

Research Paper**“ROOTLESS” OPHIOLITES ABOVE THE EXHUMING PELAGONIAN
CORE COMPLEX, NORTHERN GREECE****Anne Ewing Rassios¹, Constantina Ghikas², Yildirim Dilek³, Dimitrios
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50100, Greece,rassannie@gmail.com² Geopark Grevena-Kozani, Grevena, 51100, Greece.³ Dept of Geology, Miami University, Oxford, OH 45056⁴ Faculty of Geology and Geoenvironment, Department of Mineralogy & Petrology,
National & Kapodistrian University of Athens, Zographou, Athens, 15784, Greece.**Abstract**

The Mesohellenic ophiolites (MHO) in the Western Hellenides are part of an oceanic slab emplaced onto Pelagonian (Pangaean) continental rocks in the mid-Jurassic with a documented NE ophiolite emplacement: the MHO root zone is probably preserved as a deep ultramafic mass within the Mesohellenic Trough. Ophiolitic outliers to the east of the MHO and west of the Chalkidiki ophiolitic formations are oceanic lithospheric fragments, not complete ophiolite bodies: these are incoherent blocks preserved above exhumed Pelagonian continental rocks and not remnants of a continuous ophiolitic nappe. As these fragments lack connection to original root zone provenance, we refer to these as the “rootless” ophiolites. Pelagonian continental exhumation, possibly triggered by transcurrent shear along its continental margin with the Pindos basin, began by the Late Jurassic and continued into the mid-Cretaceous. Exhumation affected the previously emplaced oceanic slab in the following ways: i) The metamorphic facies of the basal mélange separating the ophiolite from the Pelagonian basement grades from phyllitic to schist and amphibolite-schist over the exhumed Pelagonia ii) Ophiolitic remnants are metasomatized where in contact with the exhumed Pelagonian rocks. iii) Remnant ophiolitic fragments are rotated and largely disassociated from their original relative pseudostratigraphic positions in their parent slab iv) No amphibolite emplacement soles are preserved beneath ophiolitic remnants found directly above Pelagonia. East of Vourinos, remnants of the slab were tectonically entrapped between the exhuming Pelagonian core and its sedimentary overburden, and

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demonstrate extensional, largely gravitational displacements as well as rotation from original emplacement vectors. Primary constrictive slab emplacement features are obscured, but a general westerly sense of kinematics via listric and extensional faults have been imprinted on these fragments. In the Pelagonian exhumation model, this "SW topping" direction cannot be interpreted as indicative of an eastern origin of the Pindos Basin ophiolites from the Vardar Zone, but rather as a local response to the uplift of Pelagonia and active deformation of the sedimentary overburden.

Keywords: Mesohellenic Ophiolites, exhumation, root zone.

ΠΕΡΙΛΗΨΗ

Οι Μεσοελληνικοί Οφιόλιθοι (ΜΕΟ) στις δυτικές Ελληνίδες αποτελούν τμήμα μιας ωκεάνιας πλάκας, που τοποθετήθηκαν το Μέσο Ιουρασικό στα πετρώματα της Πελαγονικής ηπείρου, με μία τεκμηριωμένη ΒΑ τοποθέτηση. Η ζώνη προέλευσης των ΜΕΟ πιθανότατα διατηρείται σαν μία υπερβασική μάζα στη Μεσοελληνική Αύλακα. Οι οφιολιθικές εμφανίσεις ανατολικά των ΜΕΟ και δυτικά των οφιολίθων της Χαλκιδικής είναι τεμάχια της ωκεάνιας λιθόσφαιρας, όχι ολόκληρα οφιολιθικά σώματα. Πρόκειται για ασυνάρτητα τεμάχια που διατηρήθηκαν πάνω στα πετρώματα της αναδυόμενης Πελαγονικής ηπείρου και όχι για απομεινάρια ενός συνεχούς οφιολιθικού καλύμματος. Καθώς τα τεμάχια αυτά στερούνται σύνδεσης με την αρχική ζώνη προέλευσης, τους αναφέρουμε σαν «ξεριζωμένους» οφιόλιθους. Η Πελαγονική ηπειρωτική εκταφή, η οποία προκλήθηκε ενδεχομένως από διακεκομμένη διάτμηση κατά μήκος του ηπειρωτικού περιθωρίου της με τη λεκάνη της Πίνδου, ξεκίνησε από το Άνω Ιουρασικό και συνέχισε μέχρι το Μέσο Κρητιδικό. Η εκταφή επηρέασε την ήδη τοποθετημένη ωκεάνια πλάκα με τους ακόλουθους τρόπους: i) Οι μεταμορφικές φάσεις του βασικού *mélange*, διαχωρίζοντας τους οφιόλιθους από πελαγονικό υπόβαθρο, ταξινομούν από φυλλίτες μέχρι σχιστόλιθο και αμφιβολιτικό σχιστόλιθο πάνω στην αναδυόμενη Πελαγονική ii) Οφιολιθικά υπολείμματα εντοπίζονται μετασωματοποιημένα όταν βρίσκονται σε επαφή με τα εκταφιασμένα πετρώματα της Πελαγονικής iii) Θραύσματα οφιολιθικών τεμαχίων περιστράφηκαν και αποσυνδέθηκαν έντονα από τις αρχικές τους ψευδοστρωματογραφικές θέσεις στην ωκεάνια πλάκα iv) Δεν διατηρούνται οι αμφιβολιτικές σόλες τοποθέτησης κάτω από τα οφιολιθικά υπολείμματα που βρίσκονται ακριβώς πάνω στη Πελαγονική. Ανατολικά του Βούρινου, υπολείμματα της πλάκας εγκλωβίστηκαν τεκτονικά, μεταξύ του αναδυόμενου Πελαγονικού πυρήνα και των υπερκείμενων ιζημάτων, παρουσιάζοντας επεκτατικές, μεγάλου βαθμού βαρυτικές μετατοπίσεις καθώς και περιστροφή από τους αρχικούς δείκτες τοποθέτησης. Παρόλο που τα χαρακτηριστικά της αρχικής τοποθέτησης της πλάκας δεν είναι ευδιάκριτα, έχει

αποτυπωθεί στα θραύσματα αυτής γενικά μία κινηματική κατευθυνόμενη δυτικά μέσω λιστρικών και κανονικών ρηγματών. Στο μοντέλο της εκταφής της Πελαγονικής, αυτή η κατεύθυνση «προς τα ΝΔ» δεν μπορεί να ερμηνευθεί με την εκδοχή της προέλευσης των οφιολίθων της λεκάνης της Πίνδου από ανατολικά, δηλ. της ζώνης του Αξιού, αλλά μάλλον σαν τοπική αντίδραση στην ανάδυση της Πελαγονικής και στην ενεργή παραμόρφωση των υπερκείμενων ιζημάτων.

Λέξεις κλειδιά: Μεσοελληνικοί Οφιολίθιοι, εκταφή, ζώνη προέλευσης

1. INTRODUCTION AND BACKGROUND

Well-over 100 small occurrences of Jurassic lithospheric origin crop out between the major ophiolites of the Meso-Hellenic ophiolite belt (MHO) belt and that of the Vardar-Maliac ophiolite belt (Figure 1). These occurrences are discontinuous bodies ranging in area from km² to m² and consist of complex structural association (including compressive and late extensional features) and inconclusive geochemical association. All are found above the Pelagonian metamorphosed continental terrain and below Cretaceous reefal formations. None of these occurrences can be categorized as to their original strato-tectonic position or relation to an ophiolitic root zone: for this reason, we refer to them as “rootless” ophiolites. Descriptions of some of these occurrences are provided in the present study to serve as examples of their variability.

The ophiolitic complexes of the Mid-Jurassic Pindos Basin in Greece (Figure 1, Smith and Rassios, 2003; Liati and others 2004) include historic sections that aided in giving rise to initial precepts of plate tectonic theory. Brunn (1956) first recognized that the rocks exposed in the Vourinos and Pindos ophiolites were like rocks described by Ewing and others (1953) found along the Mid-Atlantic Ridge and interpreted that they formed by similar processes but in differing geologic environments. The description of the Vourinos complex by Moores (1969) highly influenced our understanding of ophiolites as oceanic lithosphere and the “Penrose” definition of ophiolites (Anon 1972).

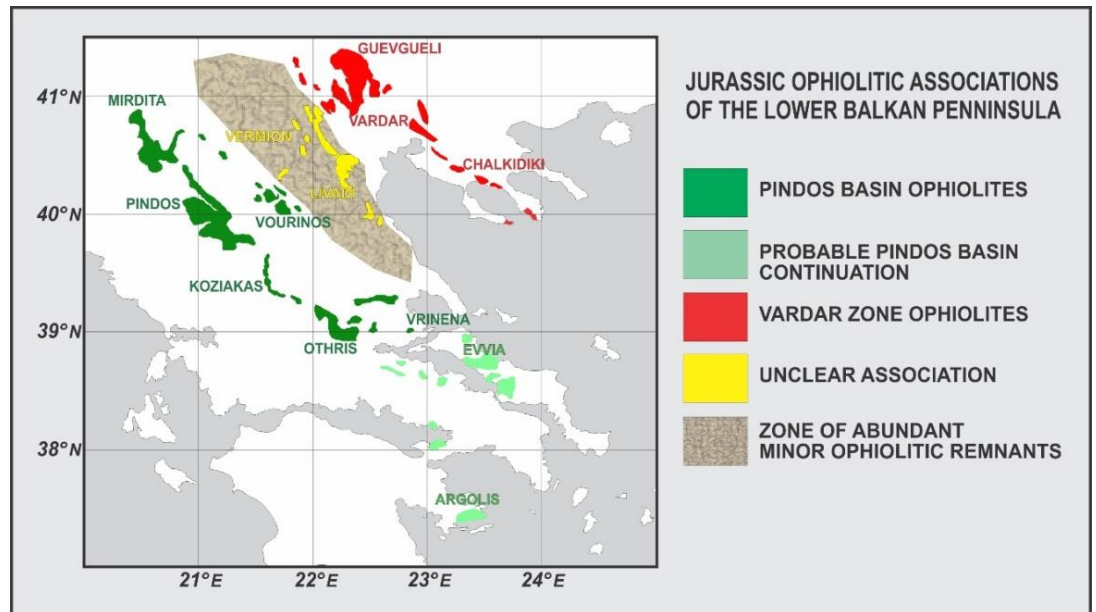


Fig. 1: Location of the Mesohellenic Ophiolites (green) associated with the Jurassic Pindos Basin in Greece.

Zimmerman's (1968) description of the contact relation between the Vourinos ophiolite and its Pelagonian basement documented reverse metamorphic zonation and led to development of the concept of "sole" formation during emplacement of an oceanic slab. Rassios (1981) documented magmatic lithospheric processes of Vourinos, and later (1991) described the intact ophiolitic sequence of Dramala within the Pindos ophiolite. Jones (1990) and Jones and Robertson (1991) described the obduction sole relations of the Pindos Ophiolite, with similar metamorphic zonation above the Avdella Mélange, an accretionary wedge. The work of Alan Smith and his students (Smith and others, 1975; Smith and others, 1979; Naylor and Harle, 1976) documented the Othris ophiolite and Vourinos sole unit, and described tectonic processes of emplacement of the ophiolite and constriction of its over-ridden continental margin. All the above investigators deduced a NE emplacement for these ophiolites based on in situ observations of geological and structural data as well as metamorphic sole ages and conditions.

During the 1980's and early 1990's, exploration for chrome and copper ores by the Institute of Geology and Mineral Exploration (today the Hellenic Survey of Geology and Mineral Exploration) in these ophiolites as well as the Koziakas ophiolite necessitated rigorous tectonic evaluation of ophiolitic host terranes (Vrahatis and Grivas, 1980; Rassios, 1994; Rassios and others, 1986; Rassios and Vacondios, 1991). Much of Othris was mapped on a 1:50,000 scale with copper districts analyzed in

1:5000 and 1:1000 scale maps (Rassios and Konstantopoulou, 1992; Rassios, 1990; Rassios, 1989); the ophiolitic rocks of the Pindos and Koziakas were mapped on a 1:20,000 scale (Konstantopoulou, 1994; Konstantopoulou and others, 1988; Rassios and Grivas, 1999; 2001; Rassios, Smith and Kostopoulos, 2009). Active drilling exploration and exploitation of chrome ores at Vourinos was based on ductile and brittle tectonic analyses of ore districts on a 1:1000 scale (Grivas and others 1993; Roberts and others 1988).

With the completion of a hydroelectric facility on the Aliakmon River, many of the critical structural and petrologic sites located along the base of the Vourinos ophiolite and its sole zone are now flooded. A final documentation of this zone (Rassios 2008) facilitated new structural and geochemical analyses using contemporary methodology (e.g. Ghikas, 2007; Myhill, 2008). The results are still coming forward, and the progressing work sheds new light on the early history of the west Pelagonian margin as well as on emplacement mechanisms of the ophiolitic slab.

Exposures of Mesohellenic ophiolites (MHO) (Figure 1) extend from Albania at least through to the ophiolitic rocks found on Evvia – extensions as far south as the Peloponnese are probable but are not considered in the present paper. The MHO is largely continuous as basement formations within the Mesohellenic Trough to depths of 25 km as demonstrated in geophysical studies (Memou and Skianis, 1993; Rassios and Dilek, 2008; Rassios and others 2009; Rassios and Moores, 2006). When modest reconstruction of Tertiary – Alpine thrusting is applied to the map pattern, including such simple reconstruction as “unfolding” the Mesohellenic Trough, the area of the preserved parts of the basin extend approximately 400 km NW-SE by 170 km E-W (Figure 2). The MHO includes ophiolitic fragments derived from diverse geotectonic environments (Kostopoulos, 1989; Rassios and Moores, 2006). The juxtaposition of geotectonic environments within the ophiolitic slab during emplacement motions (Rassios and Dilek, 2008) is likely, and inhibits our ability to adequately model the original tectono-geography of the Pindos Basin (Rassios and Moores, 2006). Strato-tectonic models create a Pindos Basin that was a narrow, short-lived, Jurassic basin peripheral to the rifted Pelagonian “ribbon” continent (Rassios Smith and Kostopoulos, 2009), though related fossil studies from the Jurassic boundaries suggest that the “basin” was at least 1000 km wide (Smith, pers. comm.).

The Vardar and Malia basins of Greece were interpreted as oceanic tracts generated by Permo-Triassic rifting at the eastern margin of the Pelagonian continent (Stampfli and Borel, 2002).

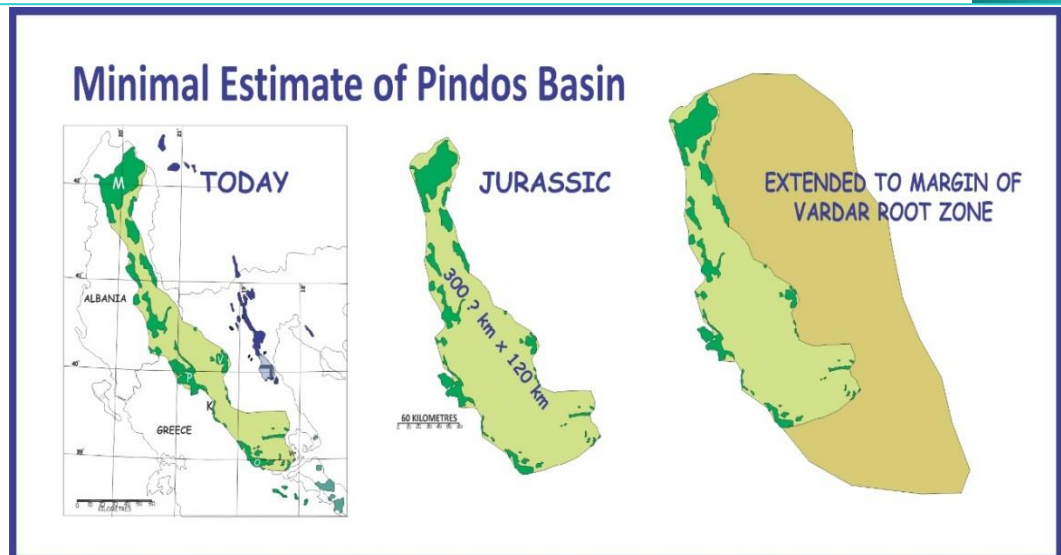


Fig. 2: Reconstructions of extent of Pindos Basin oceanic slab preserved within the Balkan Peninsula. “Today” includes area including demonstrated continuous subsurface continuities. “Jurassic” reconstruction includes expansion of the pre-Mesohellenic trough folding and other Tertiary shortening of the region. Reconstruction on right shows similar distribution if extended to include “rootless” and Vardar zone ophiolites in the same belt.

The Pelagonian massif is now more commonly accepted as part of an exhumed continental margin, subducted beneath the continent-continent collision at the closure of the Tethys (Brun and Faccenna, 2008), and originally continuous with the Pangaeo-aged basement of the Jurassic Rhodope massif of eastern Greece (Cornelius Reischmann Frei and Kostopoulos, 2007).

The root zone of the MHO is under dispute: in consensus with stratigraphic evidence from the Balkan ophiolites within the former Yugoslavia and early analyses of the Vardar Zone ophiolites of Greece (Vergely, 1984, 1977; Aubouin, 1957) the MHO are presumed to be a continuation of the Greek Axios ophiolite belt, rooted in the Vardar zone; this model would necessitate a SW emplacement history for all the ophiolitic fragments now above the Pelagonian complex as well as the massive MHO lithospheric slabs west of this zone (van Hinsbergen et al., 2005): this “consensus” deduction is not backed up by in situ structural analyses within the ophiolites themselves. An alternative root zone for these ophiolites is within today’s Mesohellenic Trough, reconciling the *in-situ* observations of NE emplacement for all the MHO ophiolites. We will summarize the main reasons for accepting the NE emplacement model herein for the purposes of putting forward a new emplacement model for all these ophiolitic systems.

The present paper does not intend to challenge previous reconstructions of the Pindos Basin itself, but does propose the following:

- Structures supporting the NE emplacement of this slab are well documented (among other references: Ghikas, 2007; Ghikas et al., 2010; Grivas et al., 1993; Konstantopoulou, 1992; Konstantopoulou, 1994; Myhill, 2008; Naylor and Harle, 1976; Rassios, 1991; Rassios, 1994; Rassios and Dilek, 2008; Rassios and Konstantopoulou, 1992; Rassios and Moores, 2005; Rassios and Smith, 2000; Rassios et al., 1994; Rassios et al., 2009; Smith et al., 1975).
- The emplacement soles of the MHO occur in situ above Pelagonian rocks (Vourinos, Othris) and the late Jurassic accretionary mélange (the Avdella Mélange of the Pindos); the temperatures and pressures recorded demand near-ridge crest sole formation (Myhill, 2008, Ghikas et al., 2010), and systematically display topping directions towards the NE and E (Ghikas et al., 2010; Ghikas, 2010; Naylor and Harle, 1976). These relations imply the continuity of the sole unit from the Avdella Mélange to Pelagonian margin.
- The provenance of remnants of ophiolitic nappe above the Pelagonian “ribbon” continent is inconclusive, but a source continuous with the MHO is put forward as an alternative to the “Vardar Zone” origin.
- The remnants of the ophiolitic nappe above the exhumed Pelagonian terrain demonstrate structures reconciling exhumation tectonic conditions; deriving original ophiolitic emplacement vectors from these fragments is not possible.
- The mechanisms of emplacement of so large a nappe as these older SW-verging models propose are difficult to envision, and require multiple, major-scale, ramping mechanisms undocumented in the region.
- A model is suggested that could explain this apparent continuation of the ophiolitic fragments between the Vardar Zone and the MHO, and their apparent concurrent but “opposite” emplacement directions; this model is compared to a modern tectonic analogue.

2. THE NE EMPLACEMENT OF THE MESOHELLENIC OPHIOLITES

A benefit of using tectonic analyses to guide explorationist drilling projects is that one is not allowed the luxury of “assuming” comprehensive strain from pre-existing models, but must document and target ore bodies based on their immediate tectonic localization. In the case of copper ores (Rassios, 1989; 1990; Konstantopoulou and others, 1988; Rassios and Grivas, 2001), the location of ore bodies can be predicted by analyses of extensional ridge crest structures, though in Greece the “key” to their preservation as

an economic target is the constrictive environment of later, brittle thrust and ramp structures related to nappe formation during emplacement: copper ores make an apparently ideal “weak” point for generation of thrusts (Konstantopoulou et al., 1988). Part of the exploration strategy in Greece employs location of pillow lava sections within imbricate blocks that remain large enough to host a potential, economically interesting volume of copper ores.

Economic chrome ores hosted in upper mantle level environments have been precisely targeted in the subsurface (Konstantopoulou, 1992; Grivas and others, 1983) following thorough tectonic analyses: their localization agrees with competency models in which the ores themselves behave as “breaking points” in the deforming peridotite complex at all T-P regimes through ductile, ductile-brittle, and brittle field deformation. Structures appear to “emanate” from the position of chrome ores, and can be traced as a continuum of deformation until the time of later, cross-cutting, Tertiary to present, brittle structures.

All the pre-Tertiary structures evaluated within peridotite localities within the MHO are constrictive. Mantle structures presumed to originate via extension in ridge crest areas, including basic S_0 structures such as mantle layering and high temperature mineral foliations, are pervasively overprinted by constrictive ductile deformation as to preclude modeling of original ridge crest orientation or paleotectonic geography in mantle level rocks. The map pattern of these structures (Rassios, 1991) show they have been rotated into a “spoon-shaped” form consistent with a large ductile-brittle thrust (obduction) nappe. High-temperature to brittle deformation occurs as a continuum, with semi-ductile, ductile-brittle, and brittle motions imprinting on older plastic deformation. All structures within this continuum top to the NE or reconcile heterogeneous motions of a NE-emplacing nappe originating in ductile conditions and crossing the ductile-brittle boundary. The presumed meaning of this is simply that structures forming during ophiolitic slab emplacement are analogous to the kinematics of a thrust nappe (Rassios and Dilek, 2008).

An independent means of establishing the chronology of ductile deformation is provided by tectonic analyses of dikes within the mantle to lower crustal levels of the Vourinos and parts of the Othris and Pindos ophiolites (Figure 3). These lithospheric sections contain late-stage pyroxenite pegmatite dikes (Rassios, 1981; Rassios and others, 1983; Rassios and Dilek, 2008). At Vourinos, these dikes are predominantly undeformed tabular features that cross-cut older high-temperature deformation: the dikes are themselves over-printed by later NE-topping brittle emplacement structures,

and rotated to the convex-shaped emplacement front of Vourinos. In rare localities, Vourinos pyroxenite dikes are deformed in ductile conditions within distinct mylonite zones. In the Pindos nappe ophiolite, these pyroxenite pegmatite dikes are deformed within >km-scale mylonitic fabric terrains (op cit). These relations constrain ductile deformation uniquely to the Jurassic slab environment, that is, to the time of ophiolite generation and emplacement.

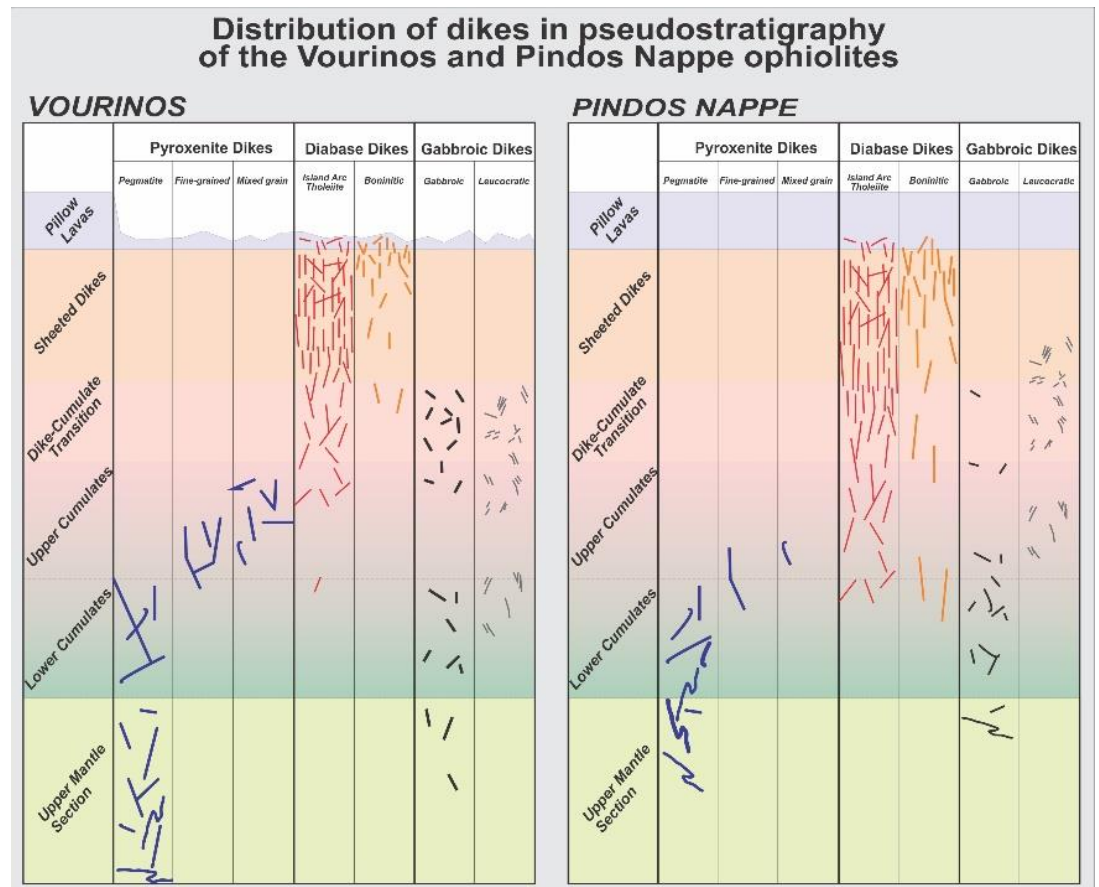


Fig. 3: Comparative distribution of all types of dikes within the Vourinos and Pindos ophiolitic sections: these tectono-stratigraphic sections display the lithospheric dimensions of these ophiolites in comparison to the rootless ophiolites described in this paper.

Rassios and Smith (2000) estimated that an ophiolitic slab of the thickness of the Vourinos complex, or rather, deep parts of this slab, can remain in ductile conditions for about four million years. During this time, the ductile-brittle boundary descends from near-ridge crest shallow levels to the base of the slab. The continuity of ductile to brittle structures in the MHO, all documenting a single topping-orientation to the time of cross-cutting Alpine structures, preclude us from postulating any secondary “ductile” deformation environment overprint, such as later deformation in a slab rollback setting or Late Jurassic to mid-Cretaceous exhumation environment.

Intact occurrences of amphibolite sole crop out in all the MHO rooted in the Mesohellenic Trough. At Vourinos, the sole (Zimmerman, 1968; Moores, 1969; Myhill, 2008) retains reverse metamorphic zoning against the Pelagonian shelf sediments. In the Pindos nappe ophiolite, the sole overlies the Avdella Mélange, a late Jurassic accretionary mélange, and the metamorphic zoning into this mélange leaves no question about its “in situ” nature (Jones, 1990; Jones and Robertson, 1991; Jones and Robertson, 1995).

Several amphibolite sole outcrops have been dated in the Othris and Koziakas ophiolites (Spray and Roddick, 1980; Pomonis and others, 2002) that are not immediately continuous to basement formations. At Vrinena in eastern Othris, though amphibolites have not been located, the presence of mylonitic (serpentinized) harzburgite and garnet-bearing over-ridden schistose carbonates implies the tectonic disruption of such a sole (Rassios, 1990). All these occurrences of sole rocks include amphibolite and garnet amphibolites, and temperature/pressure estimations necessitate their formation in the oceanic setting. By the time of slab emplacement onto a continental shelf environment, the production of a “hot” sole is no longer possible (Wakabayashi and Dilek, 2003).

Thus, if all the MHO ophiolites were derived from the Vardar zone, and transported more than 200 km over the Pelagonian continent, then they would have to have been emplaced in such a way as to also carry their in situ sole and the sole’s immediate footwall rocks (such as the Avdella Mélange with provenance in the Western Hellenides and the Pelagonian metamorphic formation) with them. None of the ophiolitic basement formations show any evidence of such transport; nor have such “transport” faults underlying the ophiolites and their basement rocks been observed in the region.

3. OPHIOLITIC FRAGMENTS ALONG AND ABOVE THE WESTERN PELAGONIAN MARGIN

The continuous MHO nappe is emplaced on its eastern flank over the western Pelagonian margin. This is observed in outcrop along the Vourinos complex and within the Othris continental margin stratigraphy (Smith and others, 1979). Above the Pelagonian complex between the Vourinos and Vardar ophiolites (Figure 4), numerous fragments of ophiolitic-derived lithologies crop out ranging in size from areas of ~10’s of km² (Livadi fragments) down to small serpentinite pods less than 50 m². Possibly as many as a hundred of these minor bodies have been documented on geologic quadrant

maps of the Greek geologic survey (IGME). Unlike the ophiolites included in the MHO area of Figures 1 and 4 that are continuous in the subsurface (Memou and Skianis, 1993), these fragments have been presumed to be strato-tectonic continuations of an originally continuous Jurassic ophiolite sheet that once extended between the MHO and Vardar ophiolites (Mountrakis, 1984, 1985; Rassios, Smith and Kostopoulos, 2009). Essentially because of this presumed strato-tectonic continuity, former models consider these rootless ophiolitic remnants as extensions of the Vardar Zone ophiolites. These fragments, it should be noted, are always located in similar strato-tectonic associations as those of the Mesohellenic-rooted MHO along the west Pelagonian margin: they occur above footwall formations consisting of Pelagonian schists or platform carbonates, often including a basal pebbly mudstone (with various degrees of metamorphism) similar to that of the Ayios Nikolas mélange of Vourinos (Ghikas et al., 2010). These rootless ophiolites are overlain unconformably by late Cretaceous transgressive limestone.

The majority of the rootless fragments do not preserve any clear ophiolitic pseudostratigraphy, and of the few bodies studied in detail, some have been proposed to represent mélange fragments (Sharp and Robertson, 2006). As we observe, most of the ophiolitic fragments are highly sheared serpentized remnants of peridotite, infused by post-ophiolitic metasomatic veins that, at least in their altered states today, consist of clay, magnesite, or hydrated silicates. Such metasomatism and metasomatic veins do not occur within the MHOs rooted in the Mesohellenic Trough, neither in peridotite nor overlying ophiolitic or Cretaceous carbonates. This metasomatic event affects only the ophiolitic floaters located above the exhumed Pelagonian complex (Figure 5) and apparently does not continue into Late Cretaceous time as exemplified by the non-metamorphosed overlying fossiliferous reefal limestones.

Our study of these ophiolitic bodies has initiated their interpretation as remnants affected by the exhumation processes of the Pelagonian core complex.

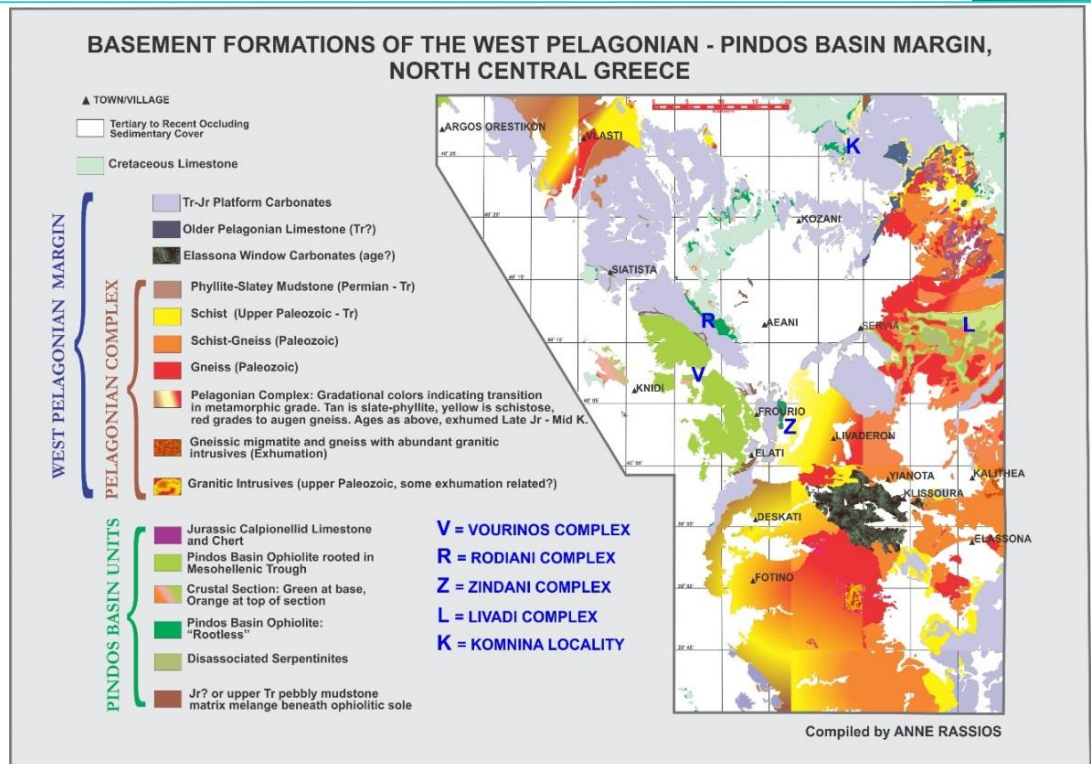


Fig. 4: Map of basement geology along the western Pelagonian margin. Vourinos is an “intact” member of the MHO. Ophiolitic fragments preserved above the exhumed Pelagonian continent crop out (small green areas) to its east: more than 20 additional ophiolitic remnants below mapping scale occur in this region. The Pelagonian units have been colored to show their metamorphic grade in order to demonstrate zoning around probable core complex.

In the present paper, we are including short documentation of some of these critical oceanic lithosphere remnants and their general kinematic properties. Among the fragments, several relatively large ophiolitic fragments crop out so near to the Vourinos complex as to make a “continuity” model particularly appealing. Thus, regional cross sections on survey quadrant maps were constructed that assumed that the Rodiani and Zidani complexes were continuous with Vourinos. However, we now question the validity of these cross sections: they may appear stratigraphically appealing, but they attempt to connect what we now recognized as “mismatched” ophiolitic sections and out-of-sequence structural imprints. Major petrologic and metasomatic differences occur among these bodies and Vourinos, though the invocation of intra-slab dislocation of primary ophiolitic assemblages (Rassios and Dilek, 2008) could explain some of these “petrogenetic-stratigraphic” discrepancies.

“CLASSIC” LITHOSTRATIGRAPHY AND “EXHUMATION” OVERPRINT OF THE WEST PALAGONIAN MARGIN

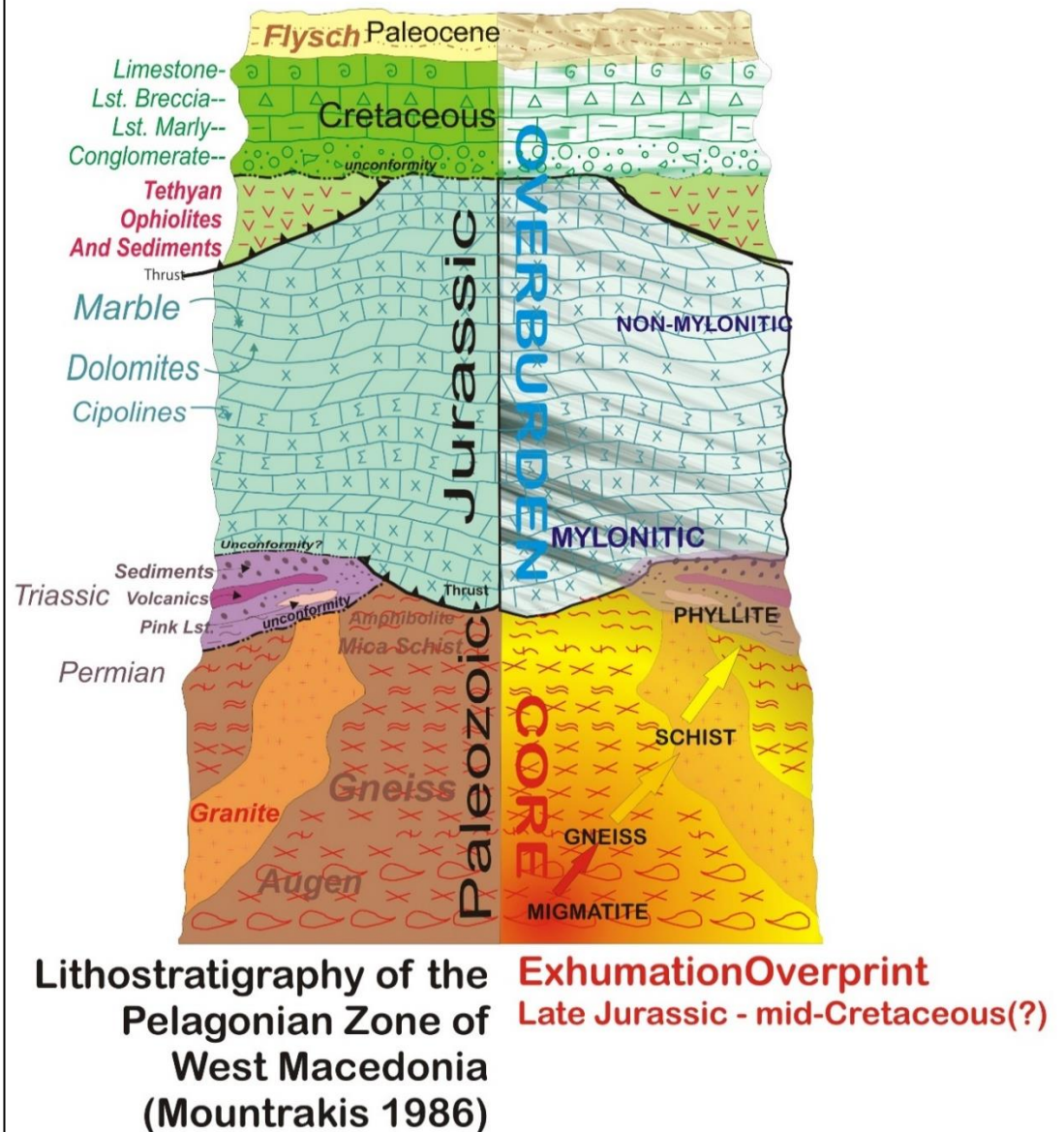


Fig. 5: Relation of Pelagonian metamorphic complex to exhumation model. The original diagram (left, after Mountrakis, 1985) has been re-interpreted into a “classic” exhumation section. Many of the ophiolitic fragments mentioned in the present paper crop out above Tr – Jr carbonate platform rocks of the Pelagonian, but others are found directly over the older Pelagonian ribbon continental rocks.

3.1. Rodiani Ophiolitic Fragments

Rodiani (formerly called Zygosti, Figure 6) includes all lithospheric members necessary to the Penrose definition of an ophiolite (Brunn, 1956; Moores, 1969), but these are juxtaposed in position and greatly “thinned”. The entire Steinman Trinity sequence is less than 1 km thick; basal peridotite is less than half a km; cumulates including ultramafic and dioritic rocks are found in discontinuous blocks, each less than 100 m in thickness; lavas and flows, less than half a km in total thickness, contain very minor outcrops of sheeted dikes, and no outcrops that are entirely pillow lava. Contacts between these pseudostratigraphic divisions are faulted in brittle conditions. No intact sole formations (garnet amphibolite) are known to us, though highly sheared sub-ophiolitic *mélange* similar to that of the Ayios Nikolaos formation of Vourinos has been located. Though peridotites appear to be originally harzburgite, the degree of serpentinization excludes verification of this for the entire complex. The extreme serpentinization of these peridotites also precludes statistically valid analyses of mantle structures. Notably, chromite deposits exploited from Rodiani are, unlike Vourinos, Al-rich rather than Cr-rich (Economou et al., 1986; Economou, 1979), and consist of massive ores rather than the schlieren and disseminate ores that characterize Vourinos. While the differences in chrome ore morphology can be explained by variation in tectonic thinning, the chemical differences describe a very different petrogenetic derivation than the ores of Vourinos. Of the few cumulate rocks preserved within Rodiani (less than tens of meters in thickness), most appear as hydrated (oikocryst bearing) ultramafics (southernmost exposures), and as highly metasomatized upper level diorites (northernmost exposures). The intact cumulate section within Vourinos is well over five km thick.

These hydrous cumulates of Rodiani resemble those of the Pindos nappe ophiolite, the westernmost member of the MHO rather than Vourinos. The lavas of Rodiani show SSZ affinity, thus resembling IAT and boninite lava localities of nearby Vourinos (Rassios et al., 1983; Beccaluva et al., 1984) but also those of the SSZ lavas within Vardar zone ophiolites (Saccani and others, 2008). This SSZ lava geochemistry is not parent to the Al-rich geochemistry of the Rodiani chrome ores. The lava section was emplaced via extensional deformation (Batsi, 2011) over the serpentinised peridotite. Remnants of a breccia zone (Figure 6b) between these major units has been invaded by calcite from overlying carbonates, but demonstrates that the lavas and serpentinites are not immediately related (Figures 6c and d). The basal contact between the ophiolitic rock units and Pelagonian

carbonate is, or was, originally a thrust fault, while all other faults bounding ophiolitic rocks are high-angle extensional faults forming part of a 4-km-wide series of NNW-SSE-striking horsts and grabens (Batsi, 2011). The ultramafic and mafic rocks lie unconformably on Triassic-Jurassic Pelagonian carbonates, and on Late Cretaceous fossiliferous debris flows and turbidites derived from collapse of the carbonate platform (Carras, Fazzuoli and Photiades, 2004; Photiades and others, 2003). These sedimentary rocks display no structural or petrologic evidence of compression; there is no metamorphism greater than diagenetic, no folding or shearing, and no deformation of fossils or clasts.

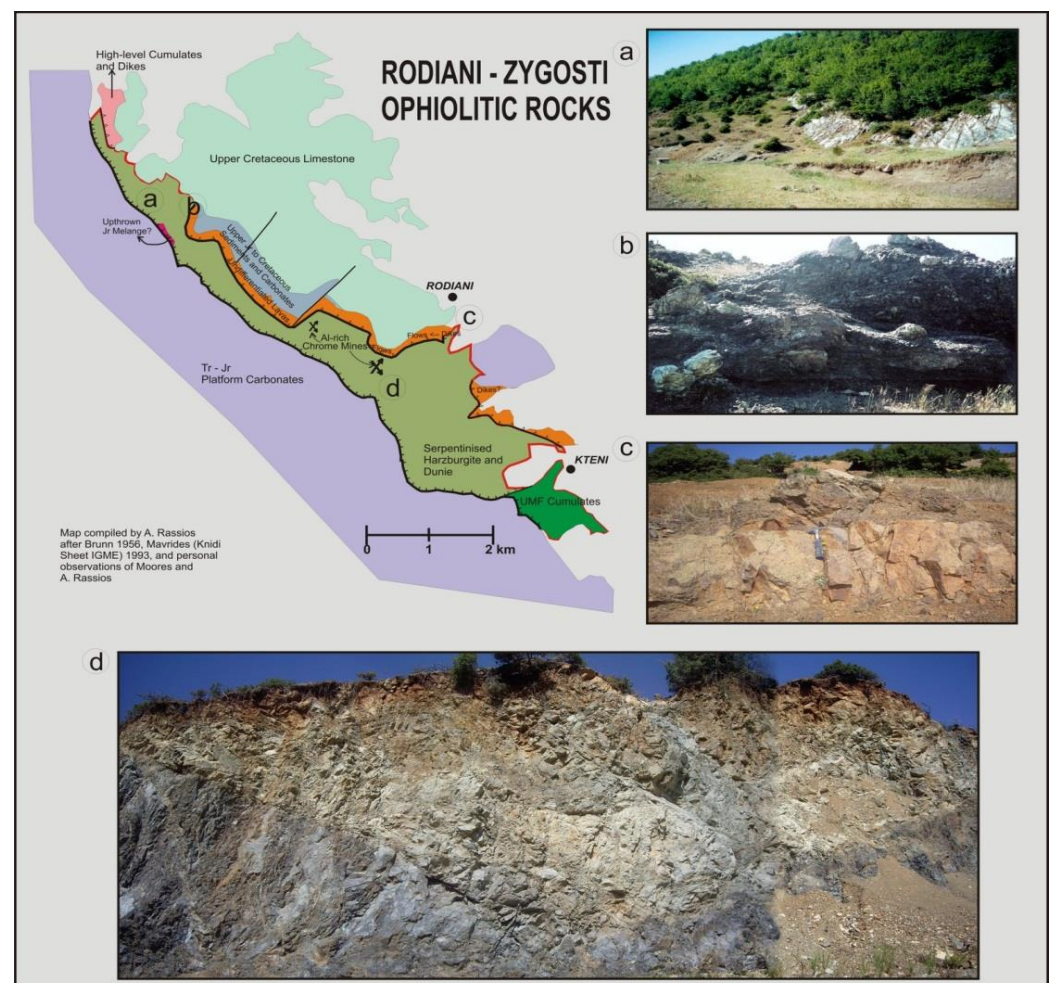


Fig. 6: Simplified map and photos of key tectonic localities of the Rodiani ophiolitic fragment (located on Figure 4) a) Scarp of Tr – Jr platform carbonates (post upper-Cretaceous deformation) against serpentinitized peridotites along western margin of Rodiani b) Mylonitic breccia formation between mylonitic basal peridotites and Tr-Jr carbonates (relict of emplacement zone) c) Dike within lava flows d) Contact of lavas (upper blocks) and serpentinites (lower grey zone). The contact surface lacks constrictive shear, and is cut by extensional faulting.

As for all the rootless ophiolitic remnants that lie above the Pelagonian formation, the Rodiani mantle and cumulate crustal fragments are also highly infused by post-ophiolitic, pre-late Cretaceous metasomatic veins. In one outcrop of lava flows with feeder dikes, constrictive structures (shears, micro ramps) that predate the overlapping Cretaceous limestones show a topping sense to due north, in disagreement with the NE topping of Vourinos. At the very least, this would require significant vertical rotation of the Rodiani crustal sequence with respect to that of the MHO ophiolitic slab. The quadrant map cross section of Mavrides and Kelepertzis (1994) reconciles a stratigraphic continuity between Rodiani and Vourinos via an intervening antiformal structure in the Pelagonian shelf carbonates. A structural traverse of this cross-section fails to show the existence of such an antiform (Ghikas, Myhill, Batsi in prep). Such a cross sectional continuation would necessitate:

- “Thinning” of the ~12 km thick Vourinos section to the <1 km thick Rodiani over a distance of 4 km.
- Up-section polarity in Vourinos is to the west (overturned in the Krappa Hills; Rassios and Moores, 2006), and the Cretaceous unconformity dips steeply west defining an angular unconformity of ~50° between the Jurassic and Late Cretaceous. The Cretaceous unconformity of Rodiani shows a shallow eastward dip. Connecting the two necessitates a horizontal rotation of ~70° along an N-S axis.
- Major petrologic discrepancies between the mantle (chrome ore geochemistry) and cumulate (hydrated cumulates in Rodiani) sections.
- A pre-upper Cretaceous tectonic phase is needed to create the discontinuity between the Rodiani lavas and underlying ophiolitic units; such a tectonic event is lacking in Vourinos.

3.2. Zidani Ophiolitic Fragment

The Zidani complex (Figure 7) consists of a hydrated serpentinite massif of about half a km thickness lacking remnants of lava or any other crustal-level ophiolitic member. Most of the serpentinite is high-temperature antigorite (Hovork et al. 1997) with segregations of chrysotile. Hydration totally obscures primary structures and mineralogy, even to the extent of altering disseminate chrome ores to nearly pure magnetite. This hydration is most likely responsible for the extreme serpentinitization of the ultramafics to an antigorite-host of “economic” chrysotile deposits (mined from ~1986 to 1994; Figure 7a and b). Pre-serpentinite lithologies

most likely consisted of harzburgite and dunite; some “bastite” pyroxenes are observed. No coherent “topping” direction can be derived from the multiply sheared serpentinites within the mine area. Cretaceous limestones are not present in the immediate area to aid in timing of rotations. The serpentine body of Zidani is emplaced immediately over Pelagonian schist-gneiss with no remnants of an obduction sole or basal “pebbly mudstones” preserved (Figure 7c). The serpentinite mass is inter-thrust with schist-gneiss and platform carbonates and crossed by several internal thrusts parallel to these contacts. This pattern of imbrication is reconciled by an ENE topping sense. Zidani has, in some past models been proposed to represent a Paleozoic ophiolite, that is, an ophiolitic remnant within the Pelagonian complex (IGME Quadrant Map Livaderon Sheet). Map patterns suggest a strato-tectonic continuity with both Rodiani, ~11 km to the NNE, and Vourinos to the west. Our interpretation is that it is a fragment of the MHO emplaced onto the Pelagonian margin, imbricated with Pelagonian lithologies during late emplacement movements of Vourinos, and metasomatized above the rising Pelagonian core complex.

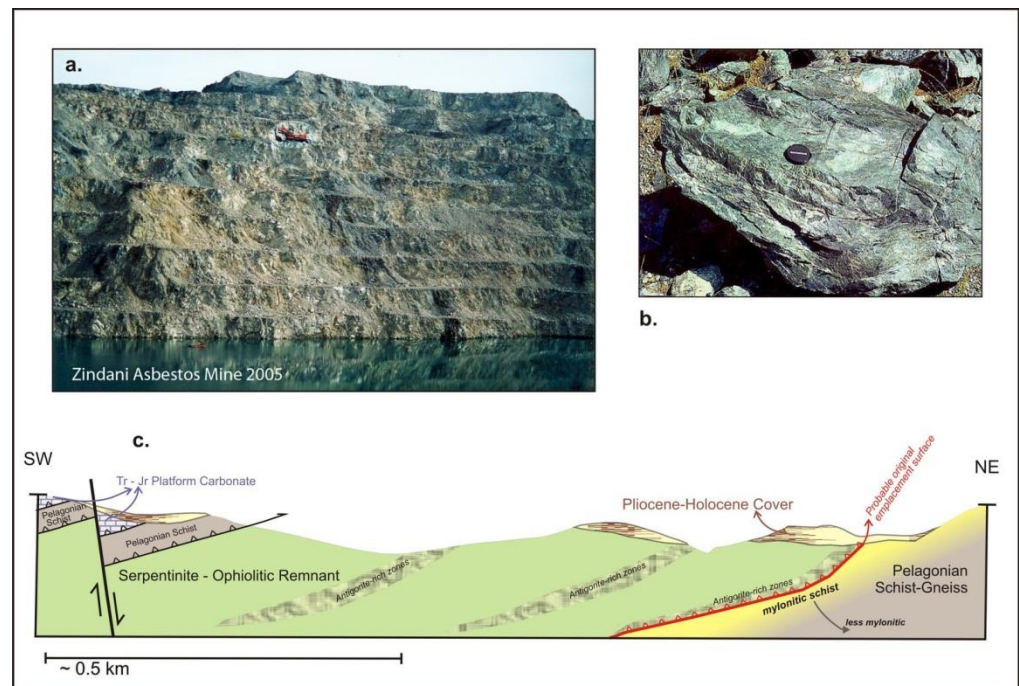


Fig. 7: Representative photos and cross section of the retired Zidani asbestos mine (located on Figure 4). a. View of extensively fractured serpentinite host from open pit (now flooded). b. Typical serpentinised (antigorite) peridotite. c. Cross section (by S. Dabitzias) of mine area. Note correlation of antigoritic zones to basal contact over mylonitic Pelagonian schists.

3.3. Komnina Ophiolitic Remnants

Serpentinites have been mapped in detail in the Komnina area (Figure 8a) as part of the footwall assemblage to nickel laterite deposits. Derivation of Early – mid Cretaceous flysch deposits in the hanging wall show provenance indicators (slump folds, flute casts) to the east, and these are overlain above an angular unconformity by Late Cretaceous limestones. The footwall formation to the serpentinites consists of mylonitic Pelagonian platform carbonates and, in a few localities, extensively sheared schists (possible extension of the Ayios Nikolaos formation of Vourinos? Figure 8b).

The serpentinites are veined by low-temperature clay and altered magnesite veins (Figure 8c): this metasomatism is lacking from all other regional formations. The serpentinites retain structures that, when rotated to a horizontality defined by the overlying late Cretaceous limestones, show them to be SW dipping planes of low-angle gravity faults (Figure 8d). These faults are relatively dated to similar structures within the Early Cretaceous structures of the hanging wall, and are most probably products of “exhumation slide” of material above the uprising core complex of Pelagonia. The entire area is strongly overprinted by transtensional faulting.

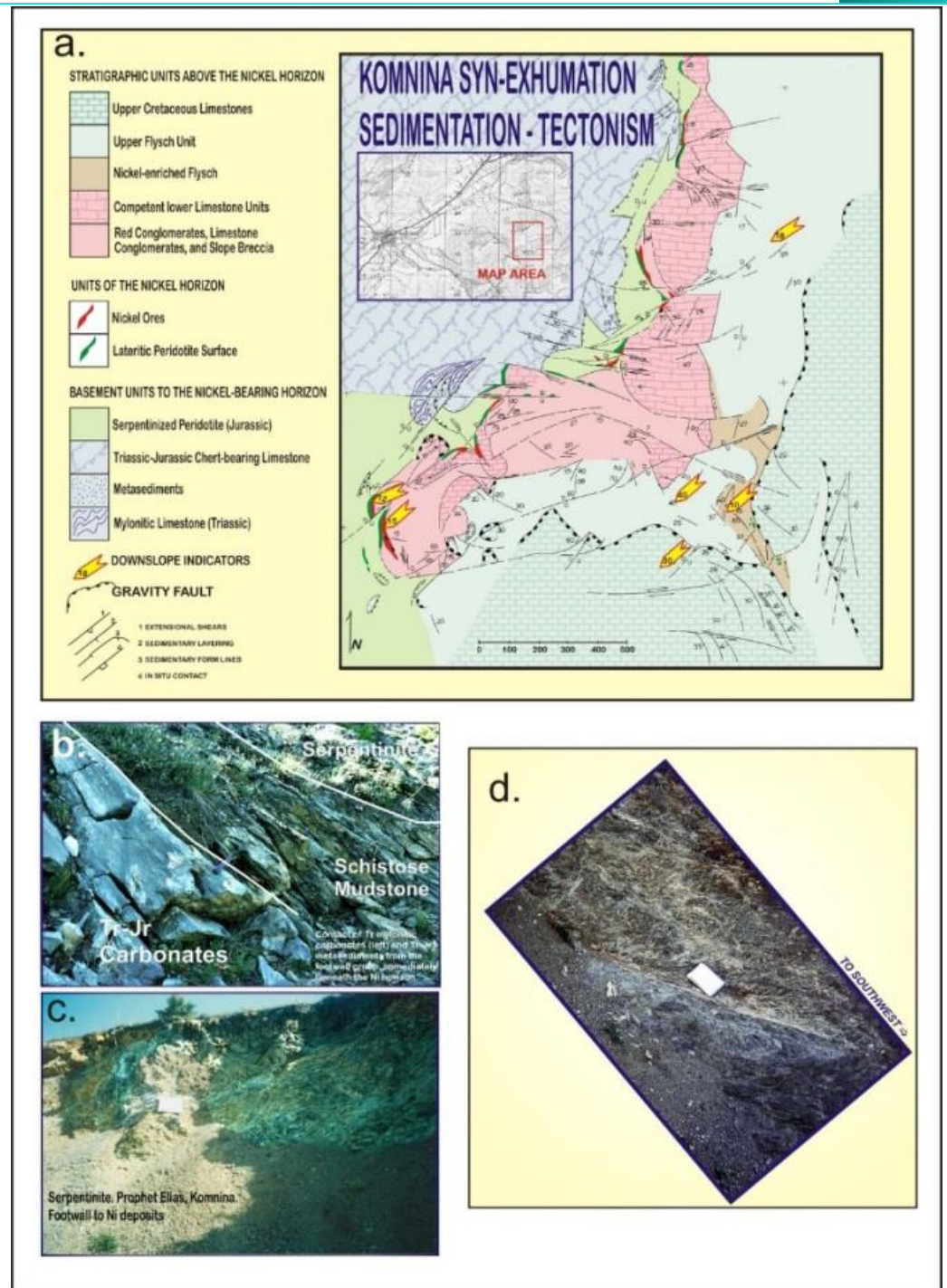


Fig. 8: a) Map of Komnina Ni-ore district (located on Figure 4) b) Schistose equivalent of “pebbly mudstone” at the base of the Komnina serpentinites c) Typical highly metasomatically altered serpentinite of Komnina d) Fault within serpentinites: photo is rotated to show orientation of this fault at time previous to upper Cretaceous deposition. This rotated orientation corresponds to a SW sloping listric fault.

3.4. Livadi Ophiolitic Remnant

The Livadi ophiolite has been interpreted as a Paleozoic ophiolite within the Pelagonian complex on the Livadi (IGME) map sheet. However, its field relations (Nance, 1976) with the underlying Pelagonian are poorly understood. No independent magmatic dating of this ophiolitic fragment has yet been done. It does not appear to be infolded or imprinted by Pelagonian structures. It appears, as do all the “rootless” ophiolitic fragments, to occur above a nappe surface on the Pelagonian (Figure 9). The Pelagonian complex at Livadi is highly metamorphosed gneiss, but the ophiolitic rocks, though altered, do not share so high a metamorphic grade. The ophiolitic rocks are primarily serpentinized dunite, never more than ~300 m thick, above a thin serpentinized peridotite (<150 m); some peridotites overlie gabbroic units, elsewhere small gabbroic bodies overlie Pelagonian units. Both ophiolitic and Pelagonian formations are overprinted by transtensional deformation (Figure 9). The primary structures and ophiolitic pseudostratigraphy of Livadi are complicated by its relation with the exhumation of nearby Mount Olympos.

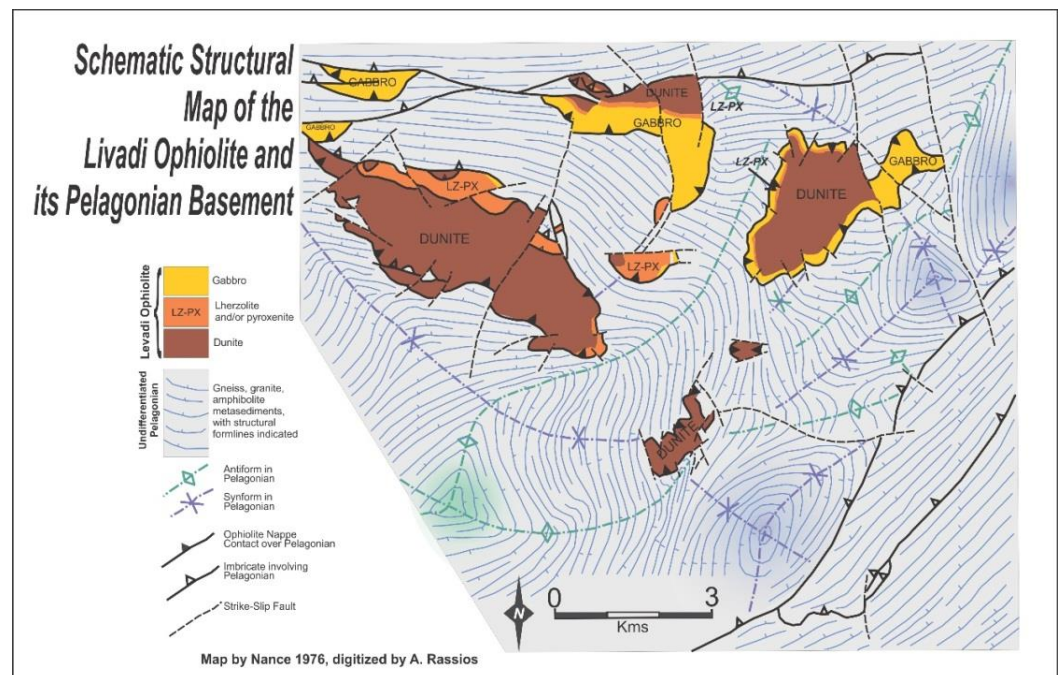


Fig. 9: Simplified map of the Livadi “ophiolitic” rocks (located on Figure 4). The high metamorphic grade Pelagonian rocks show dome and basin structures of relatively small scale (<1 km). Ophiolitic-derived units are cut by extensional faults, not traced extensively into Pelagonian basement (transtensional).

3.5. Criteria from other ophiolitic remnants

Other “rootless” occurrences: Pre-Cretaceous structural data have been documented from several other remnants of ophiolitic material that are too small for inclusion on Figure 4: GPS localities are included in Figure 10.

- Topping directions in a small rifting-mélange association near Siatista appear verging towards the NW. The scale of this occurrence is $<0.5 \text{ km}^2$ (Figure 10a).
- A serpentinite outcrop NNE of Rodiani is about $0.5 \text{ km} \times 0.2 \text{ km}$ (Figure 10bi and 10bii; Egnatia Highway Exit locality). Relations with an overlying Early Cretaceous (flysch) depositional surface shows an original NNE topping direction. A pre-upper Cretaceous nickel laterite deposit crops out along the top of the serpentinite body, then is overlain by several meters of conglomerate beneath the Late Cretaceous unconformity. A fault within the laterite section indicates SW offset, near horizontal, dislocation of the laterite. The serpentinite is, as elsewhere among these remnants, highly dissected by altered (now clay) metasomatic veins and apparently originally consisted of harzburgite and lherzolite, dunite and ultramafic cumulates; lithospheric or original emplacement directions within this unit are obscured by serpentinization and multiple shearing of the serpentinite. The immediate base of the serpentinite is obscured by recent talus deposits, but footwall mylonitic Pelagonian platform carbonates crop out adjacent to these. Tectonic orientations within the upper Cretaceous (dipping at $\sim 10\text{--}25^\circ \text{ N - NE}$) show rare SW topping Z-folds as well as NNE movements along slickenside surfaces. Structures internal to the serpentinite body, rotated to a pre-Cretaceous orientation, consist of small listric (extensional) bodies with transport towards the ~east.
- A small ophiolitic remnant ($\sim 150 \text{ m}^2$ in outcrop, Figure 10c), not more than 5 m total thickness, crops out close to the West Macedonian branch office of IGME above a base of pebbly mudstone similar to that of the Ayios Nikolaos formation of Vourinos. Several meters of highly sheared and veined serpentinite crop out below an m-scale imbricate of lavas less sheared than the serpentinite and not penetrated by the metasomatic veins of the serpentinite. These ophiolitic remnants are overlain by nickel laterite, conglomerates, and a thin lens of Early Cretaceous flysch beneath an angular unconformity (about 30° dipping SE) at the contact with Late

Cretaceous limestone. Constrictive deformation such as ramping shears are lacking from the exposure.

- Near Kalamia (Kozani) (Figure 10di, 10dii, 10diii) an ophiolitic remnant includes outcrops of complex deformed serpentinised peridotite, serpentinised brittle fragments, and jasper-rich laterite formation on serpentinised peridotite. Lacking capping Cretaceous limestone, no sense of rotation of the ophiolitic fragments can be made. Tectonic thinning as exposed within road-cut sites suggest extensional listric features with ~westward offset.

We do not, at this time, wish to present a complete documentation of these “rootless” ophiolitic remnants nor of exhumation kinematics, however we do want to emphasize that tectonic analyses of these remnants without consideration of the underlying Pelagonian exhumation is pointless. In many cases, the ophiolitic remnants overlie areas of high-temperature metamorphic rocks or very mylonitic platform carbonates, but the structures within the multiply deformed serpentinites are extensional. Further west, closer to the Pelagonian margin, the serpentinites display remnant ramping and imbrications most likely due to late emplacement motions of the MHO, but the topping directions appear rotated from the strict NE-emplacement vector of the coherent MHO lithosphere (i.e., Vourinos and Pindos ophiolites). Each fragment is tectonically and petrologically dissimilar; no intra-sheet (stratotectonic) continuity is possible between these fragments. Taken out of context, each rootless fragment would appear to be derived from variable ophiolitic sources.



Fig.10a: Large kinematic indicator of carbonate block within serpentine and sedimentary serpentine near Siatista.



Fig.10bi: Metasomatic veins within serpentinite at “Egnatia Exit” locality.

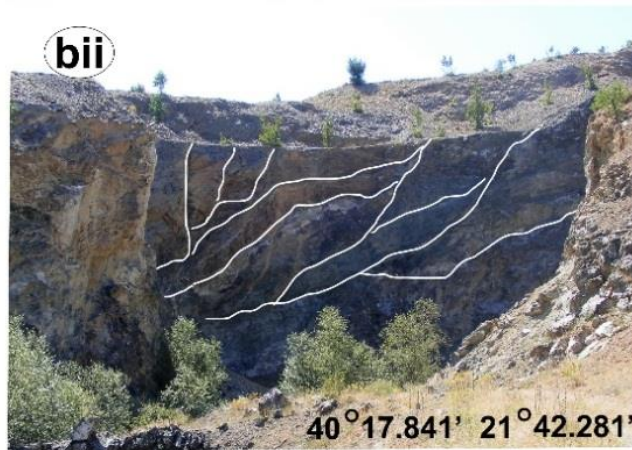


Fig.10bii: Tectonic view of serpentinised peridotite within the outcrop exhibiting extensional (listric) structures.

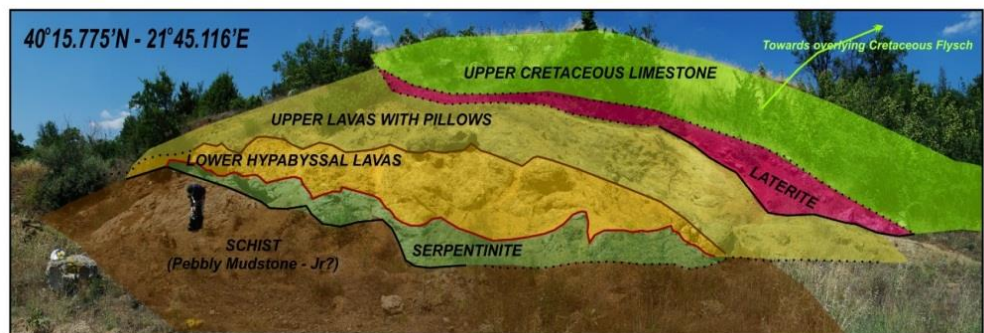


Fig.10c: Ophiolitic fragments located near the IGME offices mimicking a Steinman trinity; intra-formational contacts appear to be listric faults.

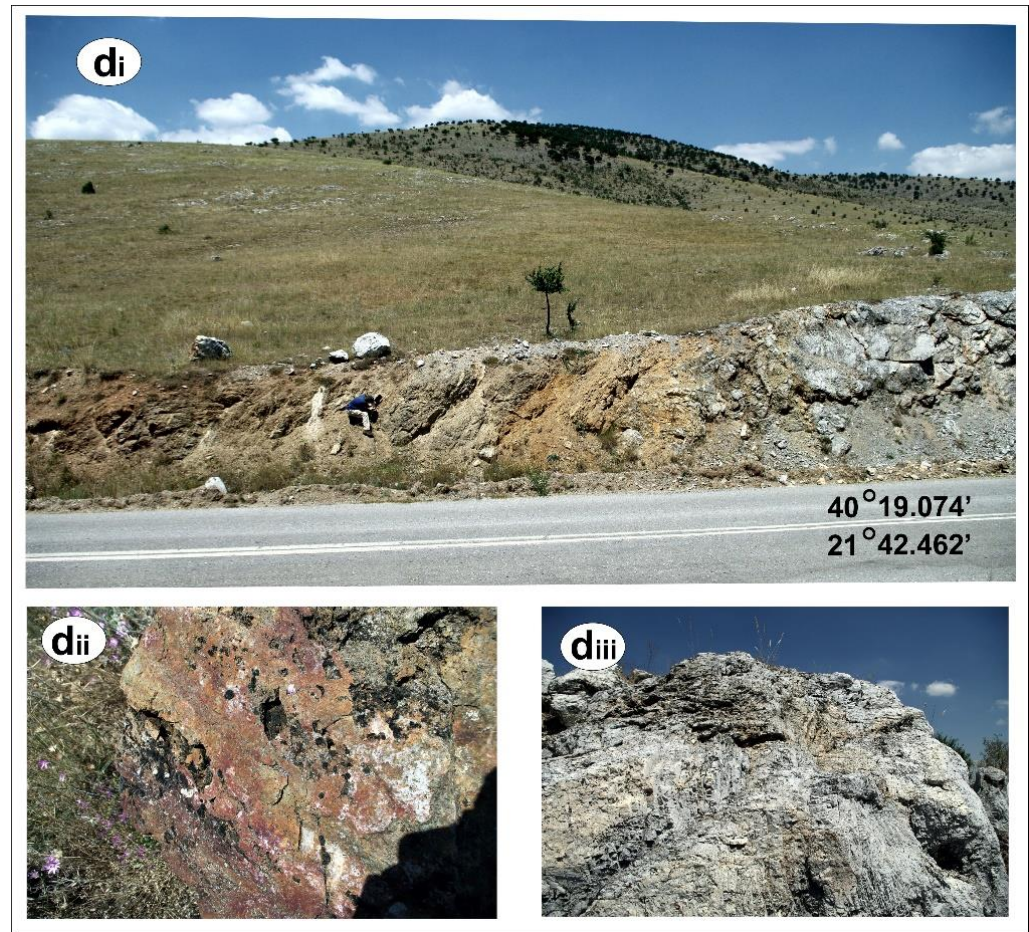


Fig. 10d: Exposures of Kalamia ophiolitic fragment, di) Demonstrates complex deformation of serpentinite body, dii) jasper-rich, diii) altered serpentinitised peridotite.

4. THE OPHIOLITIC NAPPE AND ITS RESPONSE TO EXHUMATION

The exhumation of a gneiss dome can be achieved by multiple mechanisms (Brown and others, 2002). However, by whatever causative means, domes are exhumed via shear zones that extend to great depths into continental lithosphere (Brun and van den Driessche, 1994). Ophiolitic rocks are present in the regions surrounding many metamorphic core complexes as well as in the dome “overburden” formations. The Pelagonian complex is rimmed by the Pindos Basin ophiolitic root zone to the west, and Vardar ophiolitic root zone to the east, each apparently extending more than 25 km depth as delineated by aeromagnetic surveys (Stambolides et al., 2002). Ophiolitic fragments as we describe are common occurrences above the Pelagonian rocks, removed from stratotectonic and structural continuity with either root zone.

The juxtaposition of ophiolitic rocks with gneiss domes on a global scale has given rise to several “cause and effect” models of exhumation (Ring and others, 1999; Burg and others, 2004):

a. The obduction of a relatively “heavy” oceanic lithospheric nappe of ~10-14 km thickness onto a continental crust of 30-40 km thickness could cause initial depression of the “lighter” continental material to mantle levels, initiating melting, and a gravitational instability that requires the doming of the continent to higher levels again. Only in this model are ophiolites the “sole” causative factor. The low likelihood that a single ophiolitic nappe could be obducted without substantial thinning or imbrication over the required distances involved in this model is mechanically not likely. In the case of Greece, for example, a “single” obducted nappe containing Vardar and Pindos ophiolites together would have had to be emplaced further than 400 km distance: mechanically, this is not feasible. As well, the single nappe model could not explain high temperature (oceanic conditions) in situ sole formations on the Pindos side (Vourinos, Othris, Pindos ophiolites).

b. During collision of oceanic with continental tectonic plates, initial subduction of continental crust could result in a similar gravitationally unstable condition reconciled by subsequent exhumation. In this case, ophiolitic rocks are present as evidence of collision, back-arc spreading, and supra-subduction environments. Ophiolites are not the “causative” factor in exhumation, but occur as evidence of tectonic processes that could initiate continental subduction resulting in exhumation.

c. Transcurrent shear along plate margins could depress continental crust and “emplace” oceanic crust at high levels. Again, in this model, ophiolitic rocks are present as evidence of tectonic processes, and are not in themselves a causative factor.

The “coincidence” of the association of MHO at the western Pelagonian margin ought to be one of the major clues towards determining the causative factor of Pelagonian exhumation. In Vourinos, the emplacement vector ranges from 90° - 40° from the north to south against the Pelagonian margin. The Zavordas shear zone including the emplacement sole and highly deformed Triassic rifting complex (Ghikas 2007; Ghikas and others, 2010) may mark part of what is originally transcurrent shear along plate margins. Could this shear be the initial key tectonic force leading to subsequent exhumation of Pelagonia?

The structures and kinematics of ophiolites rooted in the Mesohellenic Trough, including Vourinos, Pindos and Othris, are coherent. Structural analyses of ophiolitic fabric show vergence during ductile slab – emplacement motions oriented to the NE to NNE. All the ophiolites of the Pindos Basin are associated with emplacement soles of high temperature generated in oceanic conditions. In many localities, the soles are intact above mélangé footwalls that show zoned metamorphism. In the case of Vourinos and eastern Othris, the relation of the ophiolites with basement Pelagonian formations is preserved, and penetrative deformation between the ophiolitic slab and emplacement footwall is documented (Zimmerman, 1968; 1969; 1972; Zimmerman and Ross, 1972; Smith and others, 1975; Smith and others, 1979).

By comparison, ophiolitic remnants found above the Pelagonian ribbon continent show diverse epochs of deformation, a variety of verging directions, strong overprint by SW provenance gravity-extensional fabric, and are overprinted by transtensional faulting. Emplacement-verging directions are totally occluded by serpentinization and repeated extensional shearing of serpentinites. If these “rootless” ophiolitic remnants were once part of a contiguous nappe stretching between the Vardar ophiolitic belt and MHO, their geochemical and tectonic associations are equally as consistent with an original association with the MHO as with ophiolites of the Vardar zone. Direct observation of their emplacement vectors is moot: these rootless remnants are pervasively rotated and sheared in post-emplacement (Late Jurassic to pre-Late Cretaceous) time. This time interval is consistent with the chronology of exhumation of the Pelagonian ribbon continent (Sharp and Robertson, 2006).

The major insight that can be gained from analyses of these small remnants is their relation with the exhumation processes of the Pelagonian complex. Trapped between the exhuming crystalline complex and sedimentary overburden, these serpentinite-rich remnants provide a zone of sharp contrast in competency. The weak nature of serpentinite would have provided the optimal location for incipient “ductile” motions, possibly providing the “breaking point” for major exhumation-related detachments. Wherever the ophiolitic fragments were originally rooted, their present positions and structural conditions are due to translation within this deforming zone entrapped over the exhuming Pelagonian rocks. The evidence from ophiolitic serpentinite remnants above the Pelagonian core complex demonstrates intraformational crushing and extensional sliding penetrated by metasomatic fluids

relatively dated to the exhumation period. Only along the Pelagonian margin outlying the core exhumation do the MHO retain original Jurassic oceanic and emplacement structures. Microtectonic analysis within the “rootless” ophiolites is predicted to be able to document topographic features above the exhuming crystalline complex, and to “fine-tune” the chronology of the exhumation process.

5. A NAPPE HYPOTHESIS EXPLAINING THE ORIGIN OF THE MHO AND VARDAR OPHIOLITES

Models of the Jurassic ophiolitic nappe of Greece, extending northerly into Albania and the Balkans, conventionally invoke a single provenance direction for the ophiolites – these models “root” the entire nappe within the Vardar Ocean, generally including the Late Triassic Maliac rocks as an older part of the eastern slab. Our work in the MHO and western Pelagonian margin precludes accepting this construct. We accept that parts of the Vardar belt underwent SW constrictive emplacement, but cannot accept an original SW emplacement of the MHO. We would like to suggest herein a model that reconciles multiple emplacement origins of the Triassic - Jurassic ophiolitic fragments that is also consistent with observed relations between the ophiolitic rocks and the exhumation of the Pelagonian ribbon continent.

Rassios and Moores (2006) presented a model based on geographic and geochemical association of the Pindos-Vourinos-Rodiani reconstructed slab that necessitates a “triple junction” boundary within the MHO. If so, the MHO, Maliac, and Vardar zone ophiolites could be related in a “Horn of Africa” type relation, with the Pelagonian continent itself being analogous to the Ethiopian-Somalian plate. The west Pelagonian margin and MHO would represent the rift zone – ocean basin corresponding to a future mature African rift zone. With constriction and ophiolitic emplacement, it would seem possible to derive and emplace ophiolitic material from both east and west of Pelagonia, as well as reconcile incongruities in the orientation of subduction zones associated with these oceanic margins. The subsequent exhumation of Pelagonia would result in two types of “rootless ophiolitic” remnants over its core complex: one type would be the multiply sheared serpentinites essentially crushed between the emerging core and overlying cover, and the second would be ophiolitic remnants mobilized via gravity slides from their original position over the emerging core. Possible mixing of MHO crushed ophiolitic remnants with mobilized remnants from the Vardar provenance could be envisioned.

6. CONCLUSIONS/IMPLICATIONS

- The distribution and structures of the ophiolitic remnants found between the Meso-Hellenic ophiolites to their west and Vardar ophiolites to their east are due to their response as Jurassic lithospheric fragments entrapped between the exhuming Pelagonian core complex and overlying sediments.
- The origin of these fragments within a single ophiolitic nappe originating either from the Mesohellenic Ophiolites or the Vardar Zone ophiolites is not possible for the following reasons:
 - a. the formation of high-temperature in situ emplacement soles cannot be envisioned at the distances required for such transport.
 - b. Nappe transport would require retaining original lithospheric thickness (~12 km thick as documented for the Vourinos ophiolite) and extensive thinning of the lithospheric section between origin and final position.
 - c. All ductile and early brittle structures within the Mesohellenic ophiolites show NE transport vectors that originated near the ridge crest.
- Structural associations within the “rootless” ophiolites are strongly overprinted by exhumation extensional deformation. They are associated with metasomatic alteration lacking from the ophiolites within the Meso-Hellenic or Vardar zone.

We have proposed an origin of the Jurassic ophiolites that reconciles the existence of separate lithospheric and continental belts within a “triple-junction” Horn of Africa type area following the suggestion of E. Moores (Rassios and Moores, 2006). We are still developing models that can explain the contemporaneous origin of apparently separate Jurassic lithospheric sections within Greece. The objective of future studies is not to deny the transport directions of ophiolitic nappes, but to use them as tools to model lithospheric development and emplacement mechanisms.

7. ACKNOWLEDGEMENTS

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