Permian fusulinid-rich black limestones, covered by Early Triassic-Anisian neritic foraminifera-rich limestones;
2. Late Anisian-Ladinian volcanic and sedimentary formations: pillow-lavas, dolerites, tuffites, black shales, sandstones and few limestones (breccia) (rifting period);
3. Cherty limestones with Conodonts (Pirgaki Unit) or red radiolarites (Garmeni Unit) Carnian in age (early post-rift period);
4. Norian to Dogger cherty micritic limestones and calciturbidites showing major thickness variations (especially in Pirgaki Unit);
5. Red pelitic radiolarites dated as early-middle Bajocian (biozone UAZ 3 in Baumgartner et al. 1995) to late Bathonian-early Callovian (UAZ 7) in the Garmeni Unit (collaboration with Gingins and Schauner 2005).

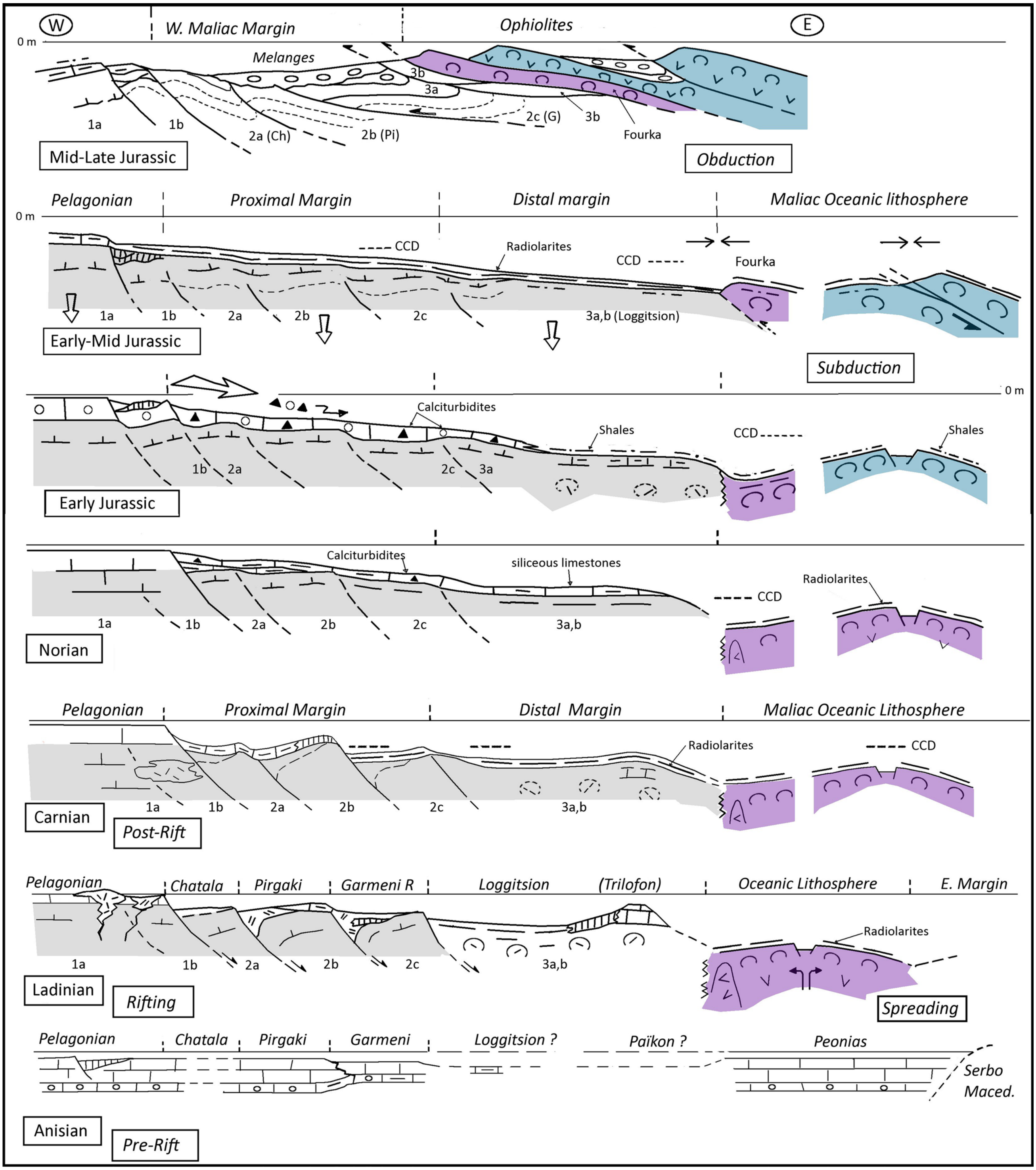

Fig. 5 Triassic–Jurassic evolution of the Western Maliac Oceanic Margin and Lithosphere from pre-rift to obduction times. The Rifting and the beginning of Spreading are shown together during Ladinian times. Oceanic lithosphere: Triassic Fourka pillow-lavas unit (*violet*); Jurassic main peridotitic-bearing ophiolitic units (*blue*)

Thick mélanges with blocks and olistolites coming from the syn-obduction nappes are often present at the top of the series (especially in the Pirgaki Unit).

The most proximal W-Maliac unit corresponds to the Chatala Unit, which marks the transition between the Pelagonian realm and the W-Margin. This unit is characterized by an abundance of calcarenites and calcirudites (Figs. 2, 3, 4).

The distal W-Margin (Loggitsion units)

These series of deep-sea deposits have no pre-Ladinian (pre-rift) sediments. The typical Loggitsion units show from bottom to top (Fig. 4):

1. A thick volcanic unit composed of OIB and MORB-type violet pillow-lavas and flows (Hynes 1974; Ferriere 1982; Lefèvre et al. 1993) and also a few back-arc basalts and Island Arc tholeïtes (Monjoie et al. 2008);
2. Carnian red radiolarites, locally Late Ladinian (near Neochorion, Central Othris, Fig. 3) just above the lavas;
3. Norian Conodont-rich cherty limestones;
4. Red-violet shales, locally very thick (c. 30 m) with rare fine-grained calcarenites.

Near Kalamakion (Figs. 3, 4), few meters of red thin-bedded radiolarites above the Norian limestones are Norian-Rhetian in age (collaboration Gingins and Schauner 2005). Consequently, the overlying red shales are probably Early Jurassic deposits.

In the westernmost Loggitsion series (Grammeni-Trilofon areas, 25 km west of Lamia, Fig. 2) the syn-rift thick Ladinian pillow-lavas are locally covered by blocks and small slivers of nodular red limestones or neritic white limestones Ladinian-Late Triassic in age (Courtin et al. 1981; Ferriere 1982). These limestones are the markers of local reliefs corresponding either to seamounts or to structural highs linked to the syn-rift tectonic events.

The Sperchios transverse structure

Distinctive series characterize the "Sperchios Transverse structure" said to be a transform zone because of the peridotitic units bounded by the ENE–WSW faults (Figs. 1, 2).

These pelagic series look like Loggitsion series but with some notable differences. Just west of Lamia (Profitis Ilias, Fig. 4), the series shows a gap between Carnian pelagic limestones and Middle Jurassic calcarenites covering pillow-lavas but also a thick trachytic formation (Ferriere 1982).

Other distinctive series with Triassic dolerites, shales, sandstones and radiolarites exist all along the Sperchios zone, especially west of Lamia (Fig. 2). They confirm that the Sperchios tectonic structure was an intra-oceanic active structure, most probably a Transform Zone, during the Middle Triassic-Middle Jurassic period. The lithological characteristics of these series (e.g., calcarenites, sandstones) show that this transform zone was located relatively close to the continental margin.

The W-Maliac margin and ophiolitic nappes of the Argolis Peninsula: another type-area

Maliac margin and ocean floor occurrences of the Argolis Peninsula

The outcrops of the Argolis Peninsula and Hydra Island (Peloponnesus, Fig. 1 and 6) represent a shortened but complete transect across the Pelagonian microcontinent. According to Baumgartner (1985) two Composite Units, composed of (1) Pelagonian sedimentary series, originally deposited on Variscan basement, and (2) syn-obduction Maliac nappes, can be distinguished. These Composite Nappes were probably superposed during Tertiary phases of nappe thrusting.

1. The external Adhami Composite Unit (Fig. 7) of the central Argolis Peninsula is composed of a Basal Pelagonian Sequence, and the Asklipion Nappe, which represents the Maliac W-margin.
   (a) The Middle Triassic-Upper Jurassic Basal Sequence was part of the Mesozoic Pelagonian continental domain. The shallow-water Pantokrator Limestone (Late Triassic–Early Jurassic) is overlain by an upward-deepening succession of Rosso Ammonitico facies (Early to Middle Jurassic) and radiolarian cherts (late Oxfordian–early Kimmeridgian, Baumgartner 1995). Finally, a limestone-chert deep-water breccia that includes interbedded layers of radiolarian chert of the same age documents the syn-tectonic erosion of the Asklipion Nappe and contains also few ophiolite detritus.
   (b) The Asklipion Unit and the Theokafta Sub-Unit represent the Maliac margin. Lime-free radiolarite facies and the oldest ophiolitic detritus are clearly older than in the Basal Pelagonian Sequence (Baumgartner 1985). These Units include acidic tuffites (Pietra verde facies) of early-Middle Triassic age, late Anisian–Liassic cherty limestones and Middle–Late Jurassic radiolarian cherts (early-middle Bajocian to late Bajocian for the base, and middle Callovian–early Oxfordian for the top). The cherts are overlain by ophiolite-derived turbidites grading upward into polymictic ophiolite breccias and olistostromes.
   (c) A remnant of the Migdhalitsa Ophiolitic Nappe overlies the Main Asklipion Unit near Koliaki.
   (d) Several Latest Jurassic to Late Cretaceous, shallow and deep-water series, the Mesoautochthonous Sequences (Vrielynck 1982, Baumgartner 1985) seal the Late Jurassic Nappe contacts.

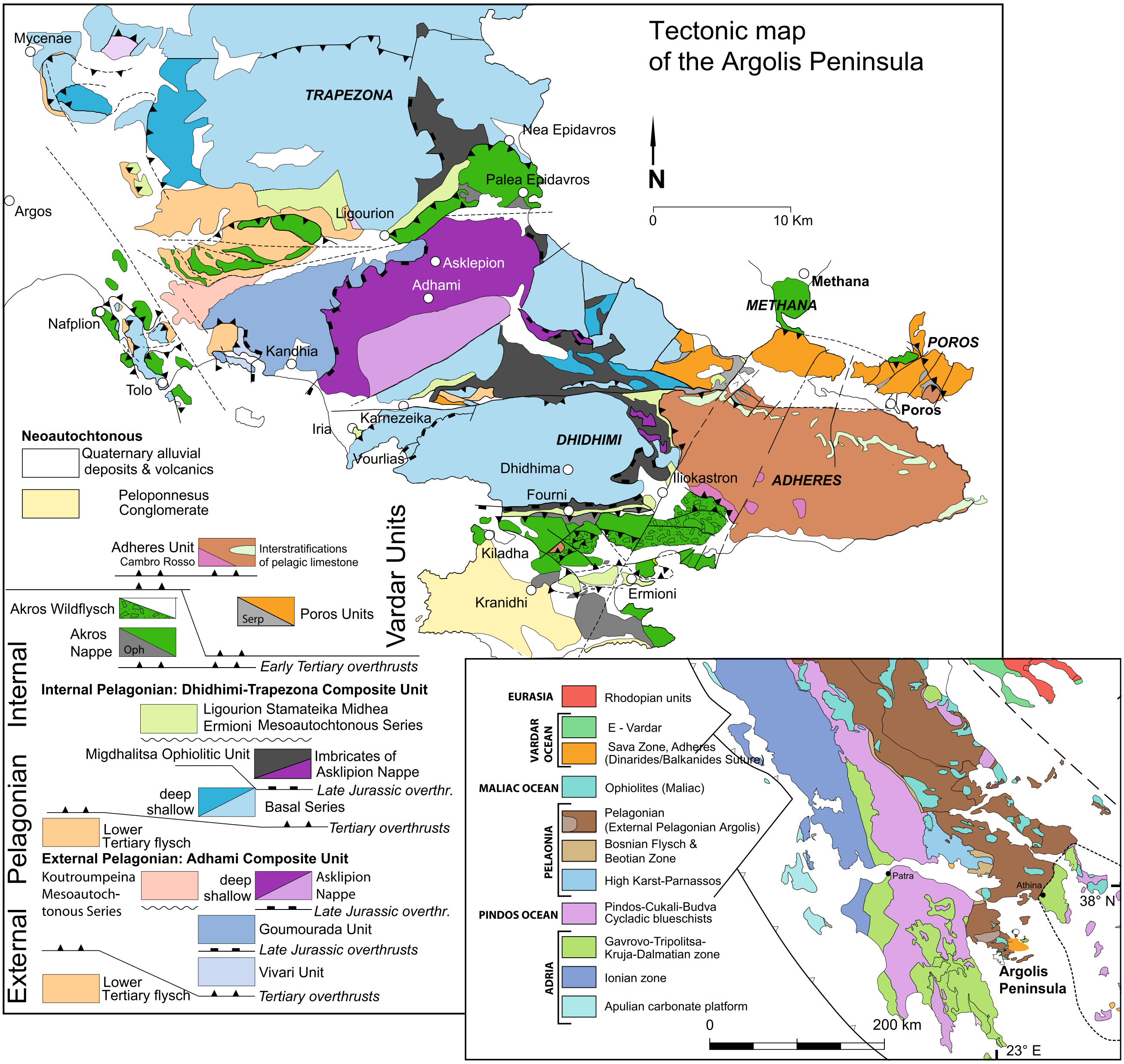

Fig. 6 Tectonic map of the Argolis Peninsula. The Tertiary external Pelagonian Adhami Composite Unit contains at its base a Jurassic nappe without ophiolitic material (Vivari Unit, see columns Fig. 7). Ophiolitic detritus increase E-wards in the Gourmourada Unit, which is overlain by the Asklipion Unit (Maliac W-margin), in turn overlain by an ophiolitic remnant (see Fig. 7). The Tertiary internal Pelagonian Dhidimi-Trapezona Composite Unit contains abundant ophiolitic detritus in its Basal Series (see Fig. 7). Jurassic nappes include imbricates of the Asklipion Unit (W-Maliac margin) and the Migdhalitsa Ophiolitic Unit (MOL and intraoceanic accretionary complex). The next higher Tertiary Pelagonian unit is the Akros Nappe composed of Ophiolitic basement (MOL and supra-subduction basalts) with a Cretaceous shallow-water cover (see Fig. 7). The highest Tertiary nappes in the Argolis, not detailed here, are the Poros and Adheres Units, associated with the Vardar realm. *Inset lower right*: Position of the Argolis Peninsula in the Southern Hellenides

2. The internal Dhidhimi—Trapezona Composite Unit (Fig. 7), occurring in the northern and southern Argolis, includes a Basal Pelagonian Sequence, tectonic slivers of the Asklipion Unit and the Migdhalitsa Ophiolitic Unit

(a) The drowning of the Pantokrator Limestone of the basal sequence began in the middle–late Liassic (Baumgartner 1985). It is documented in the southeastern Argolis by an expanded pelagic and turbiditic succession (Siniais Limestone, mid-

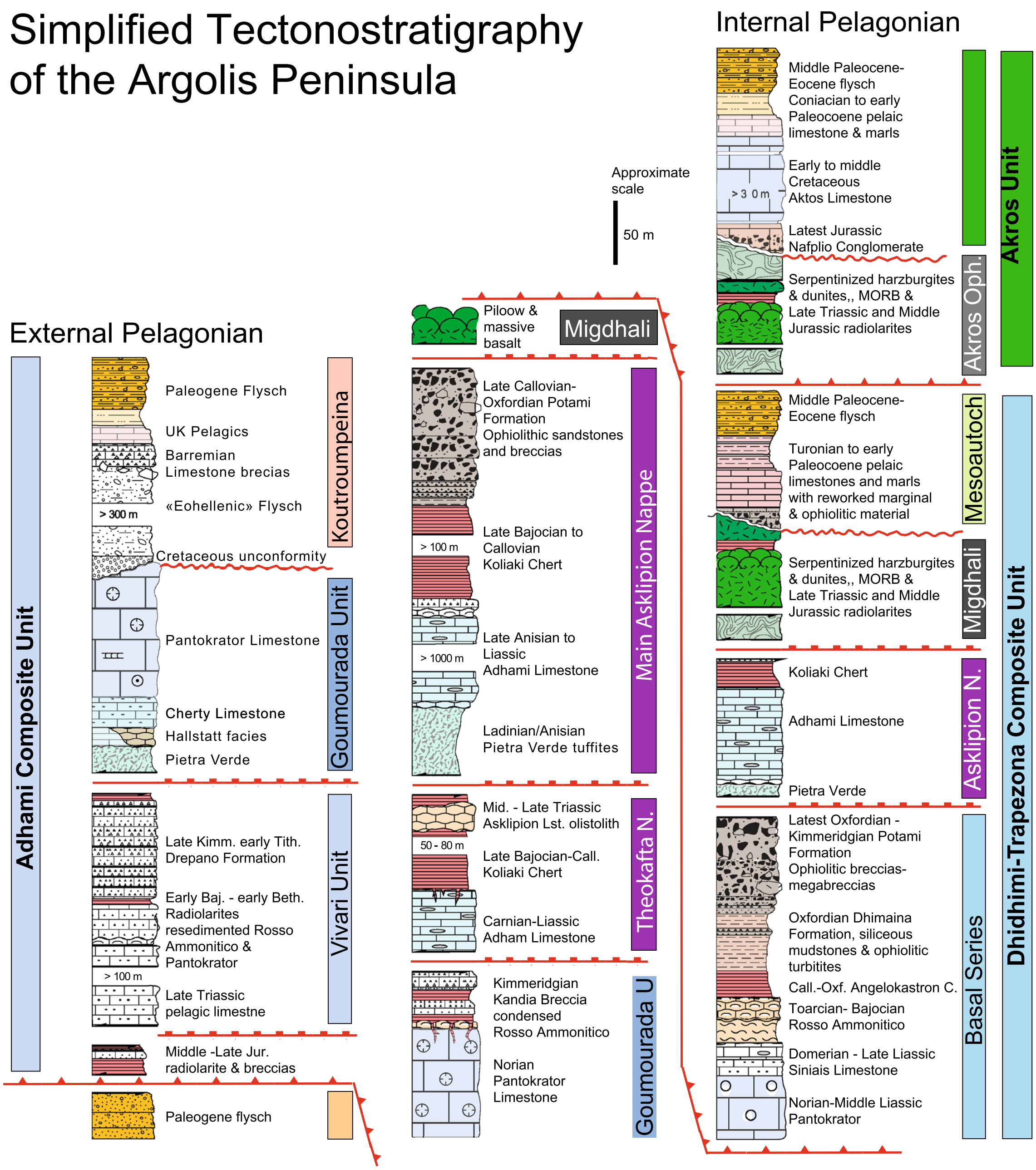

Fig. 7 Simplified tectonostratigraphic columns of the Argolis Peninsula. Jurassic thrust contacts are indicated by *rectangles*, Tertiary thrusts by *triangles*. For further explanation see caption of Fig. 6 and text

dle Liassic), then condensed pelagic limestones (Rosso Ammonitico, Toarcian to Middle Jurassic), overlain by late Middle–Upper Jurassic radiolarian cherts (Angelokastron Chert; base: middle Callovian–early Oxfordian, top: middle–late Oxfordian, Baumgartner 1995). The radiolarian cherts grade up-section into siliceous mudstones interbedded with upward-coarsening and thickening ophiolitic sandstones (Dhimaina Fm; base: middle–late Oxfordian, top: late Oxfordian–early Kimmeridgian, Baumgartner 1995) documenting the initial obduction and erosion of ophiolites.

(b) Slivers of the Asklipion Unit overlie the Basal Sequence and consist of Adhami Limestone and tectonically reduced Koliaki Chert.

(c) The Migdhalitsa Ophiolitic Unit consists of internally folded thrust sheets of MOR-basalts (transitional-type MORB and normal-type MORB, Saccani et al. 2004) with associated radiolarian cherts. Serpentinite slivers occur locally along the base of the thrust sheets. 10–100 m-sized bodies of cumulate gabbros occur locally, but no ophiolite stratigraphy is preserved. The radiolarian cherts yielded well-preserved radiolarian faunas that indicate two groups of ages: Middle and Late Triassic, exceptionally Early Jurassic (Bortolotti, et al. 2002a; Chiari et al. 2013)

Initially, a Middle Jurassic age recovered from the center of the Migdhalitsa Unit was interpreted as the age of ocean floor formation (Baumgartner 1985). However, the late Bajocan-early Bathonian (UAZ 4–5, Baumgartner 1995) radiolarians were recovered from siliceous shales and graded basaltic silt/sandstones, which in turn are related to ophiolitic breccias that form elongated bodies within the Migdhalitsa Unit (Baumgartner 1985). In addition, >10 m-sized blocks of massive carbonates occasionally occur like “exotic blocks” within the Migdhalitsa Unit. These observations indicate that the Migdhalitsa Unit could represent an obducted intraoceanic accretionary prism of Middle Jurassic age that predominantly is composed of Middle to Late Triassic MOR-type Maliac Ocean floor, but also received polymict “trench-fill” breccias including platform-derived olistoliths that were incorporated when the prism approached the Maliac W-margin.

Other W-Margin series

Beside the series of the Othris and Argolis areas, some other series, in part metamorphic, can be considered as W-Margin series because of their facies and their location between the ophiolitic nappes and the Pelagonian autochthonous basement.

The non-metamorphic series are those of: (1) Troupi, west of Prokopi, in Evia (Ferriere et al. 1988); (2) some klippen in the northern part of the Parnassus Zone rich in red Triassic and Jurassic radiolarites.

Among the metamorphic series which evoke the W-margin series, there are the followings:

1. The pelagic series of the Pagasitic units of the Pelion area (Fig. 1). They are constituted of siliceous platy marbles, locally bearing Conodonts, covered by micaceous schists with ophiolitic blocks in its upper part (Ferriere 1976b, 1982);
2. Some units (Eohellenic series) known in the Sporades Islands especially Skyros Island (Jacobshagen and Matarangas 1989);
3. The Infra-Pierian neritic to pelagic metasedimentary units, often covered by ophiolitic nappes, around the Olympos mountains (Fig. 1) have been attributed to the Maliac series (Schmitt 1983). Unlike to the other W-Margin series, these units seem to occupy locally, an Infra-Pelagonian structural position, but this present geometry could be the result of the Tertiary tectonic events.

Overview of the Western Margin of the Maliac Ocean

The W-Margin of the Maliac Ocean is clearly a Passive Rifted Margin from Middle Triassic to earliest Middle Jurassic times. The series observed in Othris testify for the distinction of two different domains: (1) a proximal margin with pre-rift sedimentary formations; (2) a distal deep margin (>2000 m water-depth) characterized by an important mafic syn-rift volcanism.

The various W-Margin series observed in the Hellenides reflect a similar pre-convergence geodynamic evolution, with three distinctive periods (Figs. 4, 5, 6 and 7):

1. Pre-Anisian pp represented by the pre-rift series with shallow facies (especially the Early Triassic-Anisian pp carbonate platform, well-represented in the whole Tethyan domain);
2. Anisian pp-Ladinian pp, the syn-rift period, characterized by volcanism and various detrital and pelagic sediments indicating a deepening (subsidence) of the basin. The coexistence of presumed subduction-related and no subduction-related lavas is differently interpreted (cf infra, “Characteristics and evolution of the Maliac Ocean: discussion” section).
3. Post-Ladinian, the post-rift period, mainly represented by calcareous deposits on the proximal margin (pelagic cherty limestones of Pirgaki unit with Carnian radiolarites within the Garmeni Unit, evolving to prograding detrital calcarenites) and siliceous deposits on the distal margin (Carnian radiolarites and Liassic (?) shales separated by Norian cherty limestones).

The pre-convergence Eastern Maliac Margin

The accurate description of the Eastern Maliac Margin (E-Margin) is naturally closely related to interpretation on the original location of the Maliac Ocean.

According to our work (e.g., Ferrière et al. 2012) this-Ocean was located on the eastern side of the Pelagonian Zone. Consequently, the E-Margin series have to be searched in the eastern Vardarian domain; such series exist in the Peonias and Paikon zones (Figs. 1, 8).

The Nea Santa series: remnants of a proximal margin

Three successive sedimentary formations can be distinguished in the Nea Santa series observed in the Peonias Zone (Ferriere and Stais 1995) (Fig. 8):

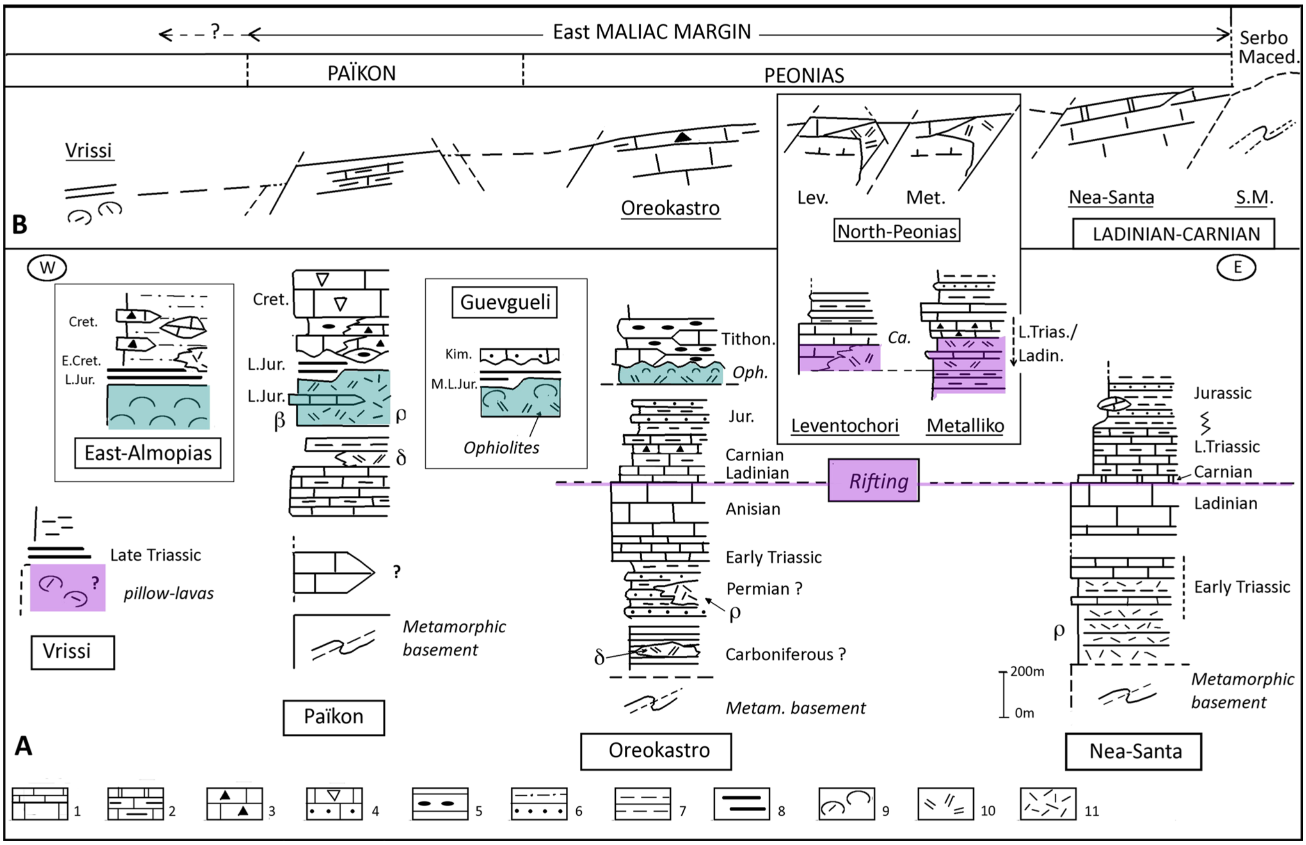

Fig. 8 The Eastern Maliac Margin. *a* Peonias and Paikon logs. The meaning of the Vrissi (E-Margin or Maliac Ocean?) and East-Almopias (syn or post-obduction oceanic crust?) logs are not well-known. *b* paleogeographic interpretation of the E-Margin during Triassic (Ladinian-Carnian) times. Magmatic events: *Violet*: Triassic; *Blue*: Jurassic; *E*: early, *M*: Middle, *L*: Late; *Ca*: Carnian; *Kim*: Kimmeridgian; Cret: Cretaceous; Jur: Jurassic. *1–4*: limestones. *1*: neritic massive (*down*) and platy (*up*) beds; *2*: fine-grained cherty and/or clayey (*down*) or nodular (up); *3*: redeposited (calcarenites); *4*: Cretaceous sandy beds (*down*) or with rudists (*up*); *5*: conglomerates; *6*: sandstones and shales (cf flysch); 7: shales and/or marls; 8: radiolarites; *9*: pillow-lavas; *10*: mafic rocks; *11*: rhyolites

1. Sandstones with rhyolitic layers, on the western side of the Serbo-Macedonian continent made of gneiss and micaschists. A limestone bed interbedded within this formation has been dated as early Triassic;
2. A thick Early Triassic to Ladinian calcareous platform. The Anisian period has not been evidenced so far;
3. A Late Triassic detrital calcareous formation grading upsection into more detrital sandstones (Melissochori flysch) of probable Jurassic age. This formation was considered Paleozoic in age according to Mercier (1968), then defined as the Svoula Formation of Mesozoic age (Kauffmann et al. 1976). A late Ladinian-Carnian nodular limestone with ammonites and Orthoceras (Hallstatt Facies) is observed at the lower boundary of this formation (Kockel 1979; Stais and Ferriere 1991).

The Oreokastro series: marker of an intermediate margin

This series, the most complete, shows a large variety of sedimentary formations. The discovery of many new paleontological data (Foraminifera and Conodonts) has allowed us to demonstrate that the series is overturned (Ferriere and Stais 1995), thus modifying the earlier interpretation of Mercier (1968).

We can observe from stratigraphic bottom to top (from east to west), above the metamorphic basement mainly made of gneiss, the following succession (Fig. 8):

1. Black siliceous beds with dolerites and red sandstones with rhyolites, respectively, considered to be Carboniferous and Permian in age by comparison with other Hellenic series;

2. Early Triassic to Anisian massive neritic limestones similar to those observed in Othris;
3. Calcarenites and marls bearing Ladinian-Late Triassic Conodonts. Olistolites of Anisian limestones locally exist.
4. A fine-grained detrital formation of shales and few sandstones probably Jurassic in age. A massive limestone bed bearing foraminifera and ammonite embryos has been attributed to the Late Triassic-Early Jurassic. The absence of Conodonts supports also a Jurassic age.

The E-Margin Triassic volcanism

Two small units (Leventochori and Metalliko) located north of the Nea Santa unit show outcrops of dolerites intercalated between sediments containing Middle-Late Triassic foraminifera (Stais and Ferriere 1991; Asvesta and Dimitriadis 1992; Ferriere and Stais 1995) (Fig. 8).

The Paikon series: the distal E-margin?

It is likely that the Paikon series are part of the E-Maliac Margin, if we take into account that the Paikon and Peonias domains were separated by the opening of the Mid-Late Jurassic Guevgueli backarc basin (Mercier et al. 1975; Saccani et al. 2008b).

The deepening of depositional environments from east (Nea Santa) to west (Oreokastro), strongly supports the interpretation of the Paikon series as being the most distal observable part of the E-Maliac Margin.

The precise sedimentological and stratigraphic analysis is unfortunately not feasible to the extent that the sedimentary formations older than the Middle-Late Jurassic are metamorphosed. However, most of these metasediments are very consistent with metamorphosed pelagic facies (e.g., violet siliceous thin-bedded marbles) that is supporting a distal domain.

Overview of the pre-convergence Eastern Margin of the Maliac Ocean

The location (eastern Vardar) and the facies distribution of the Peonias and Paikon series lead to interpret them as the Eastern Margin of the Maliac Ocean, which was deepening from east to west (Fig. 9). This hypothesis is reinforced by the fact that the geodynamic evolution of this area is very similar to this of the opposite western margin:

1. The age (Ladinian, locally Carnian) of the rifting events (deepening and volcanism) is the same on both conjugate Margins;
2. The facies of both margins are very similar: Permian sandstones and rhyolites; Early Triassic-Anisian neritic limestones; locally Triassic Hallstatt-type facies. However, Jurassic facies are different. This can be due to the differences in nature of the detrital input coming from the adjacent continental margins: quartzofeldspathic terrigenous input from the Serbo-Macedonian metamorphic basement to the east, calcareous lithoclasts and ooliths from the Pelagonian platform to the west.

Characteristics and evolution of the Maliac Ocean: discussion

Definition of the Maliac Ocean

The exposed data lead to reconstruct a major Ocean, part of the Tethyan domain, that lasted for about 70 My from the Middle Triassic to the Middle Jurassic, the "Maliac Ocean" (Fig. 10).

The studied outcrops correspond to the Maliac Oceanic Lithosphere (MOL, especially the Triassic one) and to the two conjugate margins, the W-Margin (mainly in Othris and Argolis areas) and the E-margin (in the Peonias and Paikon areas).

The name "Maliac Ocean" has been previously proposed (Ferriere 1976a, 1982) on the basis of the western part of this ocean (W-margin and MOL). We propose to use this name to design the whole Ocean, including its E-Margin.

The Middle Triassic times (c. 245–235 Ma): the rifting events

The rifting period is characterized on the margins by sedimentary and volcanic events. The associated tectonic structures are not well identified but are mainly deduced from units distribution.

Concerning the sedimentation, the rifting period is attested by the input of new sediments indicating a tectonic activity (detrital and brecciated facies), the genesis of a new basin (black shale sediments) and the deepening of the sedimentation area (Ladinian or Carnian pelagic facies on top of Anisian platform limestones).

These sediments lead to attribute a Ladinian age to the Rifting events (c. 242–235 Ma). However, some data, in Argolis (the Mid-Triassic age of the volcanism) and in Othris (the reduced thickness of the Early Triassic–Anisian neritic calcareous formation on the deeper proximal W-margin), indicate that the rifting could have began slightly before, as early as the Late Anisian times (c. 245 Ma).

The syn-rift volcanism shows a great diversity on the Maliac margins, even within the same margin, and the distinction between convergent (Paleotethys subduction

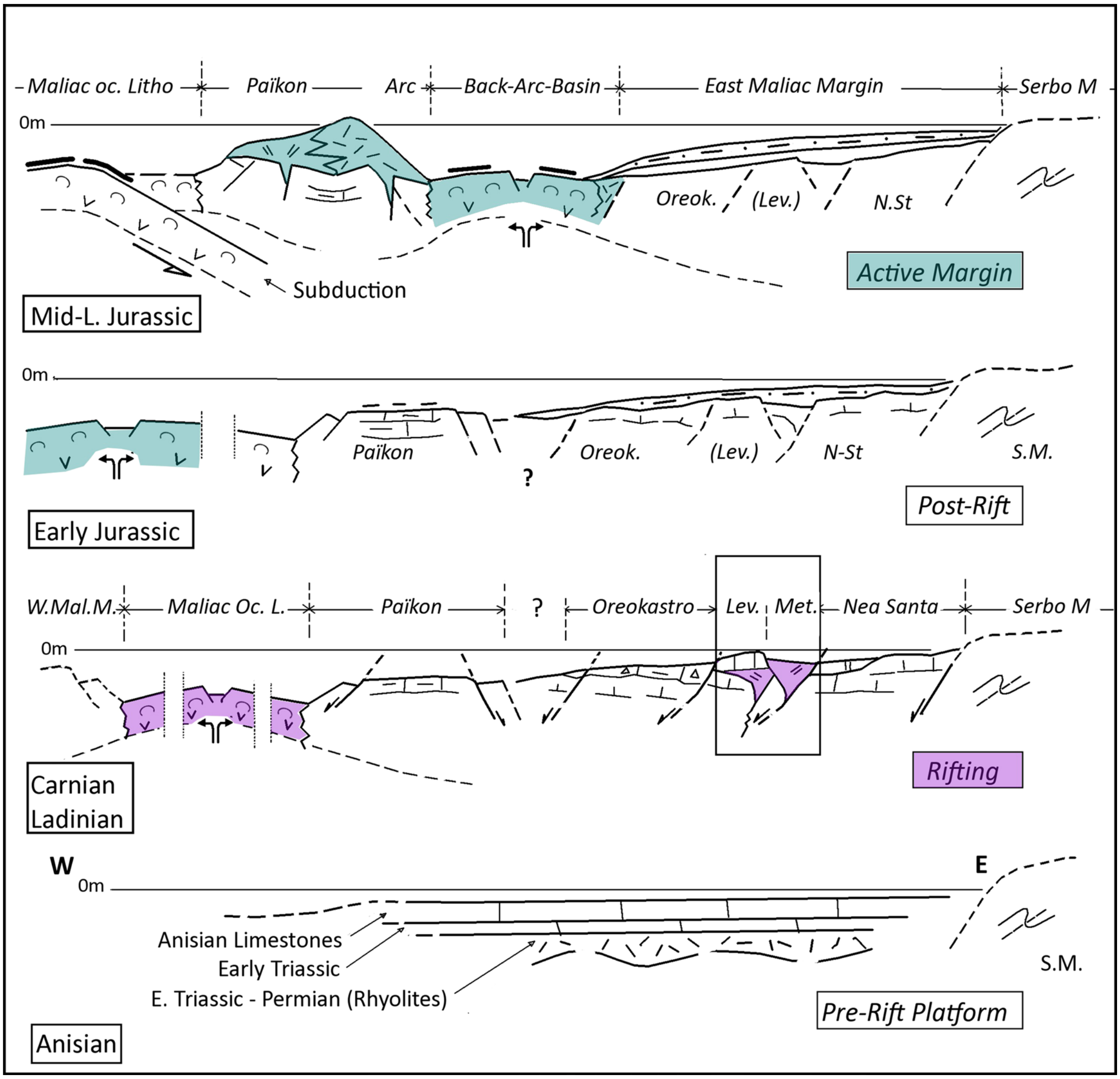

Fig. 9 Triassic–Jurassic evolution of the Eastern Maliac margin from pre-rift to subduction-times. *Lev* Leventochori, *Met* Metalliko units, *S.M.* and *Serbo-M* Serbo-Macedonian area. Magmatic events: *Violet* Triassic, *Blue* Jurassic

related) and extensional (rifting related) volcanism is not very clear: e.g., acidic volcanics and tuffites in Argolis, mafic pillow-lavas and alkaline trachytes in Othris.

If some types of syn-rift volcanism, such as MORB and OIB-type lavas observed on the W-Margin, can be explained by an extensional tectonic period linked to a regional divergence setting, many others, in the Hellenides (e.g., Argolis Peninsula, Vardoussia or Pindos series) testify for a convergent setting implying subduction zones in the Paleotethys at that time (Stampfli and Borel 2002; Stampfli and Kozur 2006). Some authors have shown that seemingly subduction-related rocks were generated during continental rift tectonics (Pe-Piper 1998) and that mantle heterogeneities could explain such affinities (Saccani et al. 2015).

As syn-rift Triassic OIB and MORB lavas exist on the margins, they can be confused with lavas of the triassic Maliac Oceanic Lithosphere (MOL), especially in places where they appear as blocks in Jurassic mélanges. For this reason, we prefer to define the MOL based on major units, such as the Fourka unit.

The development of syn-rift deep basins implies tectonic events especially normal faulting. These faults can also explain:

1. The development of the tectonic contacts at the lower boundary of the syn-obduction sedimentary nappes by tectonic inversion (from extensional to compressional tectonics);

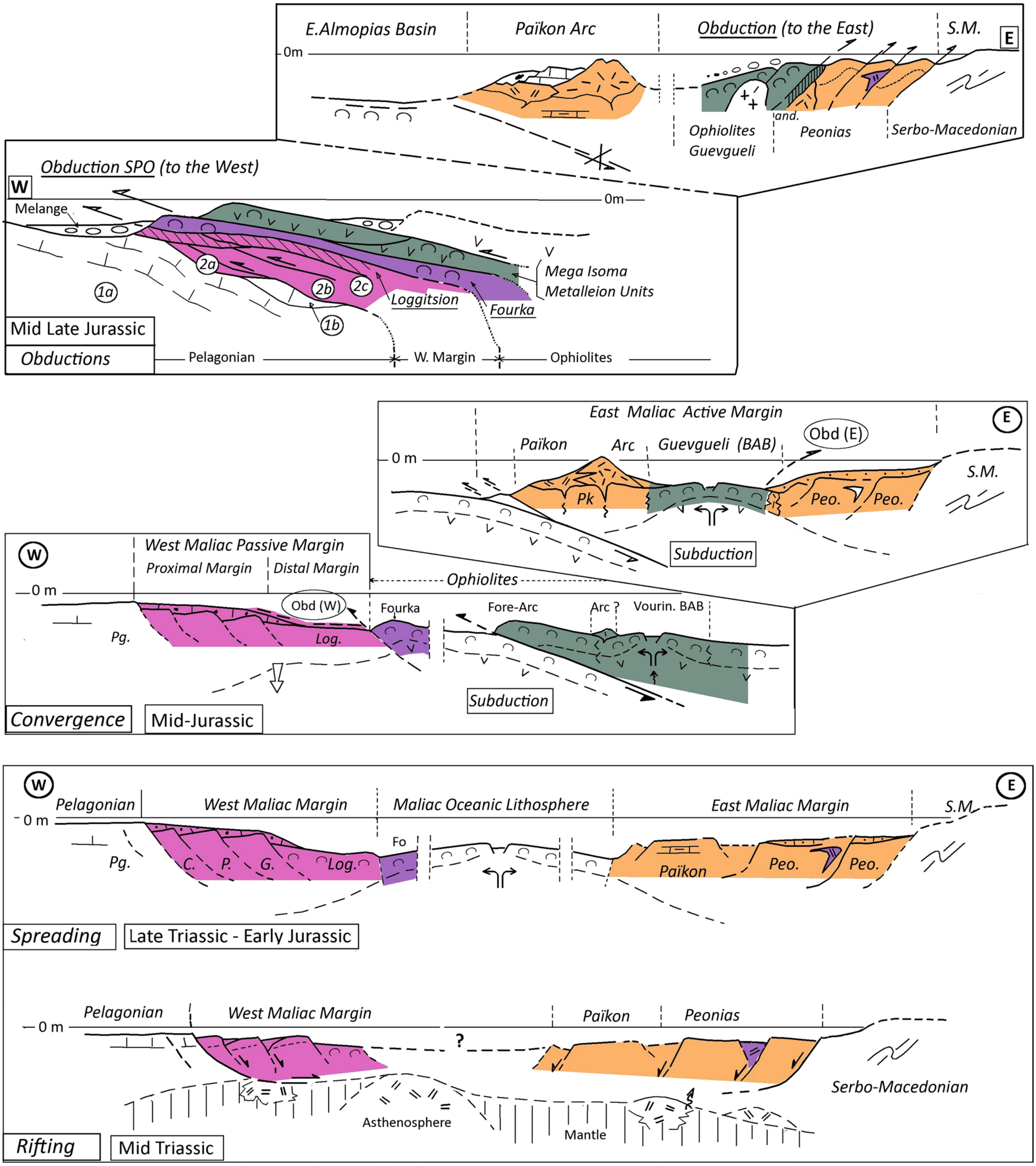

Fig. 10 Geodynamic evolution of the Maliac Ocean. *Abbreviations*: W-Margin: *C* Chatala, *P* Pirgaki, *G* Garmeni Rachi, and *Log* Loggitsion; *Fo* Fourka, *Peo* Peonias, *Pg* Pelagonian, *SM* Serbo-Macedonian area, *BAB* Back-arc Basalts, *Obd* obduction. Margins: *pink* W-Maliac, *orange* E-Maliac. Oceanic lithosphere: *violet* (Triassic Fourka unit) and *green* (Mid-Late Jurassic ophiolites, mainly of SSZ-type). Units *1a–2c* refer to Figs. 2, 3 and 4

2. The apparently abrupt boundary between the proximal and distal margins (W-Margin);
3. The variable thickness of some sedimentary syn- or post-rift formations due to bathymetric variations linked to the reliefs of faulted crustal blocks, especially on the proximal W-margin.

The apparent larger volume of volcanic products on the W-Margin as compared to the E-Margin could be of tectonic origin, e.g., a dissymmetric extensional detachment fault cutting through the crust or deeper in the mantle as in the Wernicke's model (1985).

Characteristics of the W- and E-margins at the end of the Mid-Triassic Rifting

Our results show that the series described above (W- and E-Maliac) correspond to the conjugate margins of a single ocean, the Maliac Ocean. We evidence notably that the rifting evolution is synchronous on both margins, mainly Ladinian in age (Ferriere and Stais 1995).

The distinction between a proximal and a distal margin has only been clearly established in Othris, where the syn-obduction nappes are well-exposed. Loggitsion-like series (distal margin in Othris) seem to be unknown in other regions including Albania. The Sperchios Transform zone is also well evidenced since the Rifting period (e.g., abundant trachytes and dolerites) in this area.

The development on both margins of syn-rift volcanism, sometimes with large volumes as in the W-Margin, lead to question their type: are they "Volcanic Rifted Margin (VRM)" or "Non-Volcanic Rifted margin?

The VRM are mainly defined on present oceanic margins, especially with Seaward Deeping Reflectors (SDR). Among other characteristics are the huge magmatic formations, dykes cutting the margin, the short duration of volcanism and the presence of listric faults dipping toward the continent (cf Geoffroy 2005).

The available data on both Maliac Ocean margins do not allow to consider these margins as VRM. For instance, the syn-rift volcanism is widespread, but its volume is much smaller than those described of true VRM and very few dykes can be observed across the W-margin series. The distinction between the distal deeper part of a VRM and a true oceanic lithosphere is not easy to do on current oceanic margins. This problem has been discussed for the Fourka unit that we have interpreted as representing the upper part of a true Triassic oceanic lithosphere and not as a VRM (cf supra).

Some other characters as the absence of peridotitic bodies corresponding to serpentinized continental mantle lithosphere and the existence of large volumes of syn-rift lavas on the W-Margin lead to conclude that the Maliac margins are not real "non-volcanic rifted margins".

Rifted Tethyan margins have been named "intermediate" by Robertson (2007). This is a possibility for the Maliac margins. Another possibility would be to name them "mild volcanic margin" as this term refers to its volcanic character as for the main types.

The first half of the post-rift period: the Mid(pp)-Late Triassic times (ca. 40 My in duration; 240–235 to 200 Ma)

This is the best known period, since good outcrops and datings provide insights to the margin series and to the MOL. The only important tectonic activities are that of the Mid-Oceanic Ridge (MOR), and of the transform zones such as the Sperchios.

The beginning of the post-rift stage corresponds to the end of the syn-rift normal faulting activity, and to the start of formation of oceanic lithosphere at a spreading center to where the extension is transferred.

The oldest MOL would be Late Anisian-Early Ladinian in age. This age is very close to that of the rifting period defined by the volcanism and the main sedimentary changes discussed above, even if local observations indicate that the rifting could have began earlier. Anyway, our data show that: (1) the rifting period is particularly efficient during a relatively short period around late Anisian-Ladinian p.p. times; (2) the beginning of the post-rift period has to be in Ladinian times.

There is no marginal Late Triassic volcanism in the W-Margin (in Othris and Argolis series) and probably none in the E-margin. The only volcanism of this post-rift period is the OIB and MORB pillow-lavas flowing from the mid-oceanic ridge of the Maliac Ocean (Fourka unit).

As for most of the oceanic areas, the Ladinian syn-rift tectonic subsidence is followed by a Late Triassic thermal subsidence both on the margins and the MOL.

The sedimentary record of this thermal subsidence is not always clear. For instance, in the distal W-Margin, Carnian radiolarites are covered by Norian cherty limestones (Fig. 4). A deepening of the CCD during the Norian times could be considered but this phenomenon would be limited, as the Norian deposits on the MOL are radiolarites.

More likely, in addition to subsidence, this record may indicate that after a relative starvation of adjacent Pelagonian carbonate platforms during the Carnian, these carbonate platforms prograded largely over earlier pelagic domains during the Norian. Hence they produce again more peri-platform ooze that reaches the distal margin.

The ENE–WSW faults of the Sperchios zone were probably active during the Late Triassic as indicated by the specific series (e.g., sedimentary gaps, Fig. 4) all along the zone.

The second half of the post-rift period: the Early Jurassic (ca. 30 My in duration; 200–170 Ma)

The Early Jurassic data concerning the Maliac Ocean are more sparse than those of Triassic age. The margin series exist but good datings are scarce. The evolution of the margins is in agreement with a continuous development of the MOL at a spreading center, but Liassic MOL is so far undated.

The sedimentation became more detrital during the Liassic period. The lithology of the Liassic detrital sediments (proximal W-Margin: calcarenites; E-margin: sandstones and marls) is linked to the characteristics of both continental edges: the Pelagonian platform on the West, the metamorphic Serbo-Macedonian zone on the East.

On the distal W-margin (Loggitsion Units) the Liassic deposits are only red siliceous shales with few fine-grained calciturbidites. These tectonically incompetent and poorly-dated sediments are not easily recognized elsewhere.

In addition, no ophiolitic pillow-lavas have been dated as Liassic, even in the Fourka unit, but one series could testify for the Liassic development of the MOL. This series (N-Moschokarya, Figs. 2, 4) developed on Triassic pillow-lavas of the Fourka unit, shows red shales similar to those of the Loggitsion unit between Late Triassic and Mid-Jurassic radiolarites.

During this period, the thermal subsidence causes the deepening of the MOL and of the margins: the distal W-margin (Loggitsion) and the MOL are clearly below the CCD. This could be the consequence of a general starvation of the carbonate platforms on the adjacent margins and the scarcity of carbonate plankton at that time.

Moreover, the Pelagonian platform on the west progressively drowned, documented by the change from shallow carbonate platforms to deeper water resedimented carbonates, and Rosso Ammonitico facies especially in Argolis area.

The Maliac Ocean at the end of the divergence period

The development of a convergence setting in Middle Jurassic times in the Hellenides is known for a long time and corresponds with the better understanding of subduction and obduction processes.

The markers of the subduction processes are the lavas proven to have erupted in Supra-Subduction Zones (SSZ). The oldest ones in Greece, dated by Radiolaria stratigraphically resting on top of the lavas of the Vourinos ophiolites, are late Bajocian in age (ca. 169 Ma; Chiari et al. 2003). The datings (U-Pb zircons) of the magmatic rocks of the Vourinos and N-Pindos ophiolites are close to these paleontological ages: 173–168 Ma with a mean of 171 Ma (Liati et al. 2004).

Late Bajocian-early Bathonian radiolarian ages in the Migdhalitsa Ophiolitic Unit of the Central Argolis Peninsula (Baumgartner 1985) are now interpreted as syn-accretion sediment deposited on an intraoceanic accretionary prism.

The markers of the age of the obduction processes are: (1) the age of the sediments below and above the ophiolitic nappes; (2) the age of mélanges with ophiolitic blocks coming from the ophiolitic nappes; (3) the radiometric analyses of the metamorphic soles (eg amphibolites) developed below the ophiolitic nappes during their tectonic emplacement.

The metamorphic soles dated in N-Pindos, Vourinos and Othris give ages in the range of 171–165 Ma (mean 169 Ma) (Spray and Roddick 1980; Spray et al. 1984) and for the Koziakas (K-Ar) of 171±3 and 161±1 Ma (Pomonis et al. 2004).

With regard to the sediments, the revision of previous data by Baumgartner and Bernoulli (2015) gives the following results:

1. On the W-Maliac margin, in the Argolis Peninsula, the first ophiolite detritus (chrome spinels in the Koliaki Chert of the Asklipion Unit) is recorded in UAZ 8, Middle Callovian-Early Oxfordian (i.e., ca. 165–160 Ma);
2. On the Pelagonian margin the so far oldest ophiolite detritus is dated in the island of Hydra (S of the Argolis Peninsula) as UAZ 4–6, Late Bajocian—Early Callovian; i.e., ca. 169–166 Ma (Baumgartner et al. 1993).

Even if the age determinations are based on different methods (radiometric and paleontological analyses), all the ages indicate that the convergence setting was settled since the Bajocian times (c. 170–168 Ma) and probably a little bit before as the datings concern advanced processes.

Taking into account a spreading duration of ca. 65 Ma (235–170 Ma) and a small spreading rate of 2 cm/yr, the Maliac Ocean was at least about 1300 km wide and about 4500–5000 m deep (water-depth resulting from thermal subsidence). This is in good agreement with most plate reconstructions (Stampfli and Borel 2002; Stampfli and Kozur 2006; Bonev and Stampfli 2008).

At the beginning of the Mid-Jurassic period, a new radiolaritic episode is observed on both of the margins and on the MOL. The datings show that this event develops at the beginning of the convergence period and so that it could be the result of a subsidence linked to these processes. However, some authors have recently emphasized the fact that the external environments (fertility, monsoon) could be the main factor to explain the development of Tethyan radiolarites during the Mesozoic times (Baumgartner 2013; De Wever et al. 2014; Baumgartner et al. 2015).

If similar features characterize the Maliac Ocean all along the Hellenides in Greece and Albania (more than 600 km-long) some differences are notable, such as the amount of Triassic syn-rift volcanism or the volume of submarine Jurassic detrital sediments. Moreover, some E–W Transform zones as the Sperchios one, must have existed in this Ocean.

Evolution of the Maliac Ocean during the convergence period

Evolution of the Maliac Oceanic Lithosphere

Except for the Triassic Fourka pillow-lavas, the main ophiolitic bodies are Middle (Late?) Jurassic in age and therefore belong to the convergence period (e.g., Vourinos, W-Othris and probably N-Pindos).

Liassic ophiolites were so far never recognized in the Hellenides. Consequently, two possibilities have been discussed (cf supra "The pre-convergence Maliac Oceanic Lithosphere" section): (1) such Liassic ophiolites have not been recognized due to the fact that siliceous shales deposited during this period have poor radiolarian preservation, or Liassic lavas are hidden by younger lavas, or (2) they do not exist anymore due to subduction or erosion. It appears that, if they currently exist on present-day exposures, they are necessarily very rare.

If a single subduction affected the Maliac Ocean (below the E-Margin, then evolving by slab roll-back), the Maliac initial mid-oceanic ridge could have been active during the beginning of the convergence setting. However, many authors consider that a subduction originated at the mid-oceanic ridge (e.g., Barth et al. 2008; Moix et al. 2008; Saccani et al. 2011).

Evolution of the Maliac passive margins

Unlike to the pre-Mid-Jurassic MOL, the W- and E-Margins, despite their development on thinned easily subductable continental crust, are well represented from outcrops. Moreover, many sedimentary series of the Pelagonian Zone that were affected by ophiolite obduction show almost no metamorphism.

The W-Margin has been obducted according to a regular stacking: a deeper part of the margin is always thrust on top of a shallower one (Fig. 3). These tectonic units have been eroded or deformed during the Tertiary events but some of them are particularly well preserved in Othris and Argolis areas.

The E-margin has been much more modified than the W-margin, as it has been:

1. Separated in two parts by the later opening of Guevgueli Mid-Late Jurassic back-arc basin: the Paikon area with a volcanic arc to the west, the Peonias zone to the east;
2. Deformed by a partial Late Jurassic obduction of the back-arc oceanic lithosphere toward the Peonias side;
3. Widely deformed and eventually metamorphosed (e.g., Paikon) during the Tertiary events.

Conclusions

We show that the Maliac Ocean, located between the Pelagonian (W) and the Serbo-Macedonian (E) continental blocks, has to be considered as the main Tethyan Ocean branch from which originated the Hellenic Ophiolites obducted during the Middle-Late Jurassic times, over the Pelagonian domain (Supra-Pelagonian Ophiolites: SPO).

Thank to numerous studies within the greek Hellenides, we could describe the development of this ocean from its Mid-Triassic Rifting to the Mid-Jurassic convergence (e.g., subductions and obductions). The following conclusions contribute to better define this major oceanic domain:

1. The pre-convergence spreading responsible for the Maliac Oceanic Lithosphere (MOL) development at the Mid-Oceanic Ridge lasts about 65–70 My (240 or 235–170 Ma) from Mid-Triassic (late Anisian-early Ladinian) to Mid-Jurassic (Bajocian) times. Some transform zones, such as the Sperchios Fault Zone, have been active in the oceanic basin during the spreading times.
2. The main elements of the exposed Greek and Albanian ophiolites has been formed during the Mid-Jurassic convergence period (SSZ lavas), but parts of the Triassic MOL have been preserved as in the Fourka unit, in some smaller units in Greece, and probably in the Porava unit in Albania (Bortolotti et al. 2006). The Fourka unit is only made of pillow-lavas of OIB and MORB affinities. The lack of basement (gabbros and peridotites) is probably the result of its westward thin-skinned thrusting onto the Pelagonian continental crust.
3. The Liassic MOL is so far undated. The only data testifying for the Liassic evolution of the MOL are red shales interbedded between Triassic and Mid-Jurassic radiolarites deposited on top of the Fourka pillow-lavas in Othris (Ferriere et al. 2015). All these sediments, without calcareous component, were probably deposited below the CCD.

4. The series corresponding to the western Maliac Margin (W-Margin) are present as syn-obduction tectonic units imbricated between the ophiolitic (above) and the Pelagonian nappes (below), especially in Othris and Argolis areas. The series that we consider to correspond to the E-Margin crop out in the Peonias and Paikon zones, in the eastern Vardarian domain.
5. The similar evolution of these two margins, and their symmetrical disposition, support the interpretation that they correspond to the conjugate margins of the Maliac Ocean: a pre-rift calcareous platform; a Middle (locally Upper) Triassic syn-rift deepening and volcanism; calcareous pelagic sedimentation on the proximal parts of the margins during the Late Triassic times; increase in the detrital character of the Jurassic deposits. Series corresponding to the proximal margins have been observed on W- and E- margins, but a deep distal margin has only been recognized in Othris (Loggitsion units, Fig. 4). It shows up to 200–300 m thick syn-rift volcanic formations (mainly MORB and OIB) and deep pelagic sediments often similar to those of the Fourka unit (except for the Norian times).
6. Normal faults (listric faults?) are supposed to be the main tectonic structures on the margins. They were not clearly observed but their supposed distribution between the main sedimentary units allows to explain: (1) the syn-rift extension and thinning of the crust of the margins; (2) the main boundary between the distal and proximal margins; (3) some abrupt variations (thicknesses, facies) of sedimentary formations possibly linked to rotated faulted blocks; and (4) the development of the syn-obduction nappes by a tectonic inversion process of the main listric faults.
7. Despite the important amount of syn-rift volcanism on the distal W-Margin (Loggitsion unit), we consider that the Maliac margins are not Volcanic Rifted Margins (VRM), indeed: (1) the proximal W- and E-Margin series show limited syn-rift volcanic formations; (2) no tectonic structures testify for the presence of listric faults dipping toward the continent (a typical structure of the VRM).
8. The characteristics of the successive sediments are more or less in agreement with the syn-rift tectonic and post-rift thermal subsidence of the margins and MOL. Some particularities seem to be exceptions to this rule of a constant deepening of the basin: e.g., the deposits of Norian limestones on Carnian radiolarites in the distal W-Margin. A Norian increase in periplatform ooze from the superproducing platforms may be the reason for this anomaly.
9. After rifting and spreading, the destiny of the different parts of the Maliac Ocean became heterogeneous:
   (a) The MOL was largely obducted on top of the W-margin and the Pelagonian realm. Among the pre-convergence MOL units, the only well-preserved element is the oldest part of that ocean, Triassic in age (Fourka Unit). The Liassic MOL remains unknown, possibly entirely subducted during convergence;
   (b) The W-Margin produced syn-obduction units stacked below the large ophiolitic nappes which seem to have protected them from erosion and later tectonic deformations (Tertiary compressions);
   (c) The E-margin became an active margin with a well-expressed volcanic arc (Paikon Arc). The lithosphere of the back-arc basin (Guevgueli) was obducted on top of the eastern part of the E-Margin (Peonias) which is also amply affected by the Tertiary tectonic deformation.
10. The Maliac Ocean has to be regarded as the main Tethyan Ocean in the Greek Hellenides but also in Albania, and probably further toward the North.

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