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# Tectono-stratigraphic correlations between Northern Evvoia, Skopelos and Alonnisos, and the postulated collision of the Pelagonian carbonate platform with the Paikon forearc basin (Pelagonian-Vardar zones, Internal Hellenides)

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**Abstract**

The Pelagonian stratigraphy of the study area consists of a Permo-Triassic basement and an Upper Triassic and Jurassic carbonate platform formation that had been overthrust by the Eohellenic ophiolite sheet during the Early Cretaceous. Intensive erosion, during the Cretaceous, removed most of the ophiolite and partly the Jurassic formation. It is hypothesised that uplift and erosion of eastern Pelagonia had been triggered by the break-off of the subducted oceanic leading edge of the Pelagonian plate.

An investigation of the rocks that succeed the erosional unconformity shows that they constitute a shear-zone-formation which is tectonically overlain by Cretaceous platform carbonates that characterise the Palouki series of Skopelos and Alonnisos. Geochemical analyses of the shear-zone rocks substantiate that they are of mid ocean ridge and island arc provenience.

Eastern Pelagonia collided with a Cretaceous carbonate platform, probably the Paikon-Paeonian forearc basin, as the Almopias ocean subducted beneath that island-arc-complex. The Cretaceous platform, together with a substrate of sheared-off ocean floor mélange, overthrust eastern Pelagonia as subduction continued, and the substrate was dynamically metamorphosed to cataclastic rocks, mylonite, phyllonite and interpreted pseudotachylite. This complex of Cretaceous platform rocks and a brittle-ductile shear-zone-substrate constitute the here named *Paikon-Palouki nappe* which was emplaced during Early Palaeocene. The *Paikon-Palouki nappe* did not reach Evvoia.

Seismic tomographic models of the Aegean region apparently depict images of two broken-off ocean-plate-slabs, interpreted as Almopias-lithosphere-slabs: the western Almopias slab began to sink during the Early Cretaceous, the eastern Almopias slab broke off and sank after the Paikon-Palouki nappe was emplaced in Early Palaeocene time.

**Key Words:** Eastern Pelagonia; Paikon collision; ocean floor mélange; shear zone formation; Slab break-off

## Introduction

The study area is in the Pelagonian zone of the Internal Hellenides (Fig. 1a). An extensive, over one kilometre thick, shallow marine carbonate platform evolved during the Late Triassic through the Late Jurassic and, in the Early Cretaceous, was buried under the obducted Eohellenic ophiolite sheet.

The present contribution correlates the stratigraphies and tectonics on the eastern margin of Pelagonia, specifically between Alonnisos, Skopelos and northern Evvoia, including observations on the nearby smaller islands, Kira Panagia, Megalo Aderfi and Peristera (Fig. 1b). Especially significant is a tectonic (*brittle-ductile) shear zone* on Alonnisos and Skopelos, and the neighbouring islands, that is composed of a tectonically sheared mélange of ocean floor and carbonate rocks. This tectonic formation has previously been erroneously interpreted as transgressional conglomerates, meta-turbidites and flysch, but also as tectonically deformed erosional relics of metabasites of an oceanic subduction complex, analogous to the Eohellenic ophiolite, or as possible slivers at the base of a Palaeogene nappe (Jacobshagen and Matarangas 2004). This latter suggestion is considered here to be correct and has led to the present investigation.

Another controversial point is, whether or not Pre-Triassic, Pelagonian basement is exposed in northern Skopelos (Glossa, Fig. 1b), which had previously been positively supported by Papastamatiou (1963) and Jacobshagen and Skala (1977), but later re-interpreted (Jacobshagen and Matarangas 1988) as Eohellenic metabasite. In the present account it is argued that the formations exposed in northern Skopelos (Glossa) correlate well with the underlying Palaeozoic-Triassic formations of northern Evvoia. Furthermore this basement is presumed to extend from Evvoia to the eastern margin of Pelagonia where it borders on the Vardar Suture (Fig. 1b).

Field work was carried out during June and September in the years 2016-2018, mainly on Skopelos and Alonnisos with reconnaissance visits to Kira Panagia, Peristera and Megalo Aderfi. Field work was fundamentally aided by previously published geologic maps (Kelepertsis, 1974; Jacobshagen and Matarangas, 1988; Matarangas,1992; Jacobshagen and Matarangas, 2004), without which this account would not have been possible. Greatly advantageous was having new topographic maps of Skopelos and Alonnisos (Nakas Cartography,1:25,000, 2014 and 2017) and an Imray Tetra Nautical Chart of the Northern Sporades 1:183,000, 1995). Samples were taken for thin sections and geochemistry. The geochemical analyses of major, minor and trace-elements were performed by Activation Laboratories Ltd., Ontario, Canada. Boat-field excursions to Peristera and Megalo Aderfi were made possible with “Sea Escapes”, Alonnisos.

The results of these investigations will be discussed in eight main chapters:

1. Geological background and previous research
2. Disputed and modified stratigraphies of Alonnisos and Skopelos
3. The Paikon-Palouki nappe and the brittle-ductile shear-zone formation
4. Description of the geologic maps and cross sections of Alonnisos and Skopelos
5. Biostratigraphy
6. Geochemistry of the *shear-zone* formation
7. Discussion
8. Conclusions

**Geological Background and previous research**

The study area is shown in its regional tectonic context in a simplified cross-section through the Hellenides (Fig. 2a), here redrawn after Aubouin et al (1977). The Figure essentially shows that an ophiolite sheet, was obducted over eastern Pelagonia (“Eohellenic Phase” Jacobshagen et al.,1976) and subsequently overthrust by nappes originating from the Paikon-Paeonian sub-zones. (For greater detail of the actual complexity of the Vardar zone of northern Greece and the Dinarides the reader is referred to Mercier 1968; Brown and Robertson 2003, 2004; Mercier and Vergely 2002; Sharp and Robertson 2006, and others cited in Michail et al. 2016).

Geotectonically, the Eohellenic ophiolite of Evvoia belongs to the western Vardar ophiolitic unit (Kukoc et al. 2015) that extends through the Dinarides and the Hellenides (Ustaszewski et al., 2010); it is the western part of the Almopias oceanic plate that was obducted onto the eastern Pelagonian plate. The obduction over Alonnisos and Skopelos occurred during the Early Cretaceous (Jacobshagen and Matarangas 2004). On Evvoia the ophiolite emplacement took place during Late Jurassic-Early Cretaceous time as the leading oceanic (Almopias) edge of the Pelagonian plate was subducting (Fig. 2b)(Scherreiks et al. 2009; 2014). An analogous obduction/subduction configuration has been suggested (see General Scenario in Schmid et al. 2008), showing the Vardar/Almopias ophiolite being obducted over the Adriatic plate. Post-Eohellenic overthrusts, Y+Z shown in Figure 2a, did not reach northern Evvoia. Nevertheless, the litho-stratigraphies of Evvoia, Skopelos and Alonnisos have many similarities because during the Triassic until Early Cretaceous they had been part of a continuous carbonate platform. However, in contrast to Evvoia (Scherreiks et al. 2014), some of the formations of Skopelos and Alonnisos, had undergone low grade, sub-greenschist to greenschist metamorphism and Early Cretaceous erosion was much more severe on Skopelos and Alonnisos (Kelepertsis 1974; Jacobshagen and Skala 1977; Matarangas and Jacobshagen 1988; Matarangas 1992) than on Evvoia (Scherreiks 2000). During the Early Cretaceous, the Eohellenic ophiolite sheet had been more or less completely removed by erosion from Alonnisos, and on Skopelos erosion had also removed at least most of the Jurassic formations, as will be considered later.

It has been estimated, based on a tectonic reconstruction (Scherreiks 2000), that the region eastwards of Evvoia had been uplifted at least 3000 metres during post-Eohellenic - Early Cretaceous time; uplift, may have been caused by buoyancy-rebound of the eastern Pelagonian plate after its subducted oceanic leading edge had broken off (Fig. 2b)(Scherreiks et al. 2014) (see Discussion). Eohellenic nappe-relicts may possibly exist on Alonnisos (Eohellenic outlier, Jacobshagen and Matarangas 1988 and 2004). It is highly improbable that *In situ* relicts of Eohellenic ophiolite exist on Skopelos, because intensive erosion had not only removed the ophiolite nappe but also the subjacent Jurassic formation as well. However, the disputed area of Glossa, (see Pelagonian Basement and Discussion). has been interpreted as Eohellenic ophiolite (ibid.). On Evvoia, the Eohellenic ophiolite nappe had been only partially eroded.

**Disputed and modified stratigraphies of Alonnisos and Skopelos.**

In this presentation, new interpretations are made of rock units and their stratigraphic positions. The previous stratigraphies are compared to the new stratigraphy (Fig. 3a). The modified stratigraphy partially follows previous researchers (Papastamatiou 1964; Guernet 1970), who recognised that the Pelagonian formations of Skopelos had not been transgressed but had been overthrust by the Cretaceous formations. Kelepertsis (1974) recognised the Jurassic/Cretaceous disconformity but did not recognise the tectonic nature of the rocks that occur between the Jurassic and the Cretaceous formations (Fig 3b). He distinguished the important Palouki series as the continuation of the rock unit of Mt. Palouki of Skopelos island, and he extended the *Palouki series* from Skopelos to SW Alonnisos (Fig. 3b). Papastamatiou (1964) suggested that the Palouki series of Skopelos belonged to the Vardar Zone (Almopias Zone) (Fig. 1a and Fig. 2a), a hypothesis that Kelepertsis supported (1974) and is, as will be shown below, the envisaged viewpoint of this presentation.

The stratigraphic correlations (Fig. 3a) show that the geologic column of Evvoia is more or less continuous from the Permian through the Jurassic until Lower Cretaceous. The Permo-Triassic basement (Katsikatsos et al. 1984) and the dolomite sequence of Evvoia correlate well with the Glossa and Skiathos series, and the Triassic dolomites of Skopelos (Fig.3a). In contrast, Triassic is not exposed on Alonnisos and has not been verified on Kyra Panagia or Megalo Aderfi. The Jurassic is, besides a few small problematic outcrops, more or less absent from Skopelos, whereas Jurassic constitutes the oldest exposures on Alonnisos, where the reefal facies is similar to that of Evvoia (Fig. 3a). The stratigraphically oldest marbles observed on Kyra Panagia and Megalo Aderfi occur below metabasites and are thought to be Jurassic, but no definite verification has been made.

Widespread remnants of the Eohellenic ophiolite formation (serpentinite, peridotite, basalt, radiolarite) exist on Evvoia whereas the inferred ophiolite on the other islands of the study area had been eroded during Cretaceous time. A small *in situ* relict of Eohellenic metabasite may be preserved on Alonnisos (see below).

On Evvoia, transgressional conglomerate overlies ophiolite mélange and Tithonian-Berriasian radiolarian cherts (Baumgartner and Bernoulli 1976; Scherreiks et al.2014). The conglomerate is contains serpentinite and radiolarian chert-pebbles, and is overlain by a 30 metre limestone succession containing abundant rudist bivalves and foraminifera, which range in age from Coniacian to Maastrichtian (Scherreiks 2000). In contrast to this, on the other islands of the study area, *in situ*, sedimentary Cretaceous probably never came to be deposited (see Discussion). Instead, a brittle-ductile shear-zone-formation (terminology after Fossen and Cavalcante, 2017), composed of dynamically metamorphosed, oceanic mélange, directly overlies the Pelagonian formations.

Occurrences of laterite are widespread on Skopelos (Matarangas 1992), in contrast to Alonnisos where laterite is not conspicuous. The re-deposited laterite occurs within joints and karstic fractures in the dolomite formation as well as in cataclastic rocks that can attain up to about 150 metres thickness. Primary *in situ* laterite could not be verified. The origin of the primary laterites may have been multi-temporal, considering that the entire eroded ophiolite and Jurassic carbonates had been their source. On Evvoia laterite was deposited during the Callovian and during the post-Eohellenic period (Scherreiks et al. 2014 and 2016).

**The Paikon-Palouki nappe and the brittle-ductile shear-zone formation**

The *Palouki nappe* of Skopelos has been recognised by Jacobshagen and Matarangas (2004), who date the emplacement during Eocene time. However, their interpretation indicates that the nappe was emplaced over transgressional Cretaceous rudist limestones and "flysch" (Fig. 3b) which is disputed here. Contrary to Matarangas (1992), and Jacobshagen and Matarangas (2004), the Palouki Cretaceous is underlain by a *shear-zone* formation of dynamically metamorphosed, ocean floor and tectonically intermingled carbonate rocks. The shear-zone rocks range from sheared ocean-floor mélange to sericite schist, greenschist, phyllite and phyllonite (nomenclature following Higgins 1971; Maddock 1986; Brodie et al. 2007, Fossen and Cavalcante, 2017), (see below and discussion). Recently, Porkoláb et al. (2019) determined white mica ages (40Ar/39Ar dating) in the phyllites of south-eastern Skopelos, indicating that the deformation of the *Palouki nappe* took place around Palaeocene time.

Numerous occurrences of oceanic rocks on Alonnisos and Skopelos, have been observed previously: spilitic igneous rocks, serpentinites and metabasalts (Kelepertsis 1974; Guernet, 1970); or interpreted as Eohellenic metabasites (Matarangas 1992; Jacobshagen and Matarangas 1994). A greenschist of Kira Panagia, has been interpreted as a metabasite, arc-tholeiite basalt-rhyodacite (Pe-Piper et al. 1996; Jacobshagen and Matarangas 2004). In this contribution, these rocks are considered to actually be connected to an all encompassing tectonic shear zone, that extends from Kira Panagia over Alonnisos, Skopelos, Peristera and Megalo Aderfi which has not been hitherto recognised. The herein named *Paikon-Palouki Nappe,* documented below, is composed of allochthonous Cretaceous carbonates that were emplaced together with a subjacent *sheared oceanic mélange* over the Pelagonian formations of the investigated islands of the Northern Sporades:

*The Brittle-Ductile Shear-Zone Formation*

(The nomenclature used in this contribution takes into consideration the terminology of *shear zones* in Higgins 1971, Barker 1998; Rowe et al. 2005; Schmidt and Handy 1991; Woodcock and Mort 2008; Fossen and Cavalcante 2017; among others. *Brittle* refers to fault breccias and cataclasite as in Higgins, *ductile* (or plastic) refers to mylonites as in Schmidt and Handy, whereby neomineralisation and recrystallisation dominate over relict cataclasis).

The Cretaceous carbonates of Skopelos and Alonnisos are not in sedimentary contact with their substrate. They overlie tectonically sheared oceanic rocks everywhere, verified by geochemical analyses (see below), which in turn overlie Jurassic carbonates on Alonnisos and Triassic dolomite on Skopelos (Fig. 3). The *Shear-Zone formation* of Alonnisos and Skopelos had undergone intensive cataclasis and dynamic metamorphism, and low grade metamorphism characterised by sericitisation of plagioclase feldspars in the oceanic rocks (see below). The formation grades stratigraphically upwards from brecciated Triassic dolomite-substrate on Skopelos and brecciated-sheared Jurassic limestones and marble on Alonnisos, into *fluxion structured* schists (described in Higgins 1971 and Barker 1998), and further into sericite/chlorite dominated phyllonite (lepidoblastic texture of sericite) and finally, on top, into non-fluxion-structured cataclastic Cretaceous marble and recrystallised limestone (Fig. 3).

*(In this contribution the terms: "marble" and "recrystallisation" are not strictly defined by P/T range; they are limestones that have been recrystallised to an extent that most if not all sedimentary fabrics have been obliterated. Metamorphic marble is associated with sericite in the shear zone formation.)*

The sheared, Cretaceous, marbles within the top of the shear zone are composed of alternating, millimetre thin, flat and anastomosing calcite and sericite cleavage planes.

The shear-zone rocks are composed of porphyroclast lithic grains of still recognisable basalt, volcanic glass, radiolarian chert and mineral grains of plagioclase (Fig. 4 a, b, c). Secondary minerals are sericite and quartz having fluid inclusions, chlorite, epidote and chloritoid. The observed lithic grains range in size from a few centimetres to millimetres in rocks which, previously, have been erroneously identified as Cretaceous conglomerates (Fig. 4c). The components of these rocks underwent tectonic rounding and grain-reduction from the decimetre to centimetre scale to microscopic micron scale and the matrix material is typically the same as that of the porphyroclasts (a typical phenomenon observed in cataclastic rocks by Higgins 1971). The chlorite, epidote, and chloritoid are porphyroblastic minerals, indicating that the temperatures ranged up to about 350° (see Discussion). (A lithic grain of volcanic glass, inherited from the ocean floor mélange has fine, long needles, of supposed actinolite.)

Foliation and rock cleavage is mainly caused by aligned mica (Barker 1998; Burg 2017), or by alternating parallel porphyroclast bands that are crossed obliquely by foliation/shear planes which may be observed best under the microscope, of which numerous examples have been observed where the foliation/cleavage had been crenulated by compression (Fig. 4e-h). Other examples indicate that the sericite of the foliation plains became reoriented parallel to a secondary shear plane (Fig. 4 g-h) (a phenomenon shown in Bell and Rubenach, 1982).

Polyepisodic successions in which alternating brittle and ductile deformations had taken place have been seen in numerous thin sections from Alonnisos and Skopelos; typical of shear zones according to Higgins, 1971. Similar brittle-ductile deformations have been reported as*"ultracataclastites or pseudotachylites"* by Adams and Trupe (2006) in the Alleghanian shear zones. We observe under the microscope that fluxion structured rocks can grade into irregular bands of "*ultracataclasite"*(ibid.) which we interpret as pseudotachylite from descriptions e.g. in Maddock (1986) and Higgins (1971). The supposed pseudotachylite of the study area occurs as millimetre thin, braided sheets of opaque matter, laden with quartz porphyroclasts, that alternate with fluxion structured, aligned sericite, imbedded in interstitial, finer grained matrix, which intrudes adjacent fractures. The quartz grains of the fluxion sheets are serrated, giving the appearance of having been melted on their edges and then frozen in a once fluid medium (Fig. 4d). Pseudotachylite is not uncommon in tectonic thrust and subduction zones from the Alps to Alaska (Laubscher 1983; Maddock 1986; Johnstone and Mykura 1989; Rowe et al. 2005). Higher grade metamorphic minerals other than greenschist facies have not been observed. (Postscript: During the terminating work on this contribution in Spring of 2019, simultaneous investigations of the geology of Skopelos had also taken place (Porkoláb et al., 2019), which indicate that temperatures between 350 and 450°C in the pressure range 1-2Gpa, had prevailed during shearing.)

**Description of the geologic maps and cross sections of Alonnisos and Skopelos**

Geologic mapping was carried out on the islands of Skopelos and Alonnisos and is based on previous geologic maps (Kelepertsis 1974; Matarangas 1992). Reconnaissance visits to neighbouring islands verified similar geologic formations and structures (Peristera, Kira Panagia and Megalo Aderfi (Fig. 1b).

*Geology and tectonic sections of Alonnisos*

The new geologic map of Alonnisos is shown in Fig. 5 and two tectonic sections of Alonnisos are shown in Fig.6a. On Alonnisos (Fig. 5), Jurassic crystalline limestones and marbles are the oldest outcropping rocks (Kelepertsis 1974) ( The marbles are for the most part coarse crystalline and white, and presumed to be very low grade metamorphic, see comment above). After erosion had removed the Eohellenic nappe, the Paikon-Palouki nappe was emplaced during the Palaeocene (see biostratigraphy). The Geologic Map of Alonnisos mainly differs from the previous maps in two decisive areas where the stratigraphic order has been corrected (Fig. 5) and is shown in the tectonic sections of Alonnisos (Fig.6a). Frank (1997) in Jacobshagen and Matarangas (2004) interpreted the Mourtero series, contrary to Kelepertsis (1994) to represent relicts of the Eohellenic nappe, which lie stratigraphically above the Jurassic. This is viewed here as a correct possibility. Jacobshagen and Matarangas (2004) had correctly concluded that the Mourtero unit, as a whole, had overthrust the Jurassic marbles.

The geologic map of Skopelos is shown in Fig. 7 and sections are shown in Fig. 6b.

*The Pelagonian basement of Skopelos*

Previous authors considered the Skiathos- and Glossa-series (Fig.7) to represent the Permo-Triassic, Pelagonian basement of Skopelos (Papastamatiou 1963; Jacobshagen and Skala 1977). However, this has been contradicted and re-interpreted by Jacobshagen and Matarangas (1988) and Matarangas (1992): maintaining that the rock assemblage of the Glossa unit is identical to "Eohellenic ophiolite outliers" (Fig. 3b), with the argument that the Glossa unit has been thrust south-eastwards over the Upper Triassic formations of Skopelos.

Porkoláb et al. (2019) have dated white mica 40Ar/39Ar ages, occurring in the quartz phyllites of the Glossa unit, showing that the mica underwent low grade heating during the Early Cretaceous. These authors reiterate the stratigraphic interpretation of Jacobshagen and Matarangas (1988) and Matarangas (1992), assuming that the Glossa unit is of Eohellenic provenience. However, the Early Cretaceous white-mica metamorphosis cannot be taken as the age of the para-metamorphic Glossa unit, which is much older. The findings of the cited authors affirm that the basement of the Pelagonian carbonate platform was affected by Eohellenic thermal metamorphism, which we assume occrred as the Eohellenic sheet was obducted over the Jurassic-Triassic platform and basement of the Pelagonian plate during the early cretaceous. Most important, however, is that the *depositional age* of the Glossa unit has not been determined by Portolab et al..

The fault-trace on the map (Fig. 7), crosses the island over mountainous terrain from Klima to Ag. Ioannis and had been incorrectly interpreted as a south-eastward-vergent low-angle thrust fault (ibid. 1988). The fault-trace and topography actually indicate a low angle SE dipping (30°) thrust fault in the Klima area, which leads us to assume that the Triassic dolomite had been thrust north-westwards over the Skiathos- and Glossa-series (Fig.7 and Fig. 6b1). The Skiathos- and the Glossa-series are low-grade, para-metamorphic rocks with intercalations of metabasites, similar to the basement of Evvoia (north-western Evvoia, Katsikatsos et al. 1984), consisting of quartz-phyllites and chlorite-sericite-schists intercalated with, micaceous quartzite, calc-schist and sheared marble (Katsikatsos et al. 1984). On Skopelos (Fig. 7), Upper Triassic dolomite overlies the Skiathos series concordantly, but the dolomite is tectonically brecciated and permeated by faults in all areas where it borders on the subjacent basement suggesting that it overlies a fault zone (Vourlia in Fig. 6b1 and Fig. 7). In agreement with the older views (Papastamatiou 1963; Jacobshagen and Skala 1977), the formations of the Glossa peninsula are considered to belong to the Permo-Triassic basement of Skopelos (see further arguments in the Discussion).

*Description of the tectonic sections*

The NW-SE tectonic section through Skopelos (Fig. 6b1) shows the interpreted geology from the Pelagonian basement of Glossa through the tectonically disturbed basement-zone around Vourlia and the moderately folded Triassic dolomite formations to the area of Cape Pouda. By way of tectonic interpolation, it is suggested that the Skiathos series and basement lies about 600 metres below the dolomite of Mt. Delfi. The central area of Skopelos is dominated by typical Pelagonian, Upper Triassic dolomite. Close to the vicinity of Mt. Delfi (Fig. 7) calcareous intercalations occur in the dolomite, that are similar to the transition zone from Upper Triassic to Lower Jurassic, observed on Evvoia, where the dolomite formation extends stratigraphically into the Lower Jurassic and alternates increasingly with limestones in the centimetre to metre range. This suggests that lowest, Lower Jurassic may still be preserved on Skopelos. Flysch-facies could not be verified in the Delfi area as has been previously recorded (Matarangas 1992). Otherwise, Jurassic carbonates have been removed by erosion on Skopelos. It is noteworthy that neither dolomite-*marble* nor sericite could be observed in the Triassic stromatolitic dolomites that lie beneath the shear-zone formation. Similar to Evvoia, the tectonic deformations of the Pelagonian carbonates apparently took place below the subgreenschist-facies temperature range of around 200–250 °C (compare Scherreiks et al. 2014; also Barker 1998).

The sections (Fig. 6a-b) show that the Jurassic and Triassic Pelagonian carbonates are overlain by the *shear-zone* formation (defined above) which in turn is overlain by Upper Cretaceous carbonates. Together, the Cretaceous carbonates and the shear-zone comprise the *Paikon-Palouki* nappe. The sections (Fig. 6a-b) show gentle undulating folds, in the 100 metre scale, both on Skopelos and Alonnisos. The large-scale folds do not have pronounced or apparent preferred vergence. This substantiates the tectonic investigation carried out by Matarangas (1992), who reports three main fold-trends: NNW-SSE, NNE-SSW, and ENE-WSW. As Matarangas noted, in the metre scale, however, there are pronounced inclined and recumbent folds. Such metre-scale folds have been encountered during the present investigation in the *tectonic shear zone*, their axes trending parallel to the thrust-planes of the major faults. These thrust directions do not correspond to the usual vergence-of-emplacement of the Eohellenic nappe that one observes in Evvoia or the general thrust directions (toward the SW) in the Vardar formations (Scherreiks et al. 2014). The observations of three main fold trends (Matarangas 1992), suggest that the area of Skopelos has been progressively rotated clockwise during episodes of tectonic deformation. However, the suggested rotations that had probably taken place in the Sporades is not addressed in this presentation because this subject, although important, goes far beyond the scope of the present theme, and palaeomagnetic data is not available (Rotations affecting Pelagonia and Evvoia have been recognised and previously considered in Scherreiks, 2000).

*The allochthonous Cretaceous and subjacent shear zone*

Contrary to (Matarangas 1992), the Cretaceous formations of Skopelos are not in sedimentary contact with the subjacent Pelagonian dolomite formation. For example, in the Panormos and Agios Reginos areas radiolarian chert and metabasite occurs in tectonic contact on top of the Triassic dolomite (Fig. 6b2 and b3). Transgressional conglomerate does not occur. The *Paikon-Palouki nappe* was thrust over the islands following the erosion of the Eohellenic ophiolite and Jurassic formation. Sheared oceanic rocks overlie the Triassic dolomite of Skopelos and the Jurassic carbonate succession of Alonnisos. The hitherto interpreted “flysch” of Alonnisos and Skopelos (Fig. 3b) is not a sedimentary formation, but is a tectonic shear zone that occurs stratigraphically below the Cretaceous carbonate rocks. Cretaceous rocks are pervasively intermingled with the schists in an alternating brittle-ductile transition zone (referred to above). This *shear-zone* formation lies on top of the post-Eohellenic erosional disconformity (Fig.3a) (Fig.6a and 6b). An excellent outcrop that shows the stratigraphic sequence of Cretaceous carbonate rocks on top of mylonitic greenschists may be observed in the Glisteri-Skopelos Bay areas (Fig.6c). The *shear-zone* attains a thickness of about 100m on Alonnisos (Fig. 5, Fig. 6a) Morterio and Taxiarchis) and 100 metres in Skopelos town (Fig. 7), and attains more than two hundred metres in the Palouki fault-zone, and in the areas of Pirgos and Kalogiros (Fig. 7). The fluctuating thickness of the shear zone, swelling to hundreds of metres and diminishing to almost zero, probably is a result of imbrication and accretion, and respectively due to tectonic off-scraping as the *Paikon-Palouki-nappe* was transported and emplaced. Good exposures of the *shear-zone* formation can also be seen in the vicinity of Monastery Prodromos on the northern foot of Mt. Polouki (section 4 of Fig. 6b). The Tectonic sections (Fig.6b) also show interpreted graben structures, e.g. between Pano Karia and Athinás Temple (Fig. 6b1) and half-graben structures which post-date the emplacement of the *Paikon-Palouki nappe*. Whether or not these post-compressional tectonic structures can be related to those that exist below sea level to the north and north-west of the study area (Papanikolaou et al. 2006) has not been followed in this presentation.

**Biostratigraphy**

*Alonnisos*

Upper Jurassic age has been determined previously by Kelepertsis (1974) and is substantiated in this contribution with a Cladocoropsis find in the area of Mourtero (GPS N39°12.517’; E23°55.562’). The Upper Cretaceous formation of Alonnisos has been dated with rudists (Kelepertsis 1974), which could also be substantiated (road outcrop near trigonometric point 312m north of Mourtero, Fig. 5).

*Skopelos*

In the Palouki tectonic zone, in the vicinity of Prodromou Monastery, Matarangas reported (1992) finding Actinoporella *podolica* ALTH, in thin *bedded limestone* (actually sheared and foliated sericitic marble) with intercalations of phyllites and metasandstones. The reported foraminifera (Matarangas) indicate Early Cretaceous Berriasian-Barremian age. Above the latter sheared limestone-zone, rudist limestones and marbles occur along the road leading through the Upper Cretaceous succession of Mt. Palouki.

North of Palouki mountain, Matarangas (1992), found microfossils in *cementing material or matrix of a conglomerate* 30 cm above Triassic dolomites in the Ag. Riginou Monastery area (church symbol east of Athenás Temple, Fig. 7 and Fig. 6b1). The microfossils presented by Matarangas are not specific for Albian, as he had assumed, but have a wide stratigraphic range from at least Albian to Turonian. Table 1 shows the new names and updated age-ranges (BouDagher-Fadel 2008, 2015)

In the same area of Ag. Riginou Monastery, the present authors investigated, limestones containing recrystallised rudists, which disclosed, in thin section, foraminifera and algae suggesting Maastrichtian age (Table 1). The location is the side-road to Ag. Riginou (Fig. 7), south of Skopelos Port. The limestone-wackestone contains recrystallised rudists from the families Radiolitidae and Hippuritidae, indicating a shallow marine, reefal facies (BouDagher-Fadel 2008, 2015).

Table 1

Southeast of Ag. Riginou, stratified fossiliferous limestone occurs on top of reddened lateritic breccia (Table 1 C) (hairpin turn on the main road south of Skopelos town Fig.7). The lateritic, cataclastic limestone lies on top of Triassic dolomitic rocks, and it contains relicts of molluscs and smaller shelly organisms. Thin sections of the wackestone disclosed a shallow reefal facies with recrystallised algae and benthic foraminifera indicating Palaeocene age (BouDagher-Fadel 2008, 2015):

In numerous areas of Skopelos, Upper Cretaceous age has previously been ascertained (Matarangas 1992). In the area south of Panormos bay (Fig. 7) where Matarangas reported microfossils indicating Cenomanian age, the present authors can contribute findings of shallow reefal wackestones, containing fossils (Table 1D) which expand the age of the Cretaceous in the southern Panormos area from Cenomanian to Late Santonian to Maastrichtian/Early Palaeocene (BouDagher-Fadel 2008, 2015). The stratigraphy of these limestones is tectonically disrupted and the rocks are mingled into the shear-zone formation.

The stratigraphic range of Lithocodium aggregatum Elliott, known so far, is (Oxfordian?) Tithonian–Coniacian but there are rare records of Lithocodium aggregatum Elliott in the Late Cretaceous (e.g., Höfling 1985; Steuber 2001). The presence of a fragment of *Orbitoides* sp. indicates an age of late Santonian to Maastrichtian; Rotorbinella sp. to Late Cretaceous-Early Palaeocene. Therefore, as it appears, the limestone/marble formations of central Skopelos, north of Mt. Palouki, range in age from Late Cenomanian to Maastrichtian and may extend into Palaeocene.

**Geochemistry of the shear zone formation**

Analyses of major, minor and trace elements were carried out for 22 samples from the *shear-zone* formation (described above) of Alonnisos, Skopelos and Kira Panagia (Table 2a and 2b). For reasons of comparison, three samples were analysed from the Glossa area, and three from Evvoia: one MORB, one serpentinite and one peridotite. The analyses were made with the intention of distinguishing the regime or regimes from which the *shear-zone* rocks possibly originated (following Pearce and Cann 1973; Kay and Hubbard 1978; Bence et al, 1979; Wood et al. 1979; Perfit et al. 1980; White and Pachett 1984; Hooper and Hawkesworth 1993).

The geochemical analyses substantiate their oceanic origins, which is readily recognised in thin section especially in the porphyroclastic rocks, showing mixtures of basalt, volcanic glass, radiolarian chert, mineral grains of plagioclase (Fig. 4a-b). However, many of the rocks of the *shear-zone* are not obviously of oceanic origin: e.g. the phyllonites, consisting of concentrations of white mica, quartz and chlorite. In addition, the geochemistry of the oceanic origins is masked by admixtures of carbonate rocks, stemming from the Cretaceous formation on top of the shear zone formation (Table 2a e.g. samples A7/3.1, S7/17). The REE analyses of these rocks display plots that correspond to MORB and IAB patterns (Fig. 8a1-a3). It is quite surprising that even the analysed phyllonites in which the original minerals had undergone retrograde metamorphic, hydrothermal metasomatism (see Discussion), and mylonitisation grinding still display characteristic basalt-REE-plots (e.g. sample A6/31 in Fig. 8).

The REE plots (Fig. 8a), in all shear zone rocks, display patterns typical of basalts. Two main groups can be distinguished: those having enriched light REE (LREE), as opposed to those having flat plots displaying LREE depletion. Based on numerous observations (e.g. Pearce and Cann 1973 ibid.), Island arc basalt (IAB) is generally more variable than MORB, which is characterised by LREE depleted, flat curve patterns. IAB patterns are commonly flat but may be LREE enriched with variable Eu anomalies (White and Patchett 1984, e.g. New Britain, Aleutians, Sunda). Most of the REE examples of the study area have negative Europium anomalies, and only in a few an Europium anomaly is absent (see Discussion).

The REE plots (Fig. 8a) and discrimination diagrams (Fig. 8b)(after Vermeesch 2006) show that the samples are either distributed in the MORB or IAB fields. The AFM diagram shows that the rocks are mainly of the calc-alkaline series and fewer fall into the tholeiitic series field. These results substantiate that the *shear-zone* rocks are metabasites, mostly of a middle oceanic origin but many indicating IAB provenience (see Discussion).

*Peridotite and Serpentinite* from Evvoia have been analysed in order to compare their trace-element contents with the rocks of the *shear-zone* formation. Only one sample from Alonnisos (table 2A sample A4/17) has Cr and Ni contents comparable to serpentinite or peridotite, which probably indicates that ultrabasic porphyroclasts probably occur in the shear zone formation, although seldom.

**Discussion**

*Pelagonian Basement*

It has been maintained that the rock assemblage of the Glossa unit is identical to “Eohellenic outliers” (Jacobshagen and Matarangas 1988; Matarangas 1992) and affirmed with two arguments, each of which is disputed in this presentation:

1. According to the cited authors, the Glossa series is not of Permo-Triassic age because, as they claim, it is completely different from other Pelagonian pre-Mesozoic basements, using as an example the crystalline complex of Thessaly, where a metaclastic series is overlain by a thick sequence of Pelagonian marbles. However, this is not the case in nearby Evvoia where the Upper Triassic dolomites do not overlie a metaclastic series but on the contrary they overlie a thick (>600m), Permian-Middle Triassic succession of phyllites and schists with intercalated Prasinite-greenstones (metabasites) and fossiliferous limestones (Katsikatsos et al. 1984), that, except for the fossils, resemble the Glossa sequence excellently.
2. Jacobshagen and Matarangas (1988) base their idea of an Eohellenic origin of the Glossa unit on geochemical studies of metabasites in the Glossa series which indicate MORB affinities of a geotectonic setting comparable to a marginal or an oceanic basin. However, metabasites are not specific only for the Eohellenic nappe: metabasites also occur in the Middle Triassic basement-succession of Evvoia and have likewise been interpreted as having been derived from submarine extrusions of basic igneous rocks (Katsikatsos et al. 1984). For this reason, Glossa green-schists have been analysed geochemically, (List 2, REE plots (Fig. 8a) and discrimination diagrams have been constructed (Fig.8b); they substantiate MORB/IAB and calc-alkaline basalt affinities for the Glossa unit. Needless to say, geochemical data cannot be used to distinguish pre-Upper Triassic basement-metabasite from Eohellenic metabasite. The analysed metabasites of Glossa (Table 2 G41 and G1) are partly in the IAB field and have negative Eu anomalies, whereas G17 has a flat MORB pattern without an Eu anomaly. The “IAB” types can be interpreted as within plate basalts which formed during Pangaea rifting when the Almopias ocean began forming. G17 may indicate a flood basalt having MORB-type REE patterns.

Therefore, in agreement with previous published views (Papastamatiou 1963; Jacobshagen and Skala 1977), the formations of the Glossa peninsula are considered to belong to the pre-Upper Triassic basement of Skopelos, on grounds of topographic/stratigraphic superposition of the Triassic dolomites. The petrographic and geochemical data correlate well with the Middle Triassic basement of Evvoia, and the Glossa series bears little resemblance to the Eohellenic complex, which e.g. in Evvoia, consists of serpentinized peridotite, gabbro, basalt and radiolarian cherts.

*The shear zone formation*

The mineral assemblages are thought to indicate that retrograde phyllic metamorphism (decomposition of plagioclase) and pro-grade greenschist facies metamorphism (chlorite) had alternated with brittle-ductile deformation phases. Structurally, tectonic fabrics recur at progressively smaller scales ( e.g. anastomosing, lenticular shear planes at metre and microscopic scales), reminiscent of reiterating fractal- and unpredictable random chaotic-patterns (Mandelbrot 1982; Boeing 2016). Retrograde, metasomatic sericite and secondary quartz together with opaque matter (Fe-oxides) is older than syn-tectonic pro-grade-metamorphic chlorite, epidote and chloritoid. It is supposed that sericitisation began in the ocean-floor realm resulting from metasomatic hydration reactions (Phyllic alteration) during hydrothermal decomposition of the feldspars (Barker 1998; Mathieu 2018), and within a low temperature range below 300°C (Park Bishop 1985; Barker 1998). Later, greenschist-facies-temperatures (350°C) were reached probably during tectonic transport as a result of friction heat. The early quartz that formed as a product of sericitisation of feldspars has typical ragged outlines and fluid inclusions, as opposed to syntectonic idioblastic quartz which is partly or completely cleansed of impurities. The hydrothermal environment apparently led to the complete destruction of olivine which broke down to magnetite or hematite (Ade-Hall 1971). The greenschist-facies-mineralisation succeeded phyllic alteration.

*Pseudotachylite*

The fluxion structured fabric of porphyroclast-laden opaque matter, which is pervasively present in laminae of the shear zone rocks, indicates that the opaque matter was a more or less viscose fluid medium interpreted here as pseudotachylite (Maddock 1986; Rowe 2006). Normal optical investigations with the polarising microscope could not determine whether or not glass had been or still is present in the opaque matter and would require refined investigations. Although the *shear-zone* rocks, based on the mineral observations, only underwent low grade dynamic metamorphism in the temperature range of about 250°C to 350°C, it is nevertheless quite possible that heat of friction in the slipping and sliding planes could have caused localised melting (Maddock 1983), which in the present case is supposed to have alternated with phases of cooling and solidification at different times and levels within the nappe as it advanced. These interpretations have been tentatively supported by microscope observations and discussions carried out together with Professor S. Heuss-Asbichler (Ms Mineralogy) and A. Huber (Ms Mineralogy), of the department of Earth and Environmental Sciences, Ludwig-Maximilians University Munich.

The early “quartz” porphyroclasts were products of the sericitisation of feldspar (see above) and typically contained abundant fluid inclusions, and quite possibly were *amorphous or cryptocrystalline quartz*, which would have been soluble at lower temperatures than crystalline quartz (Gíslasona et al. 1993). Local friction heating (>350°C or more) of short duration is envisaged to have transformed shear laminae into a fluid medium that melted the outer fringes of the therein transported, quite possibly, *amorphous or cryptocrystalline quartz* porphyroclasts (Fig. 4d).

*Geochemistry and the Eu anomaly*

Negative Eu anomalies are not common in MORB and are typically absent from Ocean Island Basalt (OIB) (Weil and Drake 1973; Pearce and Cann 1973; Kay and Hubbard 1978; Bence et al. 1979; Wood et al. 1979; Perfit et al. 1980). Therefore, the negative Eu anomalies of the study area present a paradox to what should be expected because relict plagioclase laths occur in the basalt lithic grains and throughout the better preserved shear zone rocks, wherein Europium enrichment should be expected (Weill and Drake 1973; Kimata 1988). However, the observed plagioclases, for the most part, are sericitised ghosts from which, it is suggested, Eu was lost together with Ca during sericitisation (Barker 1998), which would explain the negative anomalies. Therefore it is plausible that the original magma was of MORB origin, in which subsequent ocean-floor metasomatic removal of Europium occurred. From the bio-geological point of view, the occurrences of radiolarian chert together with the observed litho-grains of basalt definitely indicate that most of the shear-zone rocks were derived from the ocean floor and not from an island arc source. Nevertheless, the discrimination diagrams (Fig.8b) show that about half of the samples have IAB affinities, which implies that the rocks of the *shear-zone* may have originated from two sources (see below).

*The geotectonic evolution of the study area*

The Cretaceous carbonates of the investigated islands do not have a sedimentary substrate; they are in allochthonous tectonic contact with shear-zone rocks of oceanic-floor origin (radiolarites and basalt), which is considered here to have been the glide horizon upon which the Cretaceous carbonate platform of the *Paikon-Palouki nappe* was transported. From the biostratigraphic evidence (see above), the Cretaceous carbonate platform was a shallow marine, reefal facies that evolved in early Late Cretaceous to Maastrichtian/Palaeocene time, so that the *Paikon-Palouki nappe* cannot have been transported before Early Palaeocene time. This leads to the question, where did the shallow marine, reefal, carbonate platform evolve? From the composition of the shear-zone-substrate, it may have been an area of uplifted ocean-floor rocks, e.g. Eohellenic metabasites, over which the carbonate platform could have accumulated *in situ*, (analogous to Evvoia, Scherreiks 2000). An alternative is that the Cretaceous carbonates are of Vardar origin in analogy to a similar Cretaceous carbonate platform reported to have developed in the Paikon subzone (Brown and Robertson 1994). We envisage here a plate-tectonic, platform-setting (Bosence 2005), inferring that the Cretaceous carbonate platform evolved in the forearc basin of the Vardar-Paikon sub-zone and subsequently was transported over ocean floor formations (Fig. 9). Present day forearc basins do not harbour carbonate platforms thicker than about 100 metres (Dorobek 2007), which is not surprising considering climatic and sea-level fluctuations of the Pleistocene. However, the supposed forearc basin proposed here, had all of Cretaceous time to accumulate and there are examples of ancient forearc basins in which thick reefal carbonate platforms had evolved (Dorobek 2007). The present model (Fig, 9) infers that the carbonate platform of the forearc basin gradually overthrust the simultaneously subsiding Sporades, together with scrapped-off MORB and IAB mélange as the Almopias oceanic plate was subducting and the eastern Pelagonian plate collided with the Paikon-Paeonian back-stop. (The indications of high temperature (450°C) and pressure reported by Porkoláb et al. (2019) are considered in this contribution to have been caused by tectonic compression of the shear zone rocks between the subducting Almopias plate and the arc back-stop.)

It has been pointed out (Jacobshagen and Matarangas 2004), that an additional overthrust, which no longer exists, presumably having been removed by erosion, may have caused the metamorphism of Cretaceous marbles (ibid.). However, considering that the marbles occur tectonically interleaved with recrystallised fossiliferous limestone, it is plausible that imbrication-faulting within the Paikon-Palouki nappe caused low-grade metamorphism with differing intensities as a result of friction heat. Recrystallisation of limestone can be enhanced at temperatures even below 200°C (Burchard 1990; Ferrill et al 2004; Nicolas et al. 2017). This alternative hypothesis would eliminate the theoretical necessity of a “Paeonian nappe Z” (Fig. 9, Fig. 2a).

*Subductions of two slabs of oceanic lithosphere*

Our model (Fig. 9) emphasises that two separate subductions had taken place, represented by slab X and slab Y in Fig. 2b. Slab X is the oceanic leading edge of the continental Pelagonian plate and Y is the subducting eastern Almopias oceanic plate. In order to test the model shown in Fig. 9, a tomographic reconstruction following the Bijwaard-Spakman, Engdahl (BSE) *model (*Bijwaard et al. 1998) was used to construct a NE-SW vertical section through the mantle below the study area using the tomographic model of the Aegean area (Fig. 10). The patterns of the seismic anomalies in the Aegean region below the study area (in the BSE models) appear to substantiate that two slabs X and Y were subducted and they best fit the envisaged surface geology.

In a corresponding vertical section through Crete and the Bosphorus, the BSE tomographic model of Bijwaard et al. (Fig. A8 in Hafenschied 2004; and section 15 in Bijwaard 1998; and 15 in Fig 5 of Hafenschied et al. 2006) shows two anomalies, which from the point of view of this presentation may represent remnants of two subducted slabs: one between 500 km and 1800km depth, the other, between the near surface to 1500-2000km depth. (However, this interpretation contradicts those of the last cited authors).

It is realised that many variables and many unknown factors make tomographic reconstructions highly complex (Bijwaard et al. 1998, Norton, 1999; Hafenschied 2004): e.g. the velocities of the sinking slabs, the drift rates and direction of the European plate, the thickening of the slabs as they sink, competing forces of buoyancy verses viscous drag, (Ichikawa et al. 2016) etc.. Further problems concern the *break-off times* of the sinking slabs which are only roughly envisaged, but are theoretically known to have occurred, based on the surface geology and the tomographic model. From Figure 10, the leading edge of the slab X sank 900km since breaking off, probably after Valanginian time because the break-off is supposed to have triggered extreme erosion on Skopelos and Alonnisos. The emplacement of the *Paikon-Palouki nappe* occurred during early Palaeocene as a result of the collision of eastern Pelagonia with the Paikon-Paeonian arc. Since its break-off, slab Y sank about 400km (Fig.10), and, from Figure 10, the leading edges of both slabs presently have reached the same depth of about 2100km.

Using the available variables, it is *not possible* to arrive at a tenable time-schedule of subduction. The rates of subsidence of the oceanic slabs are reported to range from about 3cm/yr in the upper mantle to about 1cm/yr in the lower mantle (Norton 1999). These rates are much too high for the model we envisage. However, the sinking rates can be much lower below 300-500 kilometres, in the lower mantle, eventually approaching zero (see Lallemand and Funiciello 2009; and others in Ichikawa et al. 2016).

In spite of these insecurities, a few estimates are attempted here: the depth of slab-subsidence since the break-off is known (from the model) and the times of the break-off (from the surface geology) are Post-Valanginian (~130Ma) for slab X, and Late Palaeocene (~58Ma) for slab Y.

Using an “*average”* subsidence rate of 0.68cm/y, we arrive at:

Break-off of slab X: (0.68cm/y.t = 900km) 130Ma ago Hauterivian/Baremian

Break-off of slab Y: (0.68cm/y.t = 400km) 58Ma ago Late Palaeocene,

Although the above model is speculative, the BSE model of Figure 10 supplies enough information to estimate the one-time width of the Almopias ocean by adding the lengths of the subducted slabs together, with the result: the Almopias ocean had a width of about 2500-3000 km. This does not mean that there had been an ocean of this width at any one time because subduction and obduction could have taken place simultaneously together with an actively spreading mid oceanic ridge.

The *Paikon-Palouki nappe* which is assumed to have covered the islands of the Sporades did not reach Evvoia. (Field work has not been carried out on Skiathos or on Skyros (compare Harder et al.1983). Palaeocene/Eocene uplift and normal faulting occurred on Alonnisos and Skopelos probably at the same time as on Evvoia (Scherreiks et al. 2014). Post collision faulting in the Aegean area, north and north-west of the study area, is described in (Papanikolaou et al. 2006).

**CONCLUSIONS**

The pre-Upper Triassic basement of Evvoia and the successions of rocks exposed in the Glossa area of Skopelos are considered to correlate well. They occur stratigraphically below Pelagonian Upper Triassic dolomite separated by an intra-formational fault zone. The basement of Evvoia and Skopelos is assumed to extend to the Pelagonian/Vardar suture eastwards beyond the island of Gioura. The metabasites of the basement are suggested to have been rift basalts that formed during the Permo-Triassic break-up of Pangaea.

Typical Pelagonian platform carbonates are encountered on all of the studied islands. The stratigraphic succession on Evvoia is almost complete, whereas the Eohellenic ophiolite and the Jurassic has been eroded from Skopelos and on Alonnisos the Eohellenic ophiolite has been more or less completely eroded. The Early Cretaceous period of intensive erosion is envisaged to have been caused by the buoyancy-rebound of eastern Pelagonia after the leading oceanic edge of the Pelagonian plate had broken-off and sank.

While erosion was taking place on Skopelos and Alonnisos, the eastern side of the Almopias oceanic plate continued subducting beneath the Paikon-Paeonian island arc and simultaneously, Cretaceous carbonate platforms evolved over eroded ophiolite in Evvoia and evolved in the forearc basin of the Paikon-Paeonian island arc complex. Ultimately, eastern Pelagonia collided with the Paikon-Paeonian arc whereby the Cretaceous/Palaeocene forearc platform was overthrust westwards, initially over ocean floor rocks before it was emplaced over the Pelagonian carbonates of Alonnisos and Skopelos and neighbouring islands. Documenting the emplacement of this *Paikon-Palouki nappe* is a dynamically metamorphosed shear-zone formation of oceanic and carbonate rocks, characterised by fluxion structured cataclasites, mylonites, phyllonites and pseudotachylites.

The width of the Almopias ocean was probably a few thousand kilometres. The final stages of the closure of the Almopias ocean took place during two episodes: first (Late Jurassic-Early Cretaceous), as the Eohellenic ophiolite (west Almopias) was obducted westwards and the leading oceanic edge of the Pelagonian plate was being subducted, and second (Early Palaeocene), as eastern Almopias subducted beneath the Paikon-Paeonian island arc. It is suggested that the relicts of two subducted slabs of Almopias oceanic lithosphere can be seen in BSE seismic-tomographic images of the mantle beneath the Aegean region.

Future research would be rewarding in the following fields: further correlations between the Pelagonian basement of NW Evvoia and NW Skopelos; investigations of the shear-zone formation in respect to a full-fledged fabric analysis of the mylonites and possible pseudotachylites; possible radiolarian extractions and dating; better seismic tomographic models; investigation and reconstruction of the Cretaceous carbonate platform; post collision deposition and neo-tectonics.

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**Table 1 Observed and identified fossils**

**Tables 2A and 2B Geochemistry**
Analyses performed by Actlabs, Canada, with Fusion ICP (Inductively coupled plasma atomic emission spectroscopy) and Fusion MS (Mass spectrometry)

**Description of Figures**

**Fig. 1** The study area in the Internal Hellenides
a) The outlined study area extends from northern Evvoia eastwards to Skopelos and Alonnisos and smaller islands of the Sporades. It is in the Pelagonian zone of the Internal Hellenides and borders on the Vardar zone
b) Overview map of the islands of the study area in the Northern Sporades
Field work was carried out on Evvoia, Skopelos and Alonnisos; reconnaissance field work on Kyra Panagia, Peristera and Megalo Adherfi. The Pelagonian/Vardar suture is suggested to lie between Gioura and the basalt island of Psathora.
**Fig. 2** Schematic cross section of the Internal Hellenides (modified after Aubouin et al. 1977; in consideration of: Mercier 1968, Mercier and Vergely 2002, and others in Michail et al. 2016).
a) The zones and sub-zones of the Internal Hellenides are shown and the geotectonic positions of the study areas are indicated. Oceanic crust had obducted onto the Pelagonian zone (x-x'), and, as shown, the Paikon and Paeonian thrust faults (y-y') and (z-z') do not reach Evvoia but affect the study area in the Sporades.

b) This platetectonic cartoon of the ophiolite obduction onto the Pelagonian plate is modified from Scherreiks et al. 2014). The Eohellenic ophiolite obduction over the Sporades and Evvoia occurred after the oceanic leading edge of the Pelagonian plate had been subducted. After the ophiolite sheet had reached Evvoia, during Valanginian time, the leading oceanic edge of Pelagonia is supposed to have broken off (slab x), thereby initiating uplifting of the eastern part the Pelagonian plate and erosion on Skopelos and Alonnisos. Convergence and subduction of the eastern Almopias ocean continued (slab y). (V-SM = Vardar-Serbo-Macedonian complex)

**Fig. 3** The modified stratigraphies of Alonnisos and Skopelos compared to disputed previous stratigraphies

a) The relatively continuous stratigraphic column of Evvoia (Permo-Triassic to Cretaceous) correlates well with the basement formations and Triassic dolomite formation of Skopelos, and with the Upper Jurassic reefal facies of Alonnisos. The Jurassic formations have been eroded from Skopelos, with the exception of some ?10s of metres of earliest Jurassic peritidal dolomite (see text). The Eohellenic ophiolite has been eroded from Skopelos and for the most part from Alonnisos. Transgressional Cretaceous is only found on Evvoia. *The shear-zone* formation is a dynamically metamorphosed mélange of ocean floor crust. The biostratigraphy (see text) indicates that the Paikon-Palouki nappe was probably emplaced during the Early Palaeocene.

b) shows stratigraphies of Alonnisos and Skopelos according to previous researchers. The disputed points are underscored in pink

- The Mourtero series of Alonnisos is actually tectonically situated on top of the disconformity (Upper Jurassic).
- Permian and Triassic formations could not be verified nor dolomite on Alonnisos.
- The microfauna that had been reported to indicate Albian age must be updated to the time-span of Albian-Turonian (see Bio-stratigraphy).
- The Glossa unit is considered to be the Palaeozoic-Permo-Triassic basement of Skopelos, stratigraphically below the Middle Triassic. The Eohellenic ophiolite of Skopelos was completely eroded. Eohellenic relicts may occur on Alonnisos.
- The Palaeocene thrust plane extends over the Pelagonian disconformity of both islands. Mesoautochthonous was either not deposited or had been eroded. The present Cretaceous and subjacent shear zone of the Palouki nappe are allochthonous.
- The “flysch“, conglomerates, metaclastics, phyllites and basic rocks, all belong to one tectonic shear-zone formation that occurs stratigraphically on top of the disconformity and below the Cretaceous carbonate formation.

**Fig. 4** Rocks of the shear zone formation

a) photomicrographs xpl, of a basalt lithic grain, Alonnisos. Acicular plagioclase in a vesicular basalt. b) photomicrograph ppl, slightly deformed radiolarian ghosts in sericitised, fine crystalline quartz, Ag. Riginos, Skopelos. c) pseudo-conglomerate, Ag. Georgios, Alonnisos, is actually a shear zone rock composed of porphyroclasts aligned parallel to the (+/- horizontal) foliation/shear planes. Secondary shear appears to have formed at an angle of about 45° with the foliation (s1). d) Photomicrograph (xpl). This fluxion-structured band of quartz clasts in opaque/isotropic? matter is interpreted as pseudotachylite. The fluxtion-band is bordered by sericite (upper left, lower right). The quartzes appear to be disintegrating along their margins, frozen in a flood of opaque matter. e-f) photomicrographs ppl, foliated phyllite. These two examples of shearing-couples show the sense of shear and the crenulation-solution cleavage that formed perpendicular to the compressional-stress-component of the shearing couple (examples are described in Burg 2017). g-h) photomicrographs ppl, foliated phyllite. These two examples show development of a new schistosity via a crenulation cleavage (stage 4 in . Bell and Rubenach, 1982). Examples e-h involve neomineralisation and recrystallisation of sericite.

**Fig. 5** Geologic Map of Alonnisos

On Alonnisos, Jurassic crystalline limestones and marbles are the oldest outcropping rocks (Kelepertsis 1974). After erosion had removed the Eohellenic nappe, the Paikon-Palouki nappe was emplaced during the Palaeocene (see biostratigraphy). The Geologic Map of Alonnisos mainly differs from the previous maps in two disputed areas: first, the Jurassic carbonates underlie the shear zone in the area between Cape Telion and Megali Ammos Bay and second, Cretaceous rudist limestones overlie the shear zone in the area between Koumarola and Mourtero.

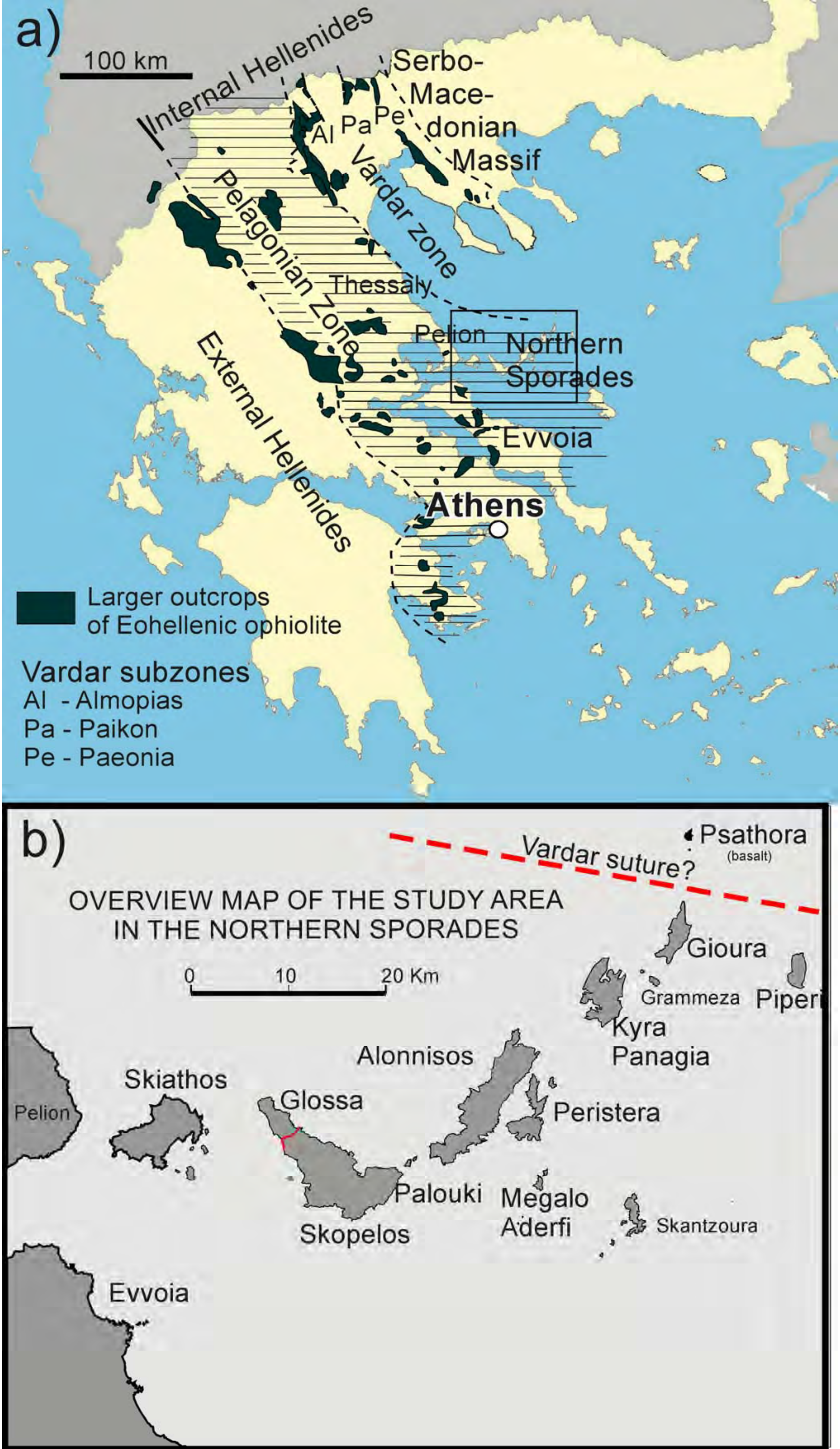
**Fig. 6** Tectonic sections of Alonnisos and skopelos

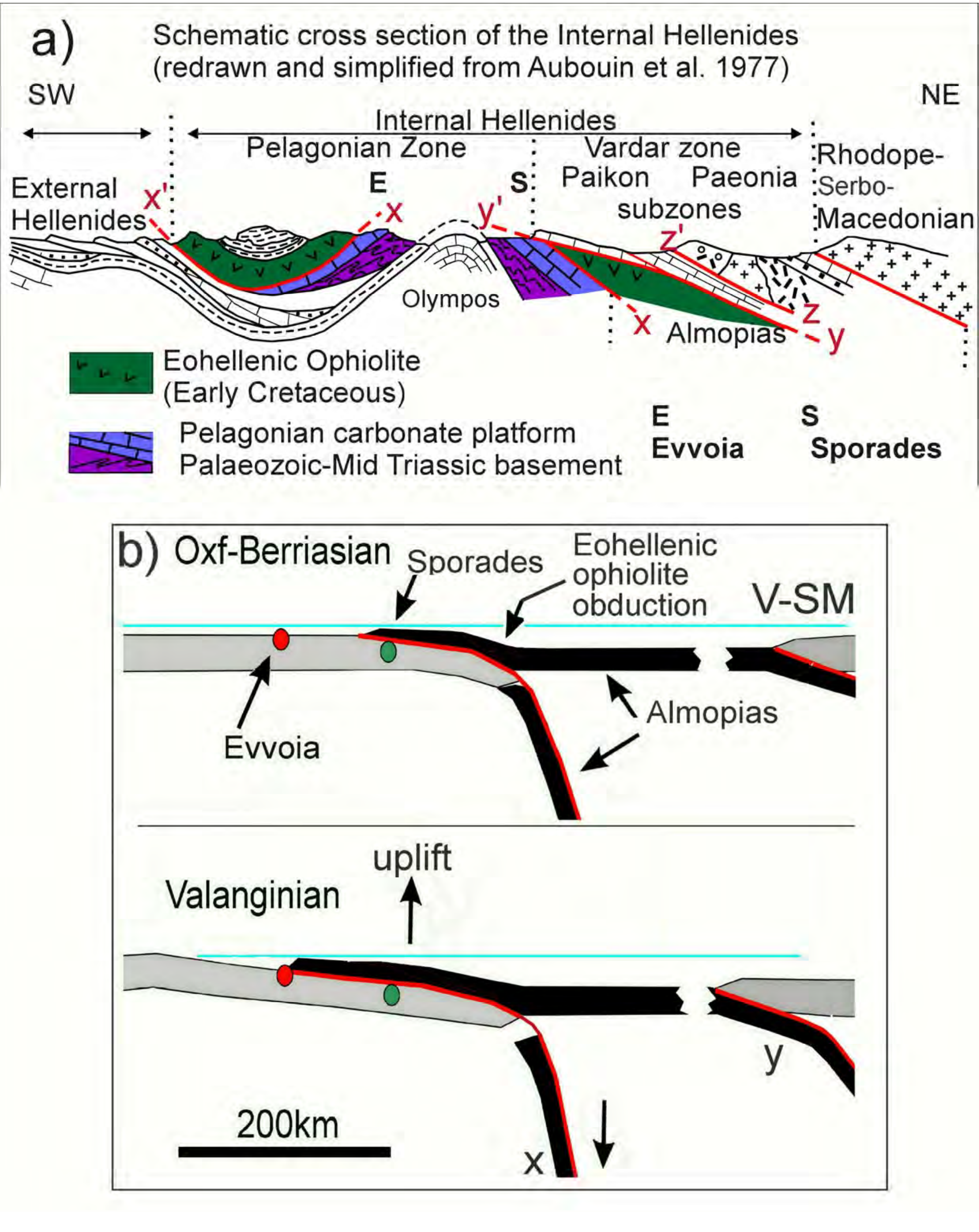
**a1-2** sections of Alonnisos show gentle folds without pronounced vergence, however in the metre range intensive folding had occurred in the *shear-zone* formation. The Cretaceous carbonates are exposed on the highest areas of Alonnisos, e.g. Kouvouli and Geladias. Jurassic carbonates underlie the *shear-zone* formation which in turn is overlain by the Cretaceous carbonates that outcrop on the hilltop of Vouno (south of Tsoukalia bay). The section crosses Vati Rema and Vouno, showing folds without pronounced inclination. In the area of Koumarola and Mourtero Rudist bearing Cretaceous marble is exposed along a new road outcrop. Upper Cretaceous overlies the Mourtero unit in a broad antiform. The Jurassic carbonates extend beneath the metabasites at Vati Rema where the correct stratigraphic sequence had already been mapped by Kelepertsis (1974).

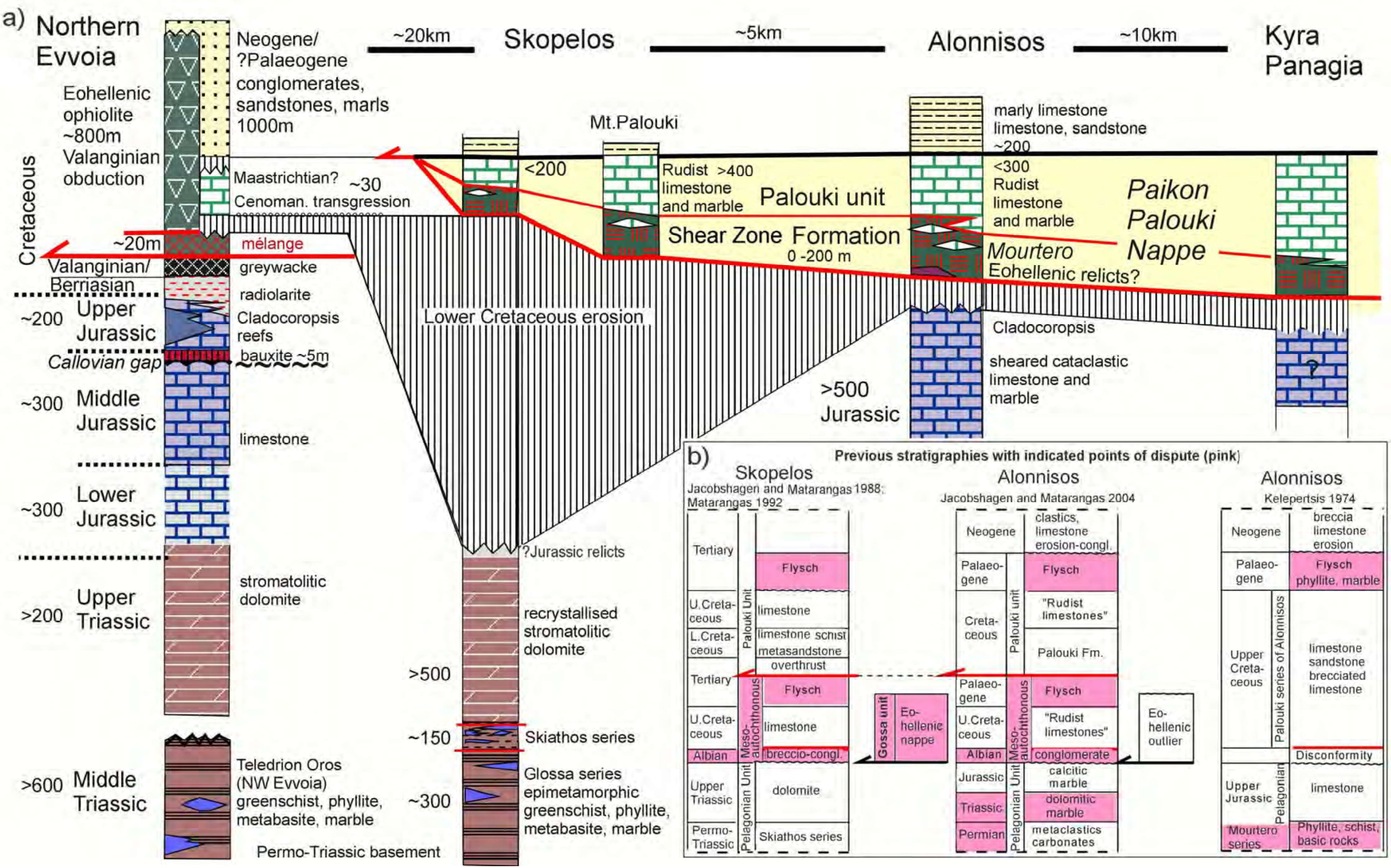
**b1** The Skopelos section, Glossa - Cape Pouda, shows the stratigraphic succession of the Pelagonian formations between the pre-Upper Triassic basement and the Upper Triassic dolomite. Intra-formational thrusting probably took place between the Triassic dolomite and the Skiathos series, and the basement formations. A distinct NE-SW striking thrust-fault zone, is located between the basement formations and the Upper Triassic dolomite formation, indicating NW vergence. The basement formations probably underlie the dolomite beneath Mt. Delfi of central Skopelos, suggesting that it is about 600m thick. A graben structure is indicated in the Pano Karia and Athinás-Temple area, in which mainly the *shear-zone* formation is exposed.
**b2** Agios Riginos – Cape Veloni: radiolarian cherts, in which pseudotachylite occurs, is exposed in a graben structure at Agios Riginos where the cherts underlie a large area of brecciated Cretaceous limestones and marbles south of Pirgos.
**b3** This section from Panormos to Glisteri Monastery, crosses Panormos bay, where radiolarite and basalt are exposed along the sole of the *shear-zone* formation. The central part of this section shows the shear zone formation overlying the Triassic dolomite.
**b4** This section transects the nappe structure of Mt. Palouki, showing that the Mt Palouki Cretaceous carbonate formation together with the shear-zone formation overthrust Upper Triassic dolomite. Some of the best insights of the shear-zone rocks can be seen at Monastery Prodromou.
**c** Photograph: road to Glisteri Monastery**,** showing the outcropping tectonic contact between brecciated Cretaceous crystalline limestones on top of intensively folded, greenschist.

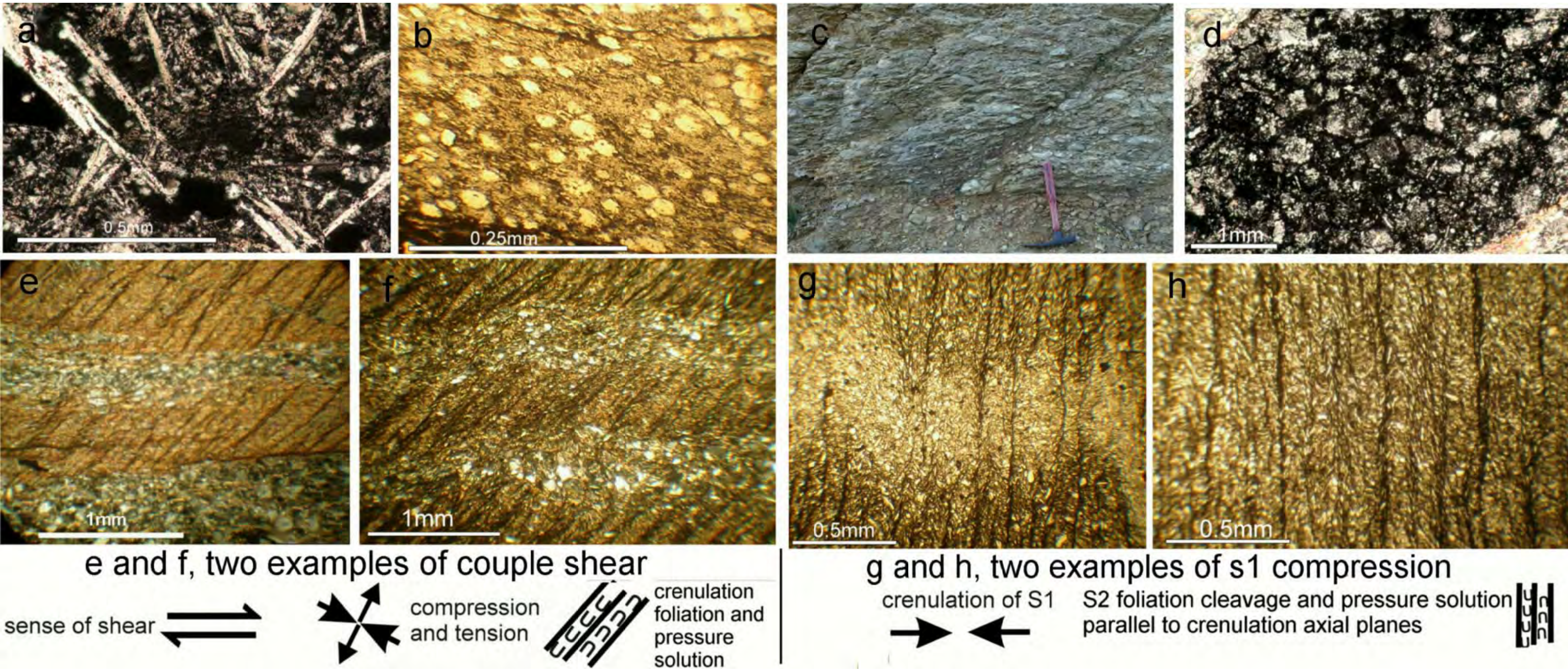
**Fig. 7** Geologic Map of Skopelos
The Pelagonian formations extend stratigraphically from the pre-Middle Triassic basement (Glossa and Skiathos series) to Upper Triassic / ?Lower Jurassic dolomites (Mt. Delfi). The Triassic dolomite is brecciated and permeated by faults in all areas where it overlies the basement. The Eohellenic ophiolite that once covered the Pelagonian formations has been removed by erosion. A tectonically emplaced shear zone formation overlies the dolomite formation and is overlain by allochthonous Cretaceous limestones and marbles of the *Paikon-Palouki nappe*. These formations occur in the southern part of Skopelos and also build the Palouki Peninsula. The position and traces of the tectonic sections 1-4 are indicated on the map and are shown in Fig.6b.

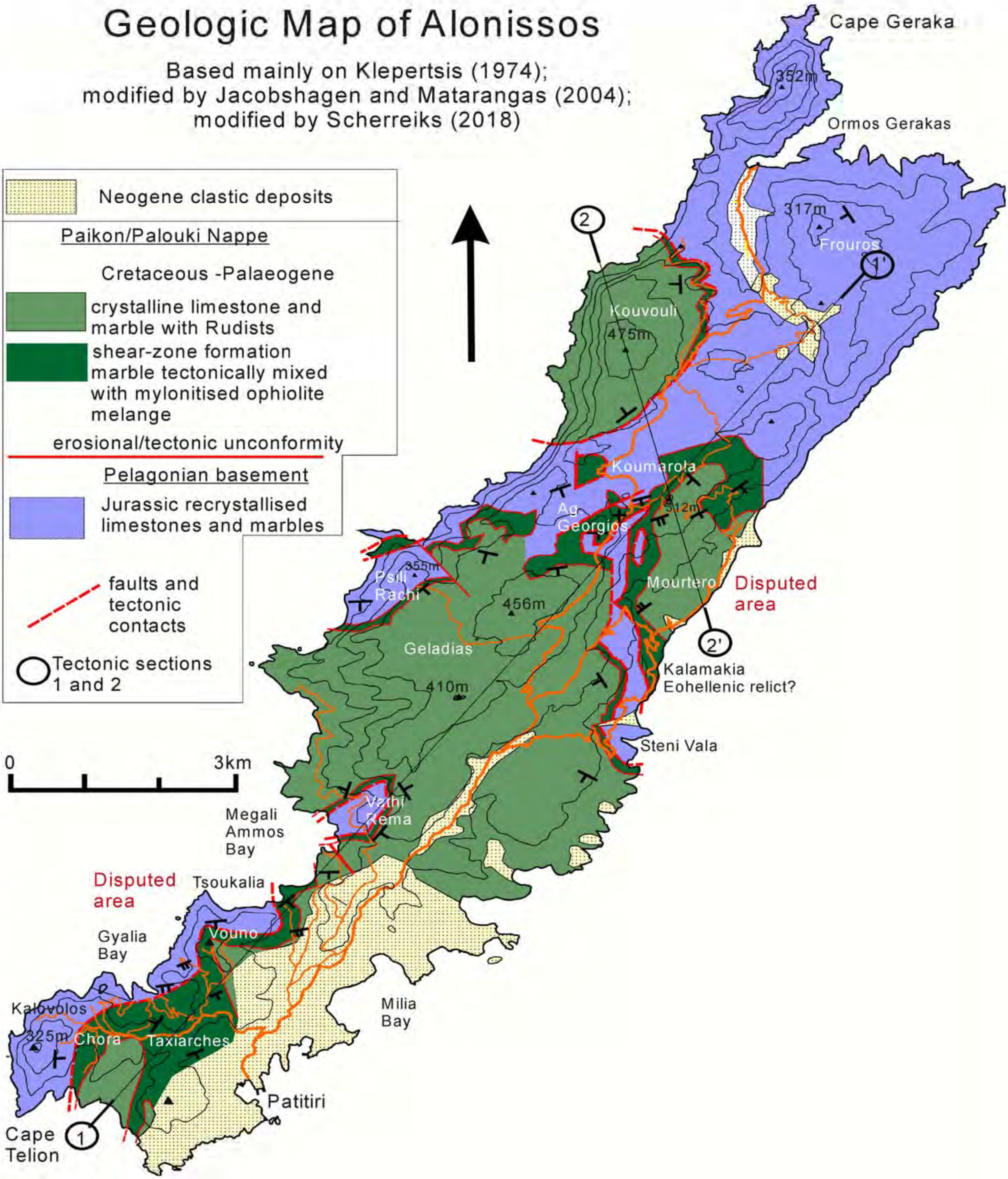
**Fig. 8** REE plots against chondrite (ppm) and discrimination diagrams
**a1-a3)**The REE plots are of rocks from the *shear-zone* formation with the exception of a MOR basalt and peridotite from Evvoia and three samples from the Glossa area (G41, G1, G17). The plots indicate that the samples from the shear zone are of basaltic origin, mostly having negative Eu anomalies. There are mainly two groups: those with relative light REE enrichment and those with relative light REE depletion. Contamination occurred because of tectonic mixing with limestones, for example S7/17, a calc-schist. (The plots, a1-a3, of the individual samples are coincidentally arranged in the order that they came from the laboratory, the sample codes are on the left. Their order does not correspond to the Geochemistry Table 2A and 2B.)
**b)** Discrimination diagrams compiled from samples of Table 2A and 2B
The AFM diagram shows that the samples correspond to the calc-alkaline series with few exceptions. The discrimination diagrams indicate MORB provenience and IAB affinities (see text).
**Fig. 9** Cartoon of the Palaeocene, Pelagonian-Paikon-Arc collision (approximate scale).
The Eohellenic ophiolite (Almopias oceanic crust) was obducted westwards onto the eastern, continental Pelagonian plate, and the eastern Almopias plate subducted eastwards beneath the Paikon Arc. Two subductions are indicated: slab x (= the leading oceanic edge of the Pelagonia), and slab y (= the eastern half of the Almopias plate). Slab x is supposed to have broken off during the Early Cretaceous, thereby liberating the relatively buoyant eastern-Pelagonia and initiating uplift and erosion on the Sporades. Continued convergence finally caused the collision of eastern Pelagonia with the Cretaceous, carbonate-forearc-basin, whereby the Paikon-Paeonian arc acted as a back-stop. The Cretaceous carbonate platform overthrust eastern Pelagonia (Sporades) together with scraped off ocean floor mélange (shear-zone formation) (see text).
**Fig. 10** Seismic tomographic interpretation of positive seismic velocity anomalies beneath a NE-SW section through the mantle below the study area (green asterisk), constructed from BSE-images of the Bijwaard et al. (1998) Model, ascertained from Hafkenscheid (2004)
This model is based on enlargements of the Aegean region from the BSE-Model (Bijwaard et al. 1998). The images, at the left show the trace of the NE-SW vertical section through the six levels of the mantle (500-810-1040-1325-1500-2100km) below the study area; red dot at location of strongest signal. The grey cloud at the right depicts the positive seismic velocity anomalies in the cross section through the mantle, interpolated from one BSE level to the next, with the strongest signals at the centre of the cloud (red dots). The heavy lines are supposed to represent the central portions of relict oceanic slabs of which there are apparently two: X and Y. Slab X must have broken off before slab Y. The upper-most tomographic perturbations of slab X are at about 900km depth, which is the depth of subsidence since the break-off; slab Y reached a depth of about 400km presumably after the collision of Pelagonia with the Paikon arc. Both slabs, X and Y, sank down nearly to the same level, at about 2100km, which infers that they had subducted more or less simultaneously, or intermittently, and reached approximately the same depth.


a)
100 km
Internal Hellenides
Serbo-Macedonian Massif
Al
Pa
Pe
Vardar zone
Pelagonian Zone
Thessaly
Pelion
Northern Sporades
External Hellenides
Evvoia
Athens
?
Larger outcrops of Eohellenic ophiolite
Vardar subzones
Al - Almopias
Pa - Paikon
Pe - Paeonia
b)
Psathora
(basalt)
Vardar suture?
OVERVIEW MAP OF THE STUDY AREA IN THE NORTHERN SPORADES
0
10
20 Km
Gioura
Grammeza
Piperi
Kyra Panagia
Alonnisos
Skiathos
Glossa
Peristera
Pelion
Palouki
Megalo Aderfi
Skantzoura
Skopelos
Evvoia

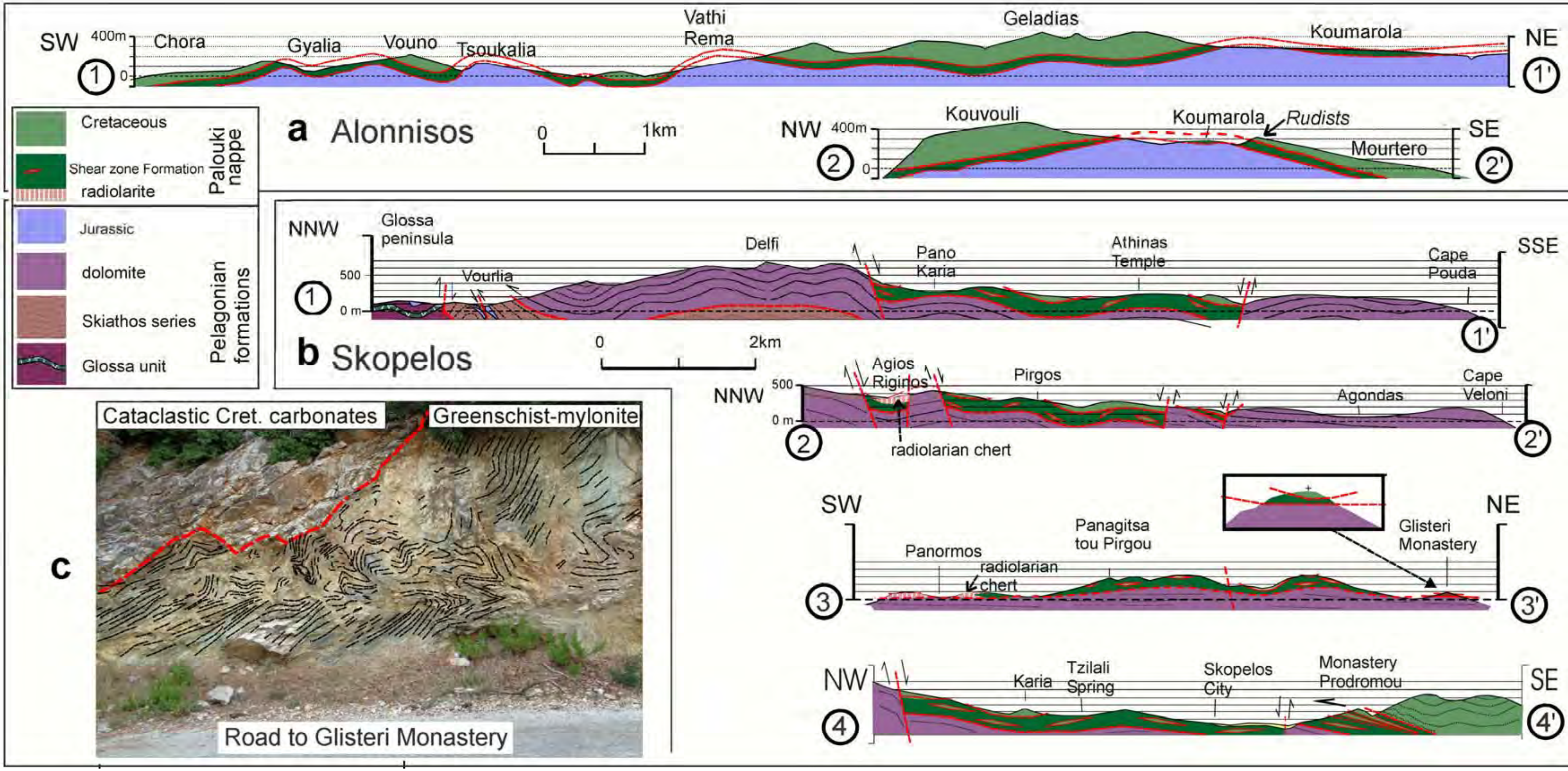

a)
Schematic cross section of the Internal Hellenides
(redrawn and simplified from Aubouin et al. 1977)
SW
NE
Internal Hellenides
Pelagonian Zone
Vardar zone
Rhodope-
Serbo-
Macedonian
External
Hellenides
E
S
Paikon
Paeonia
subzones
x'
x
y'
z'
z
y
Olympos
Almopias
Eohellenic Ophiolite
(Early Cretaceous)
Pelagonian carbonate platform
Palaeozoic-Mid Triassic basement
E
Evvoia
S
Sporades
b) Oxf-Berriasian
Sporades
Eohellenic
ophiolite
obduction
V-SM
Evvoia
Almopias
Valanginian
uplift
200km
y
x

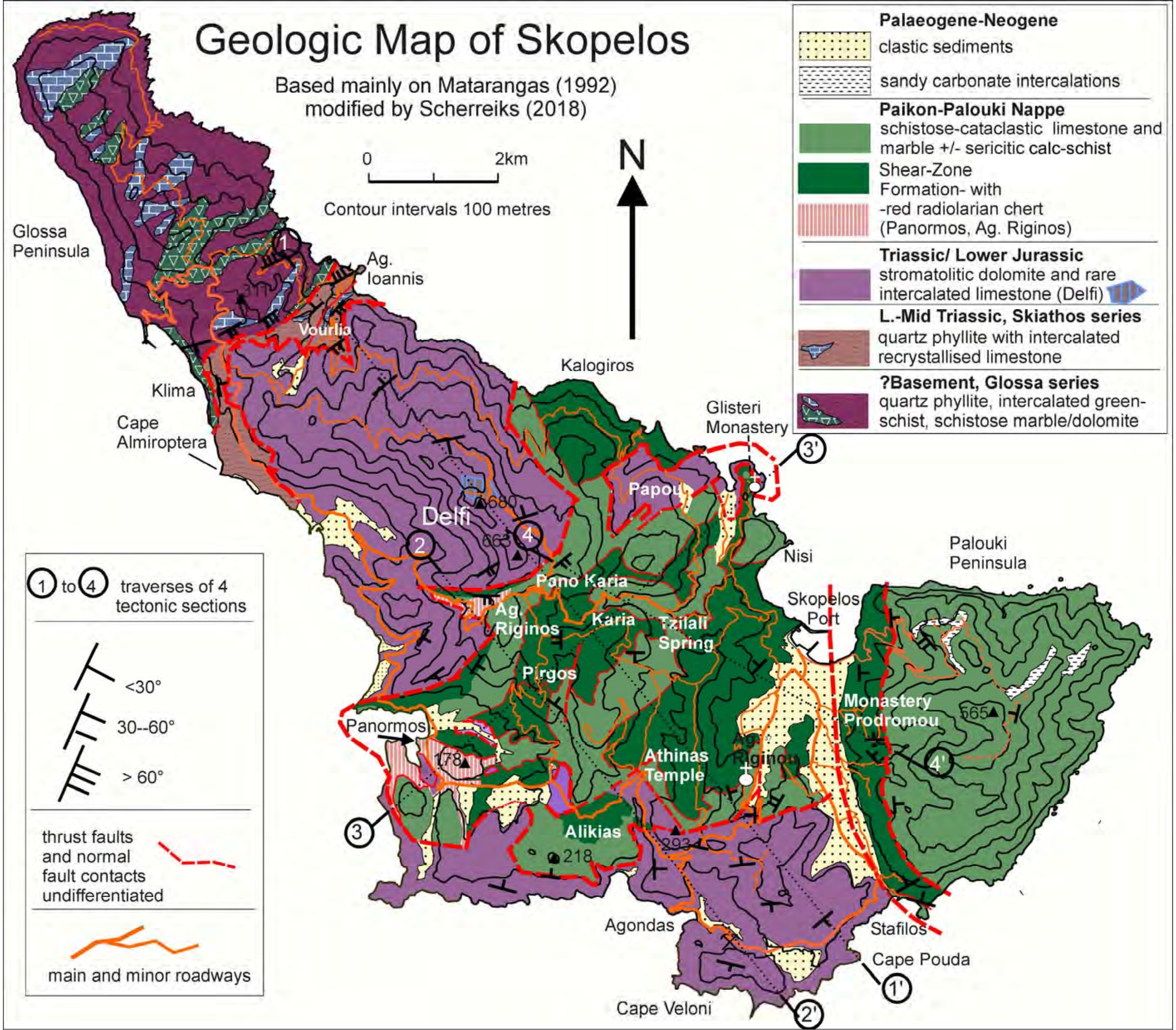

a)
Northern Evvoia
~20km
Skopelos
~5km
Alonnisos
~10km
Kyra Panagia
Neogene/ ?Palaeogene conglomerates, sandstones, marls 1000m
Eohellenic ophiolite ~800m Valanginian obduction
Cretaceous
Maastrichtian?
~30
Cenoman. transgression
~20m
mélange
Valanginian/ Berriasian
greywacke
radiolarite
~200
Upper Jurassic
Cladocoropsis reefs
Callovian gap
bauxite ~5m
~300
Middle Jurassic
limestone
~300
Lower Jurassic
>200
Upper Triassic
stromatolitic dolomite
>600
Middle Triassic
Teledrion Oros (NW Evvoia) greenschist, phyllite, metabasite, marble
Permo-Triassic basement
Mt.Palouki
<200
Rudist >400 limestone and marble
Palouki unit
Shear Zone Formation
0 -200 m
Lower Cretaceous erosion
?Jurassic relicts
recrystallised stromatolitic dolomite
>500
~150
Skiathos series
~300
Glossa series epimetamorphic greenschist, phyllite, metabasite, marble
marly limestone limestone, sandstone ~200
<300 Rudist limestone and marble
Mourtero
Eohellenic relicts?
Paikon Palouki Nappe
Cladocoropsis
sheared cataclastic limestone and marble
>500 Jurassic
?
b)
Previous stratigraphies with indicated points of dispute (pink)
Skopelos
Jacobshagen and Matarangas 1988; Matarangas 1992
Tertiary
Flysch
U.Creta-ceous
limestone
L.Creta-ceous
limestone schist metasandstone
Palouki Unit
overthrust
Tertiary
Flysch
U.Creta-ceous
limestone
Albian
breccio-congl.
Meso-autochthonous
Upper Triassic
dolomite
Pelagonian Unit
Permo-Triassic
Skiathos series
Gossa unit
Eo-hellenic nappe
Alonnisos
Jacobshagen and Matarangas 2004
Neogene
clastics, limestone erosion-congl.
Palaeo-gene
Flysch
Creta-ceous
"Rudist limestones"
Palouki Fm.
Palouki unit
Palaeo-gene
Flysch
U.Creta-ceous
"Rudist limestones"
Albian
conglomerate
Meso-autochthonous
Jurassic
calcitic marble
Triassic
dolomitic marble
Permian
metaclastics carbonates
Pelagonian Unit
Eo-hellenic outlier
Alonnisos
Kelepertsis 1974
Neogene
breccia limestone erosion
Palaeo-gene
Flysch phyllite, marble
Upper Creta-ceous
limestone sandstone brecciated limestone
Palouki series of Alonnisos
Disconformity
Upper Jurassic
limestone
Pelagonian
Mourtero series
Phyllite, schist, basic rocks


a
0.5mm
b
0.25mm
c
d
1mm
e
1mm
f
1mm
g
0.5mm
h
0.5mm
e and f, two examples of couple shear
sense of shear
compression and tension
crenulation foliation and pressure solution
g and h, two examples of s1 compression
crenulation of S1
S2 foliation cleavage and pressure solution parallel to crenulation axial planes



Geologic Map of Alonissos
Based mainly on Klepertsis (1974);
modified by Jacobshagen and Matarangas (2004);
modified by Scherreiks (2018)
Neogene clastic deposits
Paikon/Palouki Nappe
Cretaceous -Palaeogene
crystalline limestone and marble with Rudists
shear-zone formation marble tectonically mixed with mylonitised ophiolite melange
erosional/tectonic unconformity
Pelagonian basement
Jurassic recrystallised limestones and marbles
faults and tectonic contacts
Tectonic sections 1 and 2
0
3km
Cape Geraka
352m
Ormos Gerakas
317m
Frouros
1'
2
Kouvouli
475m
Koumarola
Ag. Georgios
312m
Psili Rachi
355m
456m
Mourtero
Disputed area
2'
Geladias
410m
Kalamakia
Eohellenic relict?
Steni Vala
Vathi Rema
Megali Ammos Bay
Disputed area
Tsoukalia
Gyalia Bay
Vouno
Kalovolos
325m
Chora
Taxiarches
Milia Bay
Patitiri
Cape Telion
1


SW
400m
0
Chora
Gyalia
Vouno
Tsoukalia
Vathi Rema
Geladias
Koumarola
NE
1
1'
Cretaceous
Shear zone Formation
radiolarite
Palouki nappe
a Alonnisos
0
1km
NW
400m
0
Kouvouli
Koumarola
Rudists
Mourtero
SE
2
2'
Jurassic
dolomite
Skiathos series
Glossa unit
Pelagonian formations
NNW
Glossa peninsula
Vourlia
Delfi
Pano Karia
Athinas Temple
Cape Pouda
SSE
500
0 m
b Skopelos
0
2km
NNW
500
0 m
Agios Riginos
Pirgos
Agondas
Cape Veloni
radiolarian chert
SW
NE
Panormos
radiolarian chert
Panagitsa tou Pirgou
Glisteri Monastery
3
3'
NW
Karia
Tzilali Spring
Skopelos City
Monastery Prodromou
SE
4
4'
c
Cataclastic Cret. carbonates
Greenschist-mylonite
Road to Glisteri Monastery



Geologic Map of Skopelos
Based mainly on Matarangas (1992)
modified by Scherreiks (2018)
0
2km
Contour intervals 100 metres
N
Palaeogene-Neogene
clastic sediments
sandy carbonate intercalations
Paikon-Palouki Nappe
schistose-cataclastic limestone and marble +/- sericitic calc-schist
Shear-Zone Formation- with
-red radiolarian chert (Panormos, Ag. Riginos)
Triassic/ Lower Jurassic
stromatolitic dolomite and rare intercalated limestone (Delfi)
L.-Mid Triassic, Skiathos series
quartz phyllite with intercalated recrystallised limestone
?Basement, Glossa series
quartz phyllite, intercalated green-schist, schistose marble/dolomite
1 to 4 traverses of 4 tectonic sections
<30°
30--60°
> 60°
thrust faults and normal fault contacts undifferentiated
main and minor roadways
Glossa Peninsula
Ag. Ioannis
Vourlia
Kalogiros
Klima
Cape Almiroptera
Glisteri Monastery
Papou
Delfi
680
663
Nisi
Palouki Peninsula
Pano Karia
Ag. Riginos
Karia
Tzilali Spring
Skopelos Port
Pirgos
Monastery Prodromou
565
Panormos
178
Athinas Temple
Alikias
218
293
Agondas
Stafilos
Cape Pouda
Cape Veloni
1
2
3
4
1'
2'
3'
4'

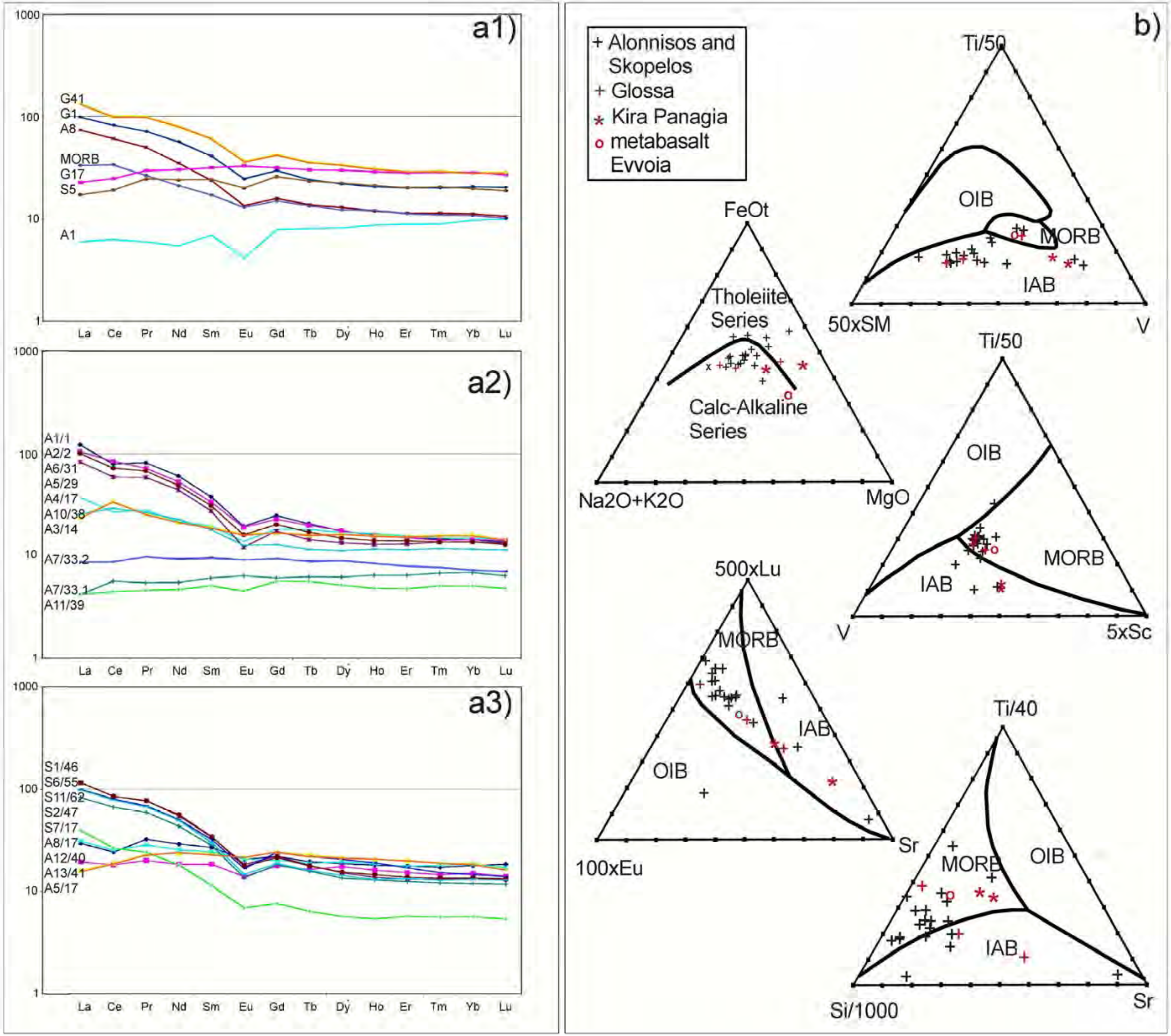

a1)
G41
G1
A8
MORB
G17
S5
A1
1000
100
10
1
La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
a2)
A1/1
A2/2
A6/31
A5/29
A4/17
A10/38
A3/14
A7/33.2
A7/33.1
A11/39
a3)
S1/46
S6/55
S11/62
S2/47
S7/17
A8/17
A12/40
A13/41
A5/17
b)
+ Alonnisos and Skopelos
+ Glossa
* Kira Panagia
o metabasalt Evvoia
Ti/50
OIB
MORB
IAB
50xSM
V
FeOt
Tholeiite Series
Calc-Alkaline Series
Na2O+K2O
MgO
5xSc
500xLu
100xEu
Sr
Ti/40
Si/1000

Table 1

A) Ag. Riginou (Matarangas 1992) updated BouDagher-Fadel

- Valvulammina *picardi* HENSON
- **Updated to: Nezzazatinella *picardi* Albian to Santonian**
- Zezzazata *convexa* FLEURY (assumed Albian age)
- **Updated to: Neoiraqia *convexa* Late Cenomanian**
- Discocyclina *schlumbergerì* MUNIER-CHALMAS
- **Updated to: Dicyclina *schlumbergeri* Albian to Santonian**

B) Ag. Riginou, side road to Monastery, 5km S. of Skopelos (ident. BouDagher-Fadel)

- Rotorbinella sp.,
- Orbitoides sp.,
- Lithocodium sp.
- recrystallised algae

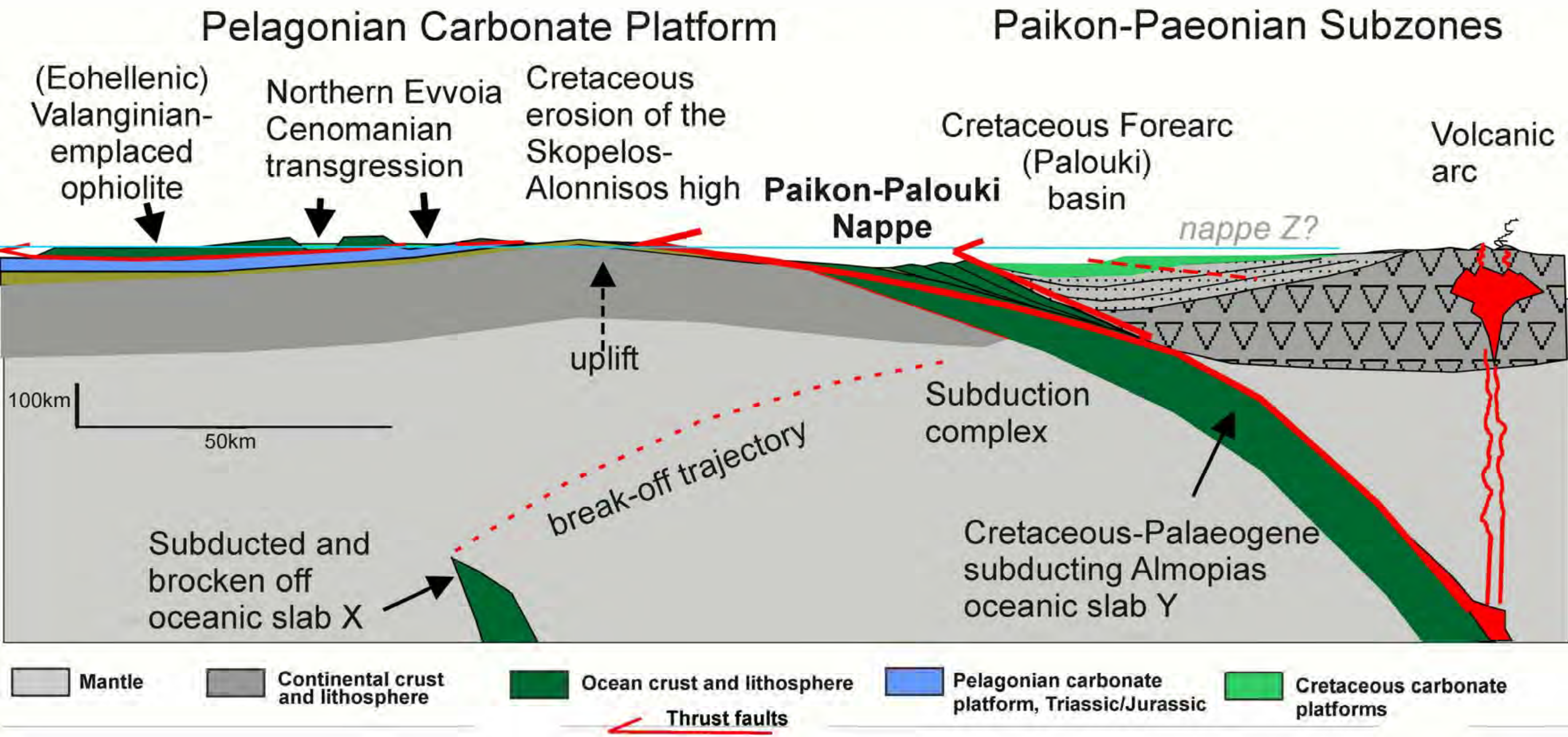
C) SE of Ag. Riginou, limestone at hairpin turn of main road (ident. BouDagher-Fadel)

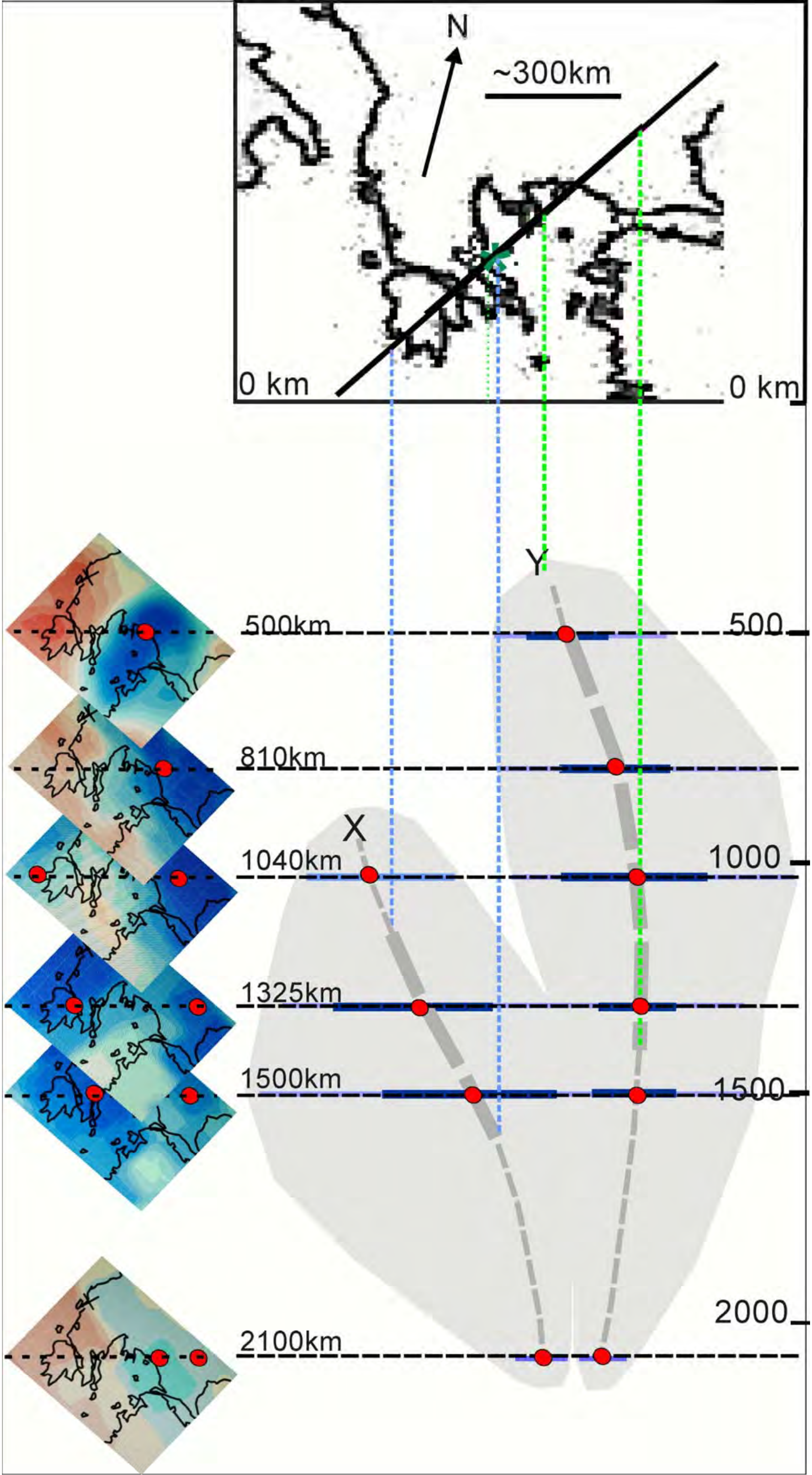
- Kathina sp.,
- Daviesina sp.,
- Lockhartia sp
- Barnacle spp.,
- recrystallised algae

D) Area south of Panormos Bay (ident. BouDagher-Fadel)

- rudists
- Orbitoides sp. (fragment)
- Rotorbinella sp.,
- Lithocodium *aggregatum*
- recrystallised algae

# The Palaeocene-Pelagonian-Paikon-Arc Collision





N
~300km
0 km
0 km
Y
X
500km
810km
1040km
1325km
1500km
2100km
500
1000
1500
2000

Table 2A

| | Si02 | A1203 | Fe203* | MnO | MgO | CaO | Na20 | K20 | Ti02 | P205 | LOI | Total | Sc | V | Sr | Y | Zr | Cr | Co | Ni |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1/1 | 58.29 | 18.12 | 7.98 | 0.055 | 4.03 | 0.38 | 1.08 | 3.42 | 0.836 | 0.11 | 6.36 | 100.7 | 19 | 139 | 44 | 28 | 184 | 250 | 19 | 100 |
| A2/2 | 66.12 | 14.36 | 6.12 | 0.034 | 2.58 | 0.36 | 1.15 | 2.91 | 0.734 | 0.13 | 5.56 | 100.1 | 16 | 125 | 48 | 27 | 185 | 240 | 13 | 90 |
| A3/14 | 73.19 | 10.08 | 7.50 | 0.083 | 2.90 | 0.27 | 1.88 | 0.82 | 0.608 | 0.04 | 2.69 | 100.1 | 17 | 201 | 74 | 29 | 83 | 130 | 17 | 30 |
| A4/17 | 57.29 | 14.41 | 12.66 | 0.129 | 6.53 | 0.05 | 0.09 | 3.31 | 0.914 | <0.01 | 4.86 | 100.2 | 25 | 161 | 5 | 28 | 147 | 1620 | 74 | 1070 |
| A5/29 | 78.56 | 7.60 | 4.14 | 0.141 | 2.86 | 0.18 | 1.26 | 0.85 | 0.563 | 0.08 | 2 84 | 99.07 | 8 | 49 | 28 | 22 | 175 | 540 | 12 | 100 |
| A6/31 | 61.12 | 17.05 | 7.16 | 0.086 | 3.73 | 0.29 | 1.14 | 3.38 | 0.756 | 0.13 | 5.18 | 100.0 | 18 | 140 | 54 | 25 | 191 | 240 | 18 | 110 |
| A7/3.1 | 47.06 | 14.20 | 9.76 | 0.184 | 8.68 | 10.21 | 1.01 | 0.54 | 0.436 | 0.03 | 8.07 | 100.2 | 43 | 214 | 307 | 10 | 28 | 490 | 39 | 110 |
| A7/3.2 | 50.76 | 15.71 | 11.17 | 0.128 | 8.56 | 3.44 | 3.30 | 2.13 | 0.587 | 0.03 | 4.12 | 99.93 | 47 | 231 | 118 | 12 | 33 | 260 | 44 | 70 |
| A10/38 | 74.03 | 10.71 | 5.47 | 0.048 | 2.84 | 0.14 | 1.42 | 1.61 | 0.532 | 0.01 | 3.11 | 99.93 | 18 | 132 | 24 | 20 | 104 | 110 | 12 | 20 |
| A11/39 | 57.55 | 13.42 | 8.02 | 0.158 | 7.51 | 3.33 | 4.93 | 0.04 | 0.441 | 0.02 | 5.41 | 100.8 | 39 | 210 | 111 | 8 | 22 | 530 | 30 | 110 |
| A12/40 | 64.89 | 13.85 | 7.88 | 0.069 | 4.25 | 0.15 | 2.53 | 1.07 | 0.865 | 0.04 | 3.50 | 98.89 | 22 | 171 | 104 | 30 | 99 | 170 | 23 | 50 |
| A13/41 | 73.85 | 8.15 | 7.02 | 0.080 | 4.24 | 0,42 | 0.59 | 0.16 | 0.527 | 0.03 | 4.05 | 99.11 | 13 | 122 | 20 | 31 | 50 | 80 | 29 | <20 |
| A5/17 | 46.78 | 15.40 | 11.53 | 0.162 | 6.52 | 8.41 | 3.12 | 0.24 | 1.908 | 0.24 | 6.24 | 100.5 | 41 | 314 | 180 | 37 | 143 | 240 | 42 | 110 |
| A8/17 | 57.23 | 15.94 | 10.94 | 0.075 | 3.33 | 0.25 | 3.15 | 1.99 | 1.248 | 0.09 | 3.86 | 98.10 | 33 | 190 | 59 | 32 | 100 | 110 | 28 | 40 |
| S1/46 | 63.16 | 16.57 | 6.65 | 0.193 | 2.88 | 0.45 | 1.07 | 3.37 | 0.787 | 0.16 | 4.97 | 100.3 | 17 | 138 | 65 | 24 | 194 | 220 | 27 | 90 |
| S2/47 | 67.54 | 14.16 | 6.14 | 0.060 | 2.57 | 0.51 | 1.57 | 2.31 | 0.730 | 0.14 | 4.90 | 100.6 | 13 | 101 | 72 | 23 | 187 | 130 | 14 | 50 |
| S6/55 | 49.22 | 19.17 | 10.84 | 0.042 | 6.5 | 1.48 | 1.81 | 3.23 | 0.924 | 0.17 | 7.32 | 100.7 | 21 | 167 | 68 | 37 | 199 | 270 | 29 | 230 |
| S11/62 | 62.48 | 16.57 | 6.13 | 0.070 | 2.03 | 0.87 | 1.27 | 4.35 | 0.837 | 0.13 | 5.85 | 100.6 | 16 | 135 | 27 | 24 | 227 | 140 | 18 | 60 |
| S7/17 | 19.12 | 5.99 | 2.58 | 0.092 | 1.25 | 37.36 | 0.68 | 1.30 | 0.246 | 0.05 | 31.49 | 100.2 | 7 | 49 | 877 | 11 | 52 | 60 | 5 | 40 |
| G1 | 55.46 | 14.64 | 6.34 | 0.072 | 3.56 | 6.36 | 1.85 | 2.69 | 0.694 | 0.10 | 7.29 | 99.05 | 16 | 135 | 208 | 19.9 | 132 | 180 | 20 | 100 |
| G17 | 47.14 | 15.20 | 10.43 | 0.175 | 8.68 | 9.39 | 2.09 | 1.08 | 1.409 | 0.14 | 4.07 | 99.79 | 41 | 274 | 136 | 32.1 | 87 | 350 | 43 | 90 |
| G41 | 51.66 | 21.17 | 8.54 | 0.059 | 3.50 | 0.31 | 0.68 | 6.39 | 1.058 | 0.17 | 5.59 | 99.13 | 22 | 178 | 15 | 34.7 | 221 | 270 | 21 | 140 |
| A1 | 55.42 | 16.18 | 9.92 | 0.111 | 5.43 | 1.03 | 6.11 | 0.03 | 0.611 | 0.04 | 4.83 | 99.71 | 46 | 338 | 103 | 17 | 28 | <20 | 34 | 20 |
| A8 | 61.38 | 16.66 | 7.44 | 0.077 | 4.11 | 0.32 | 1.25 | 2.95 | 0.815 | 0.1 | 4.43 | 99.55 | 18 | 137 | 58 | 23 | 162 | 210 | 17 | 110 |
| S5 | 47.33 | 15.64 | 12.26 | 0.160 | 7.43 | 5.78 | 3.64 | 0.28 | 1.959 | 0.22 | 5.11 | 99.81 | 41 | 361 | 32 | 38 | 153 | 240 | 42 | 110 |
| Morb | 53.08 | 13.19 | 7.30 | 0.226 | 10.44 | 2.80 | 2.56 | 1.37 | 1.147 | 0.15 | 6.46 | 98.74 | 37 | 212 | 76 | 20 | 80 | 240 | 35 | 110 |
| Serp | 36.86 | 0.59 | 8.24 | 0.089 | 40.71 | 0.20 | 0.01 | <0.01 | 0.009 | <0.01 | 11.94 | 98.66 | 8 | 31 | 2 | <1 | <2 | 2440 | 112 | 2500 |
| Perid | 42.13 | 1.08 | 8.91 | 0.130 | 45.25 | 1.32 | 0.03 | 0.01 | 0.010 | <0.01 | 0.20 | 98.67 | 12 | 47 | <2 | <1 | <2 | 3040 | 112 | 2440 |

Table 2B

| | Nb | La | Ce | Pr | Nd | Sm | Eu | Gd | Tb | Dy | Ho | Er | Tm | Yb | Lu | Th | U |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | |
| A1/1 | 12 | 38.1 | 63.9 | 9.06 | 3S.6 | 7.2 | 1.40 | 6.3 | 1.0 | 5.6 | 1.1 | 3.2 | 0.46 | 3.0 | 0.44 | 12.2 | 1.8 |
| A2/2 | 10 | 32.7 | 68.0 | 7.98 | 31.3 | 6.4 | 1.36 | 5.9 | 1.0 | 5.7 | 1.1 | 3.2 | 0.45 | 3.0 | 0.45 | 11.5 | 2.1 |
| A3/14 | <1 | 7.5 | 27.3 | 2.85 | 12.7 | 3.6 | 1.18 | 4.3 | 0.8 | 5.3 | 1.1 | 3.3 | 0.50 | 3.4 | 0.46 | 1.2 | 0.5 |
| A4/17 | 15 | 11.7 | 21.5 | 3.11 | 12.8 | 3.7 | 0.99 | 4.7 | 0.9 | 5.5 | 1.1 | 3.3 | 0.47 | 3.1 | 0.46 | 7.7 | 2.1 |
| A5/29 | 5 | 25.9 | 47.5 | 6.48 | 26.0 | 5.2 | 0.87 | 4.5 | 0.7 | 4.3 | 0.9 | 2.8 | 0.43 | 2.8 | 0.43 | 6.6 | 2.0 |
| A6/31 | 11 | 31.5 | 58.1 | 7.50 | 28.8 | 5.9 | 1.15 | 5.2 | 0.8 | 4.8 | 1.0 | 3.0 | 0.43 | 2.8 | 0.42 | 12.0 | 2.2 |
| A7/3.1 | <1 | 1.3 | 4.6 | 0.61 | 3.3 | 1.2 | 0.46 | 1.6 | 0.3 | 2.0 | 0.4 | 1.4 | 0.22 | 1.4 | 0.20 | 0.5 | 0.2 |
| A7/3.2 | <1 | 2.7 | 7.0 | 1.09 | 5.5 | 1.8 | 0.65 | 2.4 | 0.4 | 2.9 | 0.6 | 1.7 | 0.24 | 1.5 | 0.22 | 0.5 | 0.2 |
| A10/38 | <1 | 8.0 | 23.3 | 2.94 | 13.4 | 3.4 | 0.91 | 3.3 | 0.6 | 3.6 | 0.8 | 2.4 | 0.38 | 2.4 | 0.37 | 2.0 | 0.8 |
| A11/39 | <1 | 1.3 | 3.6 | 0.52 | 2.8 | 1.0 | 0.33 | 1.5 | 0.3 | 1.7 | 0.3 | 1.0 | 0.16 | 1.1 | 0.16 | 0.3 | 0.1 |
| A12/40 | 1 | 9.3 | 19.8 | 3.65 | 17.4 | 5.2 | 1.49 | 5.7 | 1.0 | 6.1 | 1.3 | 3.8 | 0.56 | 3.7 | 0.60 | 1.4 | 0.5 |
| A13/41 | <1 | 6.1 | 14.9 | 2.27 | 11.0 | 3.6 | 1.01 | 4.6 | 0.8 | 5.7 | 1.1 | 3.3 | 0.47 | 3.1 | 0.46 | 0.9 | 0.5 |
| A5/17 | 3 | 5.1 | 15.5 | 2.60 | 14.2 | 4.6 | 1.55 | 6.3 | 1.1 | 7.0 | 1.4 | 4.3 | 0.61 | 4.0 | 0.54 | 0.2 | 0.1 |
| A8/17 | <1 | 9.9 | 20.6 | 3.21 | 15.3 | 4.7 | 1.50 | 5.2 | 0.9 | 6.4 | 1.3 | 3.8 | 0.58 | 3.8 | 0.56 | 1.2 | 0.4 |
| S1/46 | 11 | 36.6 | 69.3 | 8.70 | 33.1 | 6.6 | 1.31 | 5.7 | 0.9 | 5.0 | 1.0 | 2.8 | 0.43 | 2.8 | 0.43 | 12.1 | 2.7 |
| S2/47 | 7 | 26.3 | 54.5 | 6.64 | 26.0 | 5.4 | 0.99 | 4.7 | 0.8 | 4.4 | 0.9 | 2.7 | 0.39 | 2.5 | 0.38 | 9.5 | 1.7 |
| S6/55 | 14 | 31.5 | 65.5 | 7.74 | 30.0 | 6.2 | 1.21 | 6.3 | 1.1 | 6.7 | 1.3 | 3.6 | 0.49 | 3.0 | 0.45 | 13.6 | 2.3 |
| S11/62 | 10 | 31.0 | 64.1 | 7.57 | 29.6 | 5.8 | 1.06 | 4.9 | 0.8 | 4.7 | 0.9 | 2.8 | 0.41 | 2.7 | 0.42 | 11.3 | 2.2 |
| S7/17 | 4 | 12.5 | 21.7 | 2.72 | 10.9 | 2.2 | 0.50 | 2.0 | 0.3 | 1.8 | 0.4 | 1.2 | 0.18 | 1.2 | 0.17 | 3.9 | 0.7 |
| G1 | 12.2 | 30.4 | 60.0 | 6.71 | 25.8 | 5.18 | 0.930 | 4.41 | 0.62 | 3.58 | 0.71 | 2.07 | 0.312 | 2.12 | 0.321 | 9.58 | 1.93 |
| G17 | 1.9 | 3.65 | 10.6 | 1.91 | 10.6 | 3.60 | 1.43 | 4.82 | 0.86 | 5.57 | 1.14 | 3.37 | 0.517 | 3.31 | 0.484 | 0.10 | 0.18 |
| G41 | 19.8 | 47.7 | 80.0 | 10.9 | 42.4 | 9.21 | 1.64 | 7.33 | 1.09 | 6.65 | 1.28 | 3.51 | 0.541 | 3.36 | 0.524 | 15.0 | 2.91 |
| A1 | <1 | 1.9 | 5.2 | 0.66 | 3.2 | 1.3 | 0.30 | 2.0 | 0.4 | 2.6 | 0.6 | 1.9 | 0.29 | 2.0 | 0.32 | 0.7 | 0.1 |
| A8 | 12 | 23.0 | 49.1 | 5.54 | 20.8 | 4.5 | 0.97 | 4.1 | 0.7 | 4.3 | 0.8 | 2.4 | 0.37 | 2.3 | 0.34 | 12.2 | 1.5 |
| S5 | 4 | 5.4 | 15.6 | 2.72 | 14.3 | 4.6 | 1.44 | 6.7 | 1.1 | 7.2 | 1.5 | 4.3 | 0.66 | 4.1 | 0.61 | 0.3 | <0.1 |
| Morb | 8 | 10.4 | 27.4 | 2.97 | 12.6 | 3.3 | 0.94 | 3.9 | 0.7 | 4.0 | 0.8 | 2.40 | 0.35 | 2.2 | 0.32 | 2.5 | 0.5 |
| Serp | <1 | <0.1 | <0.1 | <0.05 | <0.1 | <0.1 | <0.05 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.05 | <0.1 | <0.01 | <0.1 | <0.1 |
| Perid | <1 | <0.1 | <0.1 | <0.05 | <0.1 | <0.1 | <0.05 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.05 | <0.1 | <0.01 | <0.1 | <0.1 |