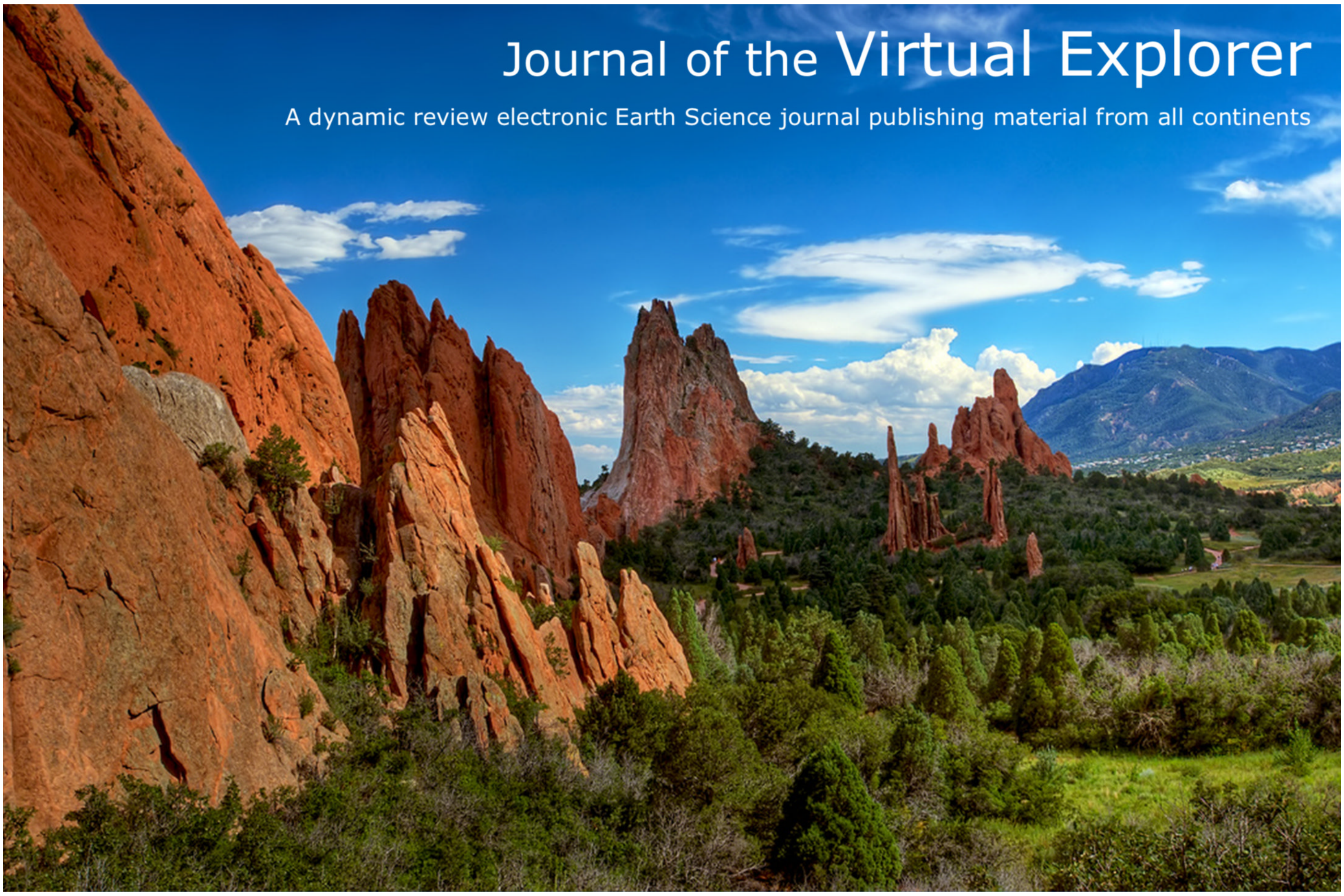

Ophiolites 2008 Guidebook: Link between the Mesohellenic Ophiolites and the Pelagonian Margin

Anne Rassios, Alan Smith, Dimitrios Kostopoulos

Journal of the Virtual Explorer, Electronic Edition, ISSN 1441-8142, volume **34**, paper 1
In: (Eds.) Anne Rassios, Alan G Smith, and Dimitrios Kostopoulos,
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Abstract: The geology of Greece is complex. The interpretation of key ophiolitic localities of Greece has, in classic studies, aided formulation of primary models of plate tectonic theory. One of these localities, exposed along the Aliakmon River below Zavordas Monastery, was described by Jan Brunn (1908 – 2006) as the best exposure of the base of an ophiolite in the world. Zimmerman (1968) and Moores (1969) used the Aliakmon exposures to document the initial description of the structural nature and zoned metamorphism of an ophiolitic sole. Unfortunately, much of this historic section will be inundated with the construction of a hydroelectric dam. A final study to document this river section has produced new data concerning the nature of this complex suture: in short, the Aliakmon valley records the rifting of Pelagonia, early formation of the Tethys, and the destruction of the Tethys with the emplacement of the Vourinos ophiolite.

To further understand the nature of the sole zone, research extended into its "footwall unit," the west Pelagonian margin. Virtually unstudied, this Paleozoic-Jurassic margin preserves a continuous section from the Pelagonian core complex gneiss-migmatites, through schistose metamorphics, and into slatey phyllites. Age dating and structural analyses are on-going, their results deciphering exhumation processes of the Pelagonian margin and in delineating the extent an "ophiolitic footprint" beneath the sole zone.

Other classic localities of the Pindos, Koziakas, and Vourinos ophiolites enable discrimination of structure within an obducting ophiolitic nappe: mantle layering and foliation, lower temperature ductile structures, ductile-brittle and brittle emplacement related deformation are demonstrated among

http://virtualexplorer.com.au/article/2009/213/ophiolites-2008-field-guide

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Paper Review

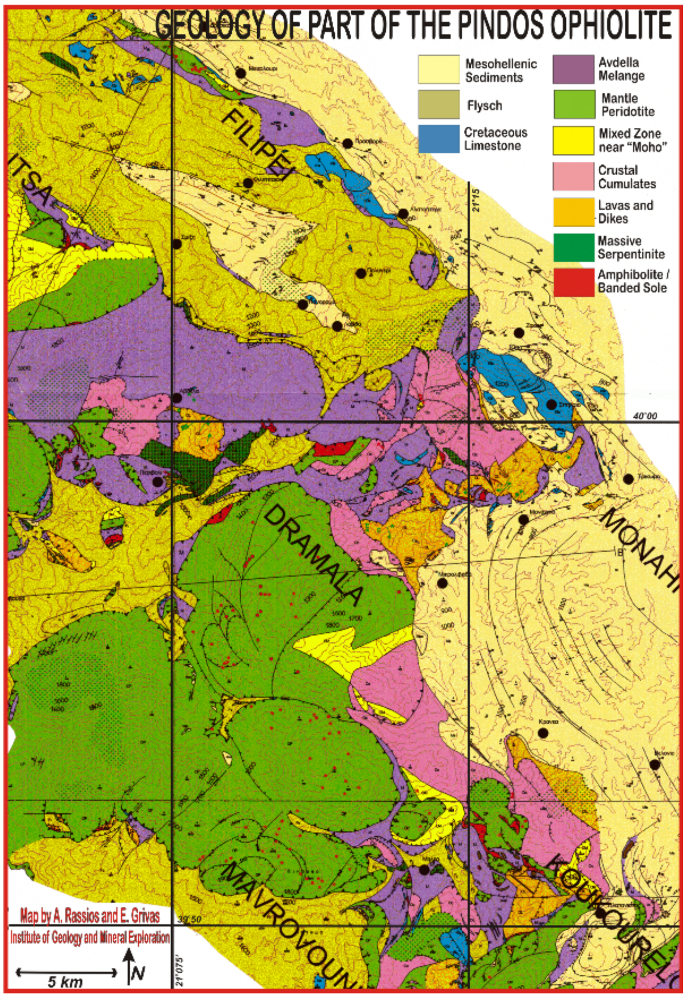
This paper is in dynamic review. Readers may email commentary to: <team@virtualexplorer.com.au>.

Introduction

This paper is a published version of the "Guidebook to the Field Symposium - OPHIOLITES 2008: Link between the Mesohellenic Ophiolites and Pelagonian Margin"

September 14 - 20, 2008, West Thessaly - West Macedonia, GREECE

We dedicate the following guidebook to our friend and mentor, Jan H. Brunn (1907-2006) who pioneered nearly all the sites documented in this guidebook.

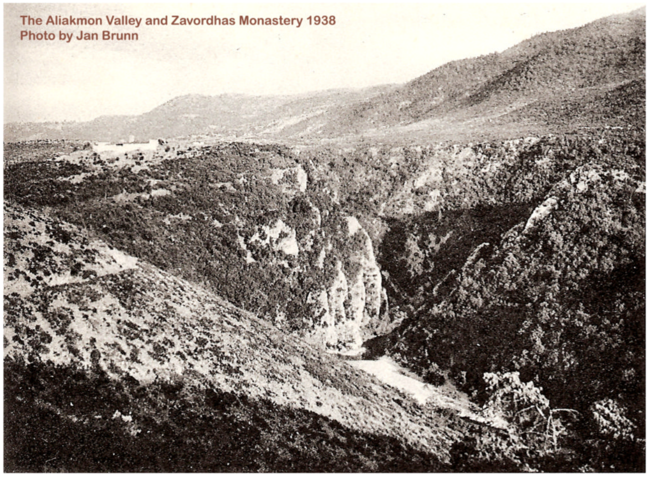


Geology of part of the Pindos Ophiolate

Symposium Goals

On behalf of the Institute of Geology and Mineral Exploration, I extend our warmest welcome to Greece. The geology of Greece is one of its greatest legacies – it is woven into the mythology of the ancients; its active volcanic and seismic activity impacts our history and, in turn, that of Western civilization; it has been decisive in our economic development. Greek geology is complex, its study has contributed to the education of geologists worldwide and continues to do so with programs such as the Aliakmon Legacy Project. During this field symposium, you will be visiting sites among the geologic wonders of our country, several among the most important in development of plate tectonic theory. Some sites on this trip are presented to the international community for the first time, and we feel certain their interpretation will be incorporated in developing scientific theory for decades to come.

—Prof. Charalambos Tsoutrellis, President of IGME



1938 photo by Jan Brunn

The importance of the Symposium field area:

"…The outcrop along the road from Deskati to the Aliakmon, I think it might be

> the most complete and significant outcrop of the base of ophiolites in the world."
>
> —Jan Brunn, 2001

Since Jan first documented that outcrop in 1938, as well as many other outcrops we will be visiting during our symposium, its geology has remained unchanged. Geological theory, however, has changed and continues to change. How we see that ophiolitic base today is within a framework of plate tectonics, of initial rifting of Pangea, the rift-drift history of a Tethyan ocean basin, complex mechanisms of ocean lithospheric emplacement, and the exhumation of a continental margin.

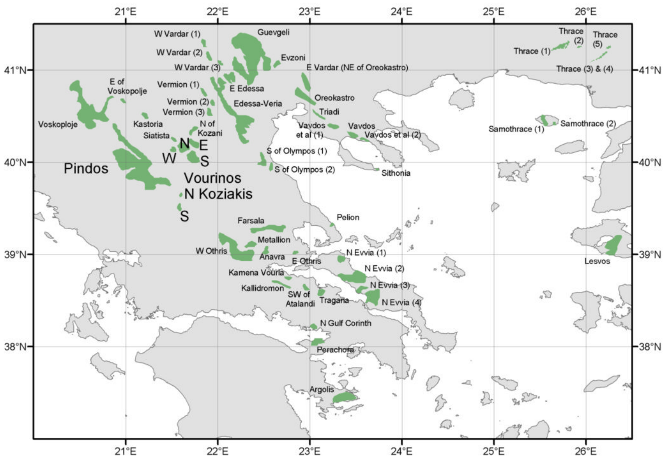
Some of this original outcrop area at the base of the Vourinos ophiolite will be lost with the completion of the Ilariona Dam, an important new energy resource. With funding from the Public Power Corporation of Greece, IGME has administered an international educational program, the Aliakmon Legacy Project, to aid in a final scientific documentation of its historic geology.

Our symposium will showcase this legacy of Greek geology, as well as examine some aspects of the regional geology essential to its interpretation. Among the areas to be visited are the Koziakas ophiolite, the W Pelagonian margin, the Vourinos ophiolite, and critical localities of the Pindos ophiolite. As we have renewed study of the Aliakmon valley, we have also found our ideas evolving in these areas as well; with the aid of the symposium participants, we hope that lively discussion will not merely clarify problems in past interpretations, but help bring the area once again to the cutting-edge of geologic research.

Framework Geology for the Symposium Fieldtrip

The geology of Greece is complex. For the purposes of this field guide only the geology of central and northern mainland Greece will be described, with particular emphasis on the ophiolites (Figure 1).

Figure 1. Distribution of ophiolitic rocks in the Hellenides.



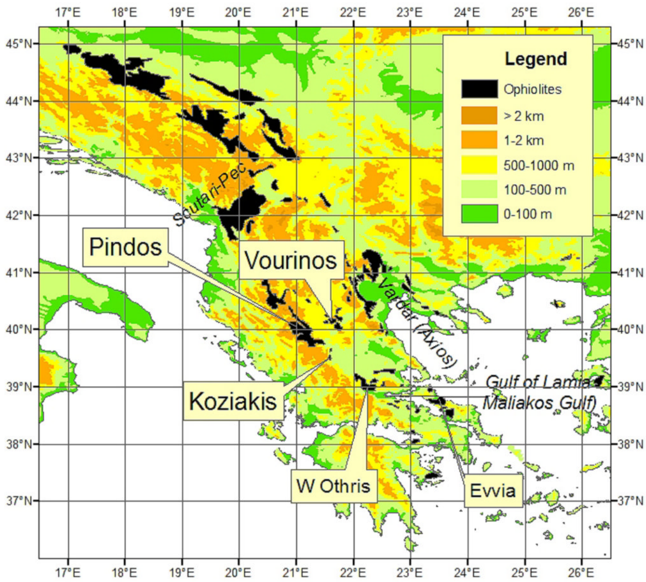
Distribution of ophiolitic rocks in the Hellenides. The complexes to be visited are in larger font: Pindos, Vourinos and Koziakis.

Ophiolite distribution in Greece and former Yugoslavia: The ophiolite distribution in Greece shows no obvious pattern (Figure 1), but when the ophiolites of former Yugoslavia are added a clearer pattern emerges (Figure 2).

Tectonically, the Greek ophiolites are part of the Hellenides, the orogenic belt that terminates in Albania along the Scutari (Skudar)-Pec line. NW of the Hellenides lie the Dinarides, which start in Albania and continue throughout most of former Yugoslavia.

From the most northerly outcrop in former Yugoslavia at about (45ºN, 17ºE) the Hellenic-Dinaric ophiolites trend SE and then split into two outcrop belts at about (44ºN, 19ºE) that gradually separate from one another until at (42.5ºN, 20.5ºE) their closest main outcrops are roughly 40 km apart.

Figure 2. Distribution of ophiolitic rocks in the Hellenides and former Yugoslavia.



Eastern ophiolite belt: The major eastern belt continues SE as a series of discontinuous outcrops that widen in extent to about 90 km at the Greek border. These ophiolites lie in the Vardar zone (named after the Vardar River in former Yugoslavia) and its Greek continuation, the Axios zone, referred to here as the eastern Hellenic ophiolite belt.

Western ophiolite belt: The western ophiolite belt has a major offset at about (42.5ºN, 20.5ºE) along the Scutari (Skadar)-Pec line, interpreted as a through-going transform fault. This fault has been suggested to cut the platform carbonates to the W of the ophiolites, but field evidence suggests that this is not the case. More likely it is a short ("leaky") transform segment connecting two offset oceanic domains.

S of the Scutari (Skadar)-Pec line, the western ophiolitic belt, including all the ophiolites to be visited on our field trip, continues as a linear belt of discontinuous outcrops about 400 km long, extending S at least to the Othris Mountains at about 39ºN and possibly including

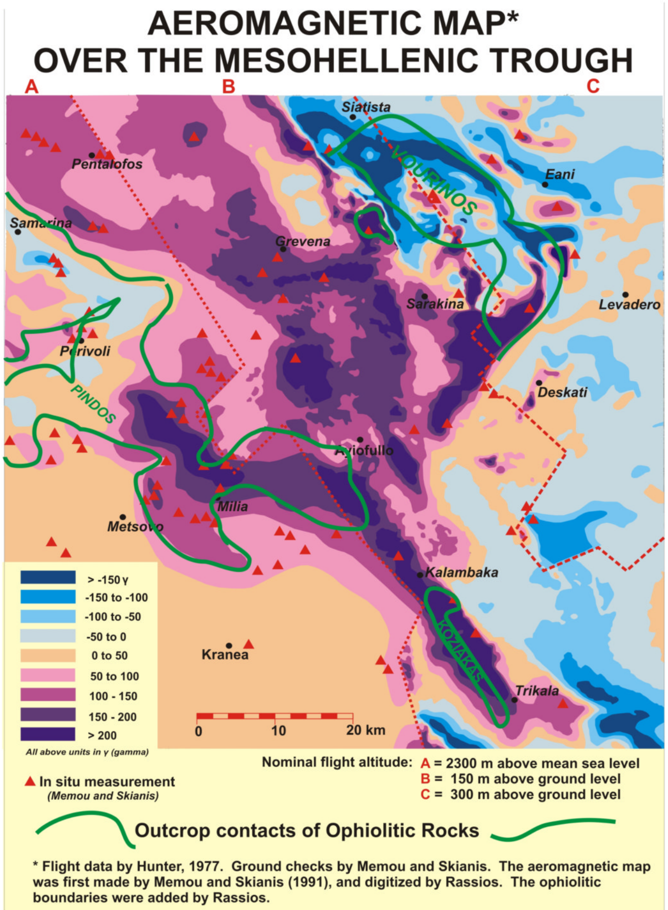
Evvian ophiolitic fragments and even those of the Peloponese. However, along Othris, outcrops appear to be offset across the Sperchios River and the Gulf of Lamia (Maliakos Gulf) in the opposite sense to that on the Scutari-Pec line. The offset is immediately S of the only large plagioclase lherzolite massifs known in the Hellenic ophiolites and it may represent a second transform zone.

The Mesohellenic trough and its relationship to the western Hellenic ophiolites: The western ophiolites are allochthonous, forming sub-horizontal sheets locally exceeding 11 km in thickness (Vourinos). The sheets are pervasively imbricated, with duplexes reflecting their emplacement history. The main outcrops in the western ophiolite belt in Greece are the Pindos (2500 km^2), Vourinos (450 km^2), Othris (800 km^2) and Evvia (=Euboea) (400 km^2) (Figure 1). Outcrop discontinuity along the western margin is mostly due to the superposition of the sediments of the Cenozoic Mesohellenic trough (MHT, Figures 4 & 5). These Mesohellenic sediments cover presumed connections between the Pindos, Koziakas ophiolite, and western Othris ophiolite and the continuation between the Pindos and Vourinos ophiolites. Geochemical variability between Pindos and Vourinos has suggested that they represent distinct ophiolites that were never joined together. However, reports of deep drilling through the Mesohellenic sediments confirmed they have an ophiolitic floor.

The MHT itself is an Eocene-Miocene sediment-filled tectonic basin extending >350 km from N Albania across Greece into Thessaly. It is ~20-30km wide, with sediments as thick as ~5 km near Grevena. Generally agreed to be constrictional, the basin originated as part of the late Apulian-Pelagonian collision, and the "fossil" African-European plate boundary has been corellated beneath its western margin. Vourinos extends to the west into the MHT; parts of the Pindos (Dotsiko strip ophiolite, Milia-Kranea strip) extend east steeply into the MHT, much like the position of Koziakas against the Pindos zone. The majority of the part of the Pindos outcrop seems to be represented by a distinct nappe broken off from the Mesohellenic slab with less clear connection to the sub-Mesohellenic ophiolites.

A magnetic anomaly map (Figure 3) shows that the Pindos, Vourinos, Koziakis and Othris are parts of the same ophiolite body, reaching a 25 km thickness beneath the MHT. Though complexly deformed internally, all the western ophiolites are most probably part of a huge ophiolite body that may have originally had dimensions of 400 km × 70 km, (assuming shortening in the MHT) referred to as the Mesohellenic Ophiolite Slab or Pindos Basin ophiolite.

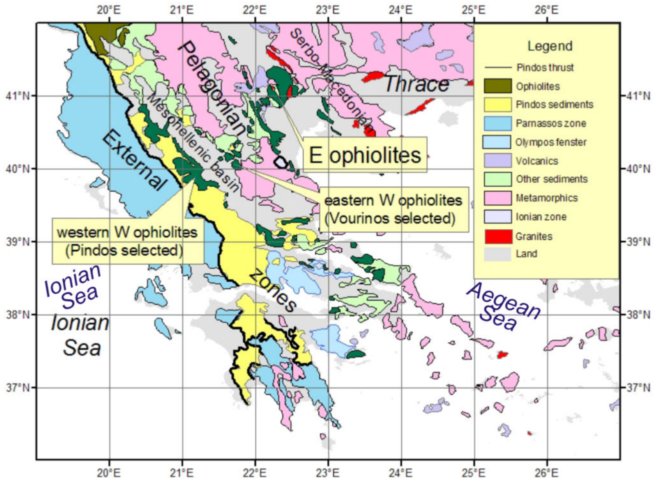
Figure 3. Magnetic anomaly map of western central Greece



Model (after Wright, 1986) of deformation of ophiolitic slab moving off-ridgecrest in constrictive ductile to brittle fields.

Geologic Section across the Fieldtrip Area: A traverse from the Ionian Sea to Thrace crosses five tectonic units.

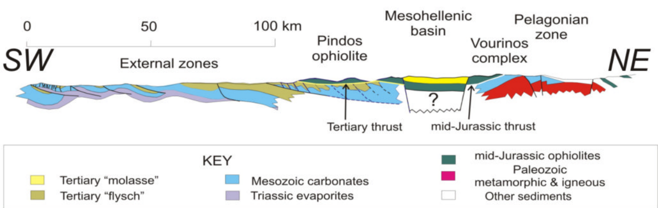
Figure 4. Outline geological map



Outline geological map showing the external zones; the western Hellenic ophiolite belt; the Pelagonian zone; the eastern Hellenic ophiolite belt; and the Serbo-Macedonia zone.

The westernmost unit comprises the so-called external zones of the Hellenides; their eastern boundary is their contact with the western Hellenic ophiolite belt. The eastern boundary of this ophiolitic belt lies along the western margin of the Pelagonian zone. The Pelagonian zone extends to the western limit of the eastern Hellenic ophiolite belt. The fifth tectonic unit, the Serbo-Macedonian zone, crops out east of this belt. Thus from SW to NE the five units that are traversed are the external zones; the western Hellenic ophiolite belt (to be visited on this field trip); the Pelagonian zone, the eastern Hellenic ophiolite belt and the Serbo-Macedonian zone.

Figure 5. Schematic section across the eastern Hellenic ophiolites and the Mesohellenic trough.



.Schematic section across the eastern Hellenic ophiolites and the Mesohellenic trough.

Mesozoic rocks of the external zones make up a series of carbonate platforms and pelagic troughs above concealed basement: the basement formation of the Pindos Zone is not exposed. However, continuation of these units southward into the Peloponnese reveals a metamorphosed continental basement. The Pindos zone, the innermost external zone, is a former pelagic basin, deformed into a stack of imbricate thrusts in the Tertiary, and tectonically emplaced above other units of the external zones. In turn, the Pindos zone is itself overthrust by a detachment of the western Hellenic ophiolites in the Eocene.

The basement of the Pelagonian and Serbo-Macedonian zones is made of metamorphic and igneous rocks that include Precambrian and early Paleozoic terrains welded during Hercynian collision. All the Hellenic ophiolites, western and eastern belts, are regarded as slices of fossil oceanic lithosphere (here including back-arc basins) emplaced at Jurassic convergent plate margins consisting of adjacent continental margins or island arcs. Dating shows their crystallization to be Middle Jurassic in age (see below).

General lithology of the western ophiolites: Harzburgite with associated dunite is the dominant ultramafic component of all the western Hellenic ophiolites. Lherzolite crops out within the Pindos and Koziakas, and dominates some massifs of W Othris. Dunite bodies within peridotite are shape-defined by overprinting ductile deformation, resulting in tabular, podiform or irregularly-shaped bodies ranging in their largest dimension from a meter to tens of kilometers. Folding is pervasive in mantle peridotite, and ranges in wavelength from a few centimeters (as observed within chromite deposits) to more than several kilometers. No km-scale recumbent folds (i.e. nappes) have been located.

Vourinos is the least disrupted massif and includes a “complete” ophiolite section from an ultramafic tectonite base, crossing an intact petrologic Moho, through a cumulate ultramafic sequence into gabbro, sheeted dykes, minor pillow lavas and oceanic sediments. The Pindos and Othris complexes lack continuous section, though several thrust units contain overlapping stratigraphic elements and include all the structural and petrological elements regarded as the hallmark of an ophiolite. In each of the thrust units of the Pindos and Othris, an essentially up-section orientation is retained, while a “reverse” pseudo-stratigraphic order is observed among the thrust sheets: the higher thrust sheets are mantle section, lower sheets crustal, with pillow lavas and sediments in the bottom-most sheets. Koziakas tectonically resembles Othris, but has been extensively sheared and imbricated against the westernmost Pindos Zone formations. Though it lacks extensive cumulates and sheeted dikes, their presence can be inferred from minor tectonic remnants, well-developed hydrothermal systems, and abundant lavas.

Geochemical and structural variations within the Mesohellenic Ophiolite slab: Data collected during exploration for chromite and copper ore in the western Hellenides indicate pronounced lateral changes in ophiolite composition: from a supra-subduction zone setting in the Vourinos Complex, a harzburgite-lherzolite unit in the Pindos including MORB to IAT and boninite affinities, that links up, via the Koziakas ophiolite, with the Othris ophiolite, dominated by plagioclase lherzolite-lherzolite-harzburgite mantle rocks and MORB-like lavas.

Chromite occurs within dunite throughout the slab, but its abundance as an economic mineral varies. In Othris, chromite shows are very rare, although several >million ton (mt) deposits were mined; in the Pindos, chromite shows are common, but all are sub-economic; in Vourinos over 800 chromite occurrences were mapped including ~8 mt of ore in six major districts.

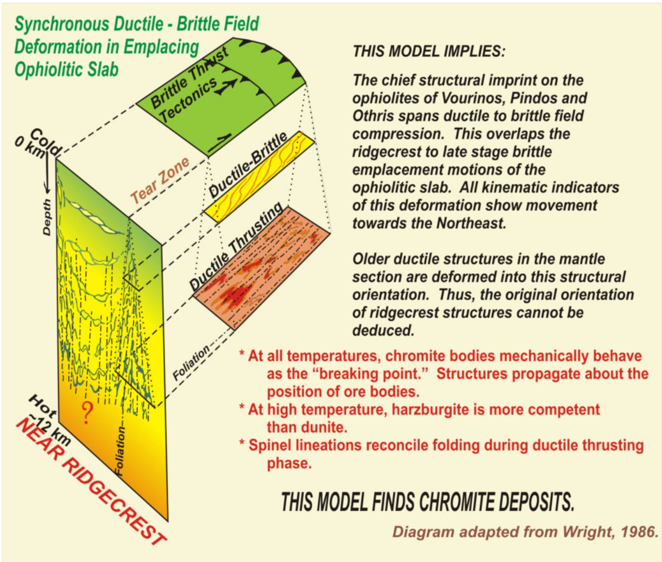
Petrogenetic variations are also reflected in the fabric: Othris and Koziakas peridotites are intensely mylonitized; Pindos peridotites are less mylonitized, with Vourinos being the least mylonitized.

Ophiolite contacts: The nature and age of the thrust surface beneath the ophiolite slab also varies. In the east (Vourinos), the ophiolite lies directly on the Pelagonian carbonate platform and the contact zone is of mid-Jurassic age. It was hot and ductile at the initial time of formation. In the west (Pindos and Othris), a detachment of the slab was thrust over Tertiary “flysch” in cold and brittle constrictional conditions. However, the original hot, Jurassic Pindos sole is preserved in situ between mantle peridotite and a Jurassic accretionary mélange (Avdella mélange). Sole dates from the Pindos, Othris, and Koziakas are indistinguishable from those at the base of the Vourinos complex (Figure 5). These dates have not been reset by Tertiary thrusting. Koziakas, again post original Jurassic obduction, appears tectonically emplaced, again in the Tertiary, directly against Pindos Zone carbonates, probably much like deeper portions of the Mesohellenic slab are deformed against the western “wall” of the MHT.

Tertiary (Eocene) overthrusting of the western margin of the Mesohellenic slab was directed towards the SW, though later Tertiary constriction movements top to the NE.

The original Jurassic emplacement direction of the Mesohellenic Slab is more controversial. In Vourinos, the only strongly developed brittle shear set is geometrically similar to the oldest shear set of the Pindos and Othris. Ductile-brittle shears display characteristics typical of both mylonitic and brittle fabrics and are assumed to have been initiated in the ductile field when the ophiolite was hot. In Vourinos the transition from these and other ductile structures, such as mylonite zones and sheath folds, into NE-verging brittle structures is gradual, and all interpreted as drift to early emplacement features. This implies that parts of the ophiolite were still in the ductile field when emplacement to the NE was initiated and that these structures record the main phase of early deformation (Figure 6).

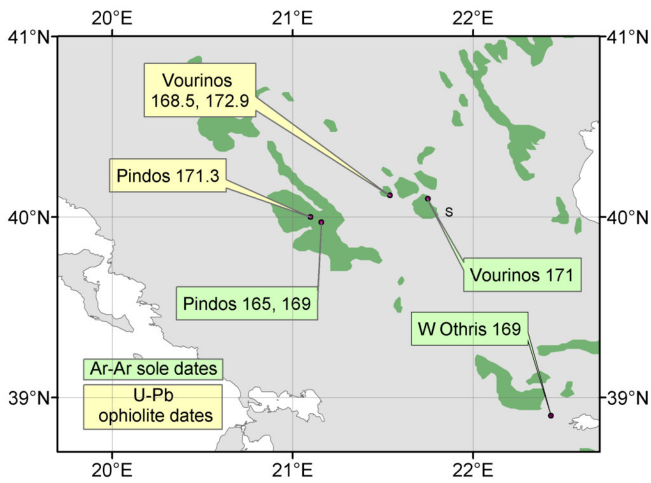
Figure 6. Deformation model



Cartoon showing distribution (after Wright, 1986) of deformation in lithospheric-ophiolitic slab from position near ridgecrest and passing into constrictive deformation. At any time, ductile to brittle deformation is concurrent at different depths in slab, with brittle field at greater depths away from ridgecrest.

Ophiolite dates: Dating of the Hellenic ophiolites is still in its infancy. Figure 7 shows U-Pb SHRIMP dates from the Vourinos and Pindos ophiolites (average 170.9 Ma), and Ar-Ar dates from amphiboles in the metamorphic soles of the Pindos, Vourinos and W Othris ophiolites (average 168.5 Ma). The 2.4 m.y. time-difference between ophiolite crystallization and sole formation is close to the time-difference between the crystallization of the well-dated Samail ophiolite and its sole in Oman.

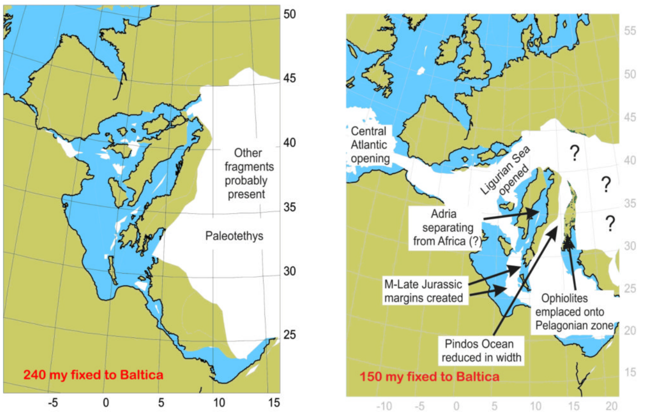
Figure 7. Ar-Ar dates in Ma on amphiboles in metamorphic soles and U-Pb SHRIMP dates on zircons in ophiolites.



Ar-Ar dates in Ma on amphiboles in metamorphic soles and U-Pb SHRIMP dates on zircons in ophiolites.

Possible paleocontinental evolution: What is now Greece coalesced tectonically from the collision of one or more Hercynian continental fragments (Pelagonian zone, Serbo-Macedonian zone) with the external zones, facilitating the emplacement of parts of intervening Jurassic oceanic regions that now are represented in the western and eastern Hellenic ophiolites (Figure 8). Exhumation of the older continental blocks, possibly as early as late Jurassic and lasting to mid-Cretaceous, certainly affected the ophiolitic belts at their margins, though this has yet to be detailed. Post-emplacement Pelagonain exhumation, and continuing deformation (largely Alpine), further constricted the Hellenides.

Figure 8. Cartoons showing speculative reconstructions at 240 and 150 Ma.



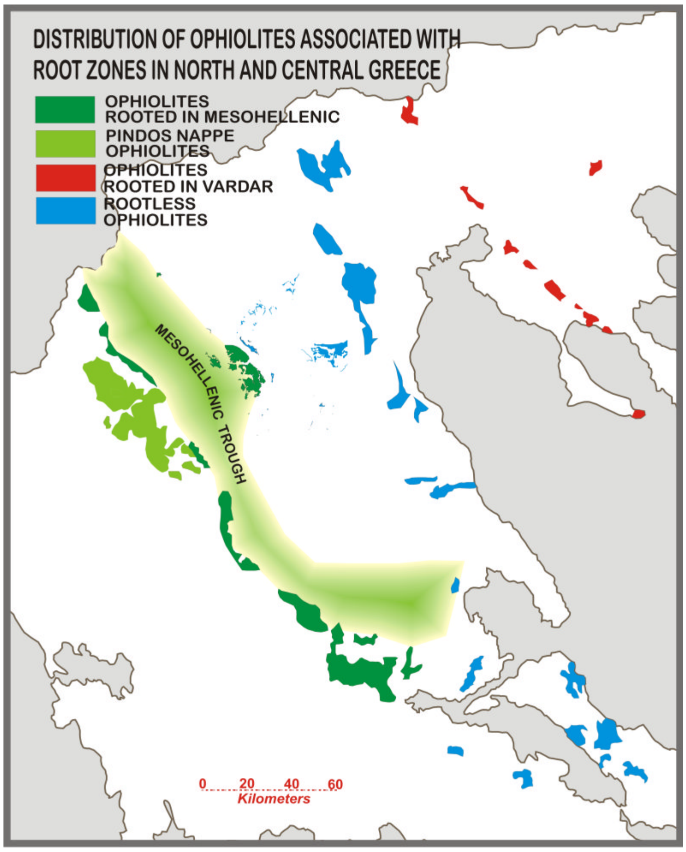
In the first (240 Ma = early middle Triassic), present-day Greece is broken along the zone of the eastern ophiolite belt and attached to eastern Italy and N Africa. In the second (150 Ma = late Jurassic) the Pelagonian zone separated from western Greece, joined to Italy to form Adria, separated from N Africa. The small ocean between the Pelagonian zone and eastern Greece (Pindos Basin) has already closed by this time, and the Pindos Basin ophiolites emplaced eastward, onto the Pelagonian zone. No attempt has been made to show the history of the eastern ophiolite belt.

Some problems: It should be clear from the caption to Figure 8 that the configuration prior to collision is not known and the details of the collisional process are disputed. In particular, the relationship of the western Hellenic ophiolites to the eastern Hellenic ophiolites is unclear. The presence of sparsely scattered, probably ophiolitic-derived serpentinite masses, lavas of unclear association, and Jurassic ocean sediments throughout the area separating the two ophiolite belts argues strongly that they were once a continuous nappe. But was this nappe an extension of the Pindos basin ophiolites, or the Vardar Zone ophiolites?

Several interpretations exist with respect to the original relation between the two ophiolite belts (Figure 9):

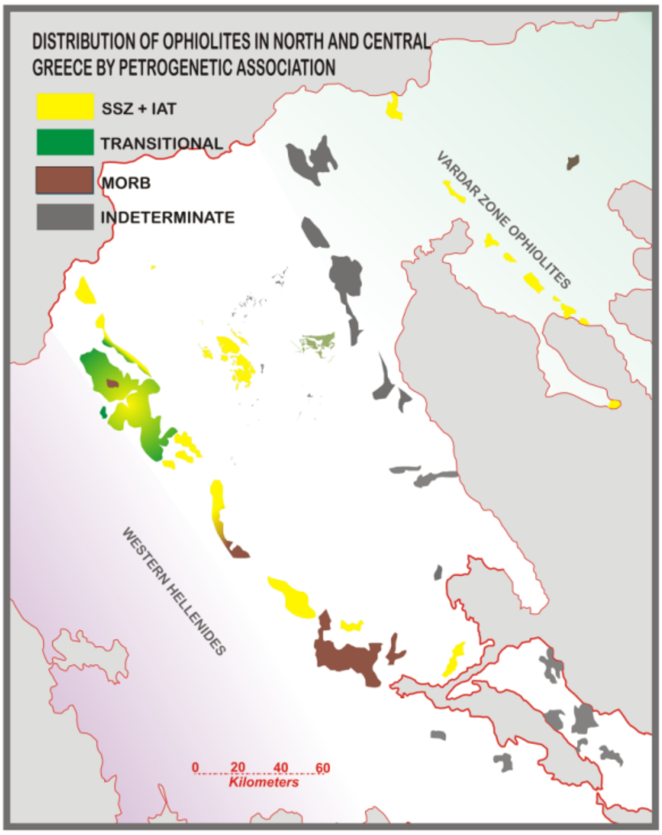
- The western and eastern ophiolites were always separate from each other. The western ophiolites originated somewhere in the original Pindos basin, and eastern ophiolites in the original Vardar basin.
- The western ophiolites were originally joined to the eastern ophiolites. The “root zone” for both belts was originally within the Vardar (Axios) zone, but their original continuity has been destroyed by Pelagonian exhumation and erosion. Conversely, recent discusion posits whether the origin of nearly all the ophiolites was from the Pindos Basin, and whether some eastern bodies are indeed ophiolites or large masses within mélange
- The western and eastern ophiolites were originally continuous, but have been separated by strike-slip (transcurrent) faulting.

Figure 9. Possible Relations between the Pindos Basin and Vardar Zone ophiolite belts with potential root zones.



There are many other basic questions to be considered, some apparently applicable to the Mesohellenic slab alone, others overlapping with basic problems inherent to using ophiolites as analogues for oceanic lithosphere.

Figure 10. Geochemical variation among ophiolites and ophiolitic fragments in north-central Greece.



Is the geochemical variation among the Pindos basin ophiolites a primary oceanic feature, or is it a construct of emplacement deformation? Do the ductile features within the slab describe the motions and mechanisms of drift and emplacement? Does the Mesohellenic trough fortuitously divide the Vourinos from the Pindos ophiolites, or does it follow an even more deep-seated structural plate tectonic divide? To what degree are the petrogenetic and structural processes demonstrated in these ophiolites unique, or do they describe processes common to all ophiolitic rocks?

Our field symposium hopes to present field data that may aid in resolution of these questions as well as to propose, through discussion, entirely new solutions to these puzzling ophiolites.

SITE ITINERARY AND GPS COORDINATES

		LOCALITY	LOCATION
Sept. 15 Koziakas Ophiolite	1	Steinman Trinity	39° 25' 30.96" N, 21° 35' 21.24" E
	2	Koziakas Fault Viewpoint	39° 32' 7.68" N, 21° 35' 8.82" E
	3	Sulphide Ores	39° 32' 21.54" N, 21° 35' 5.4" E
	4	Antilaximo Imbrication	39° 36' 39.6" N, 21° 36' 45" E
	5	Kaloneri Peridotite	39° 37' 54.72" N, 21° 35' 8.52" E
	6	Vitouma Convent Fault Breccia	39° 39' 10.14" N, 21° 34' 40.74" E
	7	Megali Kerasia Ophiocalcites	39° 45' 8.1" N, 21° 34' 19.56" E
Sept. 16 Pelagonian Margin	1	Fotino Ancient Rocks	39° 50' 30.9" N, 21° 47' 24.12" E
	2	Extensional Schist	39° 50' 41.94" N, 21° 47' 20.82" E
	3	Pebbly Mudstone	39° 51' 17.76" N, 21° 45' 0.24" E
	4	Deskati Schists	39° 57' 1.5" N, 21° 48' 27.96" E
	5	Vounassa Mountain	39° 56' 33.12" N, 21° 46' 0.42" E
	6	Tr- Red Carbonates	39° 54' 51.72" N, 21° 44' 34.02" E
	7	Tr-Metasediments	39° 55' 6.84" N, 21° 44' 15.96" E
Sept. 17 Vourinos Ophiolite	1	Doumaraki Peridotite	40° 7' 21.6" N, 21° 44' 30.48" E
	2	Aetoraches Mine	40° 6' 20.5" N, 21° 43' 3.66" E
	3	Petrologic Moho	40° 5' 56.37" N, 21° 42' 4.91" E
	4	Laterites	40° 5' 2.28" N, 21° 41' 17.54" E
	5	Pilori Roadcut	40° 5' 43.89" N, 21° 38' 0" E
	6	Sheeted Dikes	40° 7' 31.44" N, 21° 31' 59.7" E
	7	Oceanic Sediments	40° 7' 23.64" N, 21° 31' 41.2" E
Sept. 18 Vourinos Ophiolite	1	Xerolivado Mine	40° 2' 35.09" N, 21° 45' 17.1" E
	2	Sole Roadcut	39° 59' 55.72" N, 21° 47' 17.16" E
	3	Aliakmon Section	39° 59' 59.74" N, 21° 48' 11.64" E
Sept. 19 Pindos Ophiolite	1	Mesohellenic boundary	39° 59' 45.72" N, 21° 19' 13.8" E
	2	Abdela Mélange	40° 1' 0.06" N, 21° 13' 6.66" E
	3	Liagouna Sole	39° 58' 57.91" N, 21° 10' 35.45" E
	4	Valia Kalda - Stavros	39° 59' 46.42" N, 21° 7' 58.77" E
	5	Mt Dramala - Spanou Spring	39° 56' 29.31" N, 21° 9' 48.96" E
Sept. 20 Vourinos Ophiolite	1	Asprokambos Magma Chamber	40° 9' 16.42" N, 21° 30' 29.4" E
	2	Lithospheric Panorama	40° 12' 26.04" N, 21° 35' 12.48" E
	3	Paleocastro road	40° 12' 7.72" N, 21° 36' 25.84" E
	4	Mesiano Nero	40° 12' 2.43" N, 21° 38' 49.06" E
	5	Siatista Trekker's Shelter	40° 11' 55.64" N, 21° 39' 38.81" E

Day 1 -THE KOZIAKAS OPHIOLITE

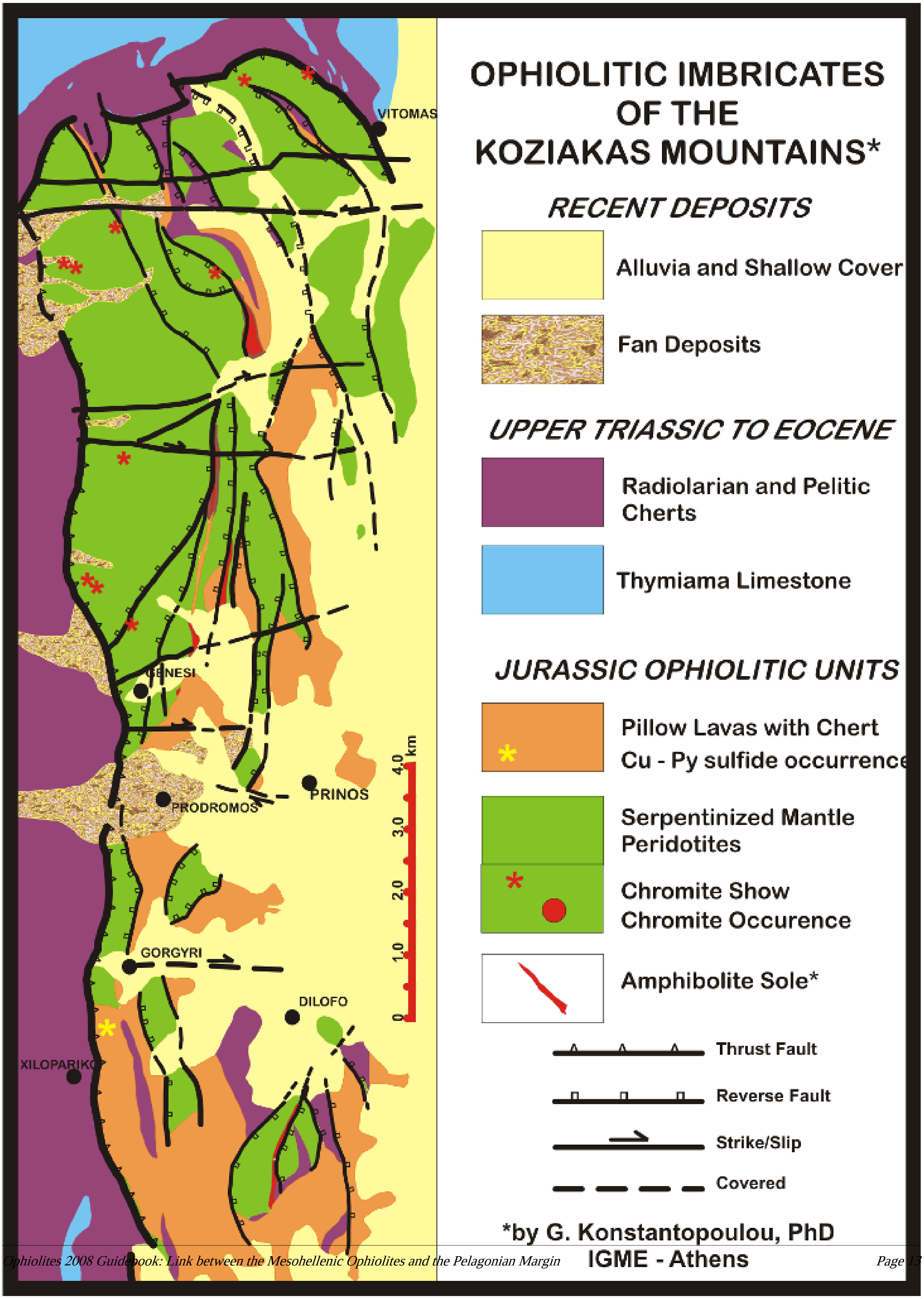
The Koziakas mountain range is a composite stack of nappes which occur in the following order, bottom to top:

- Cretaceous limestone and flysch unit
- Triassic-Jurassic limestone-chert association
- Sub-ophiolitic Mélange unit
- Metamorphic sole unit
- Mantle tectonite unit
- Lava unit

The latter two units are collectively referred to as the Koziakas ophiolite, although the sequence is far from complete, following the classical Penrose conference definition. Magma-chamber rocks are virtually absent and the same holds true for a well-developed sheeted-dyke complex. In detail, the picture is much more intricate.

- The sub-ophiolitic Mélange unit is a chaotic mix of lithologies, mainly peridotites, lavas, cherts (i.e. typical Steinmann's Trinity) and limestones, the clasts of which are set in a mudstone-siltstone matrix.
- The Metamorphic sole unit is primarily composed of amphibolites with sparse metapelite intercalations.
- The Mantle tectonite unit comprises both spinel-harzburgite and spinel-lherzolite with locally important plagioclase lherzolite. Dunite bodies occur in places. These rock types are cut by gabbroic-doleritic dykes but also small trondhjemitic bodies.
- The Lava unit encompasses both massive and pillow lavas, usually in that order towards the top, occasionally capped by manganiferous cherts. There is ample evidence for hydrothermal circulation within the lava pile and sites of fluid discharge with deposition of sulphide ore are locally observed.

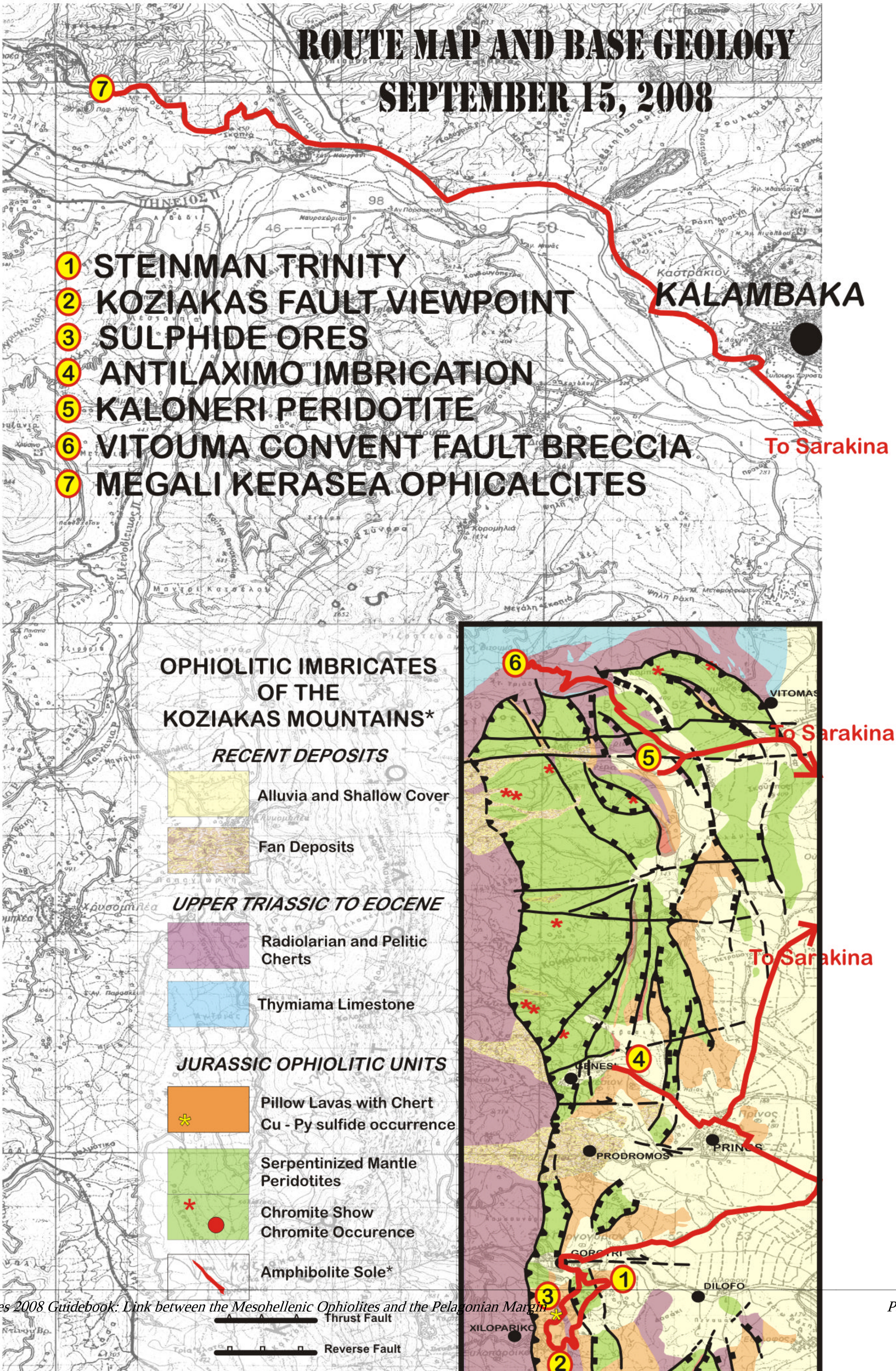
The only radiometric ages available for the Koziakas massif are those of the amphibolites from the metamorphic sole (161±1 and 174±3 Ma; K-Ar on hornblende) that constrain emplacement by Middle Jurassic. The igneous age of the ophiolitic and sub-ophiolitic rocks remains as yet indeterminate.


OPHIOLITIC IMBRICATES OF THE KOZIAKAS MOUNTAINS*
RECENT DEPOSITS
Alluvia and Shallow Cover
Fan Deposits
UPPER TRIASSIC TO EOCENE
Radiolarian and Pelitic Cherts
Thymiama Limestone
JURASSIC OPHIOLITIC UNITS
Pillow Lavas with Chert
Cu - Py sulfide occurrence
Serpentinized Mantle Peridotites
Chromite Show
Chromite Occurence
Amphibolite Sole*
Thrust Fault
Reverse Fault
Strike/Slip
Covered
*by G. Konstantopoulou, PhD
IGME - Athens
VITOMAS
GENESI
PRINOS
PRODROMOS
GORGYRI
DILOFO
XILOPARIKO
0
1.0
2.0
3.0
4.0
km

Calculations for the sole amphibolites yield peak P-T conditions of 7.1±0.9 Kb at 652±38°C. Such pressures are equivalent to a 24 Km-thick oceanic crust. It is therefore suggested that obduction occurred along a high-T subduction zone, similarly to the Oman ophiolite case. The heat that drove metamorphism was supplied by the overriding ophiolitic mantle peridotites.

Mantle peridotites yielded temperatures of two-pyroxene equilibration of 980±70°C for a nominal pressure of 5 Kb. Olivine-spinel equilibration temperatures average at 700±50°C. Mantle oxygen fugacity conditions showed a significant difference between lherzolite and harzburgite: lherzolites are considerably more reduced than harzburgites (logfO2 [re: QFM]: 0.20±0.30 vs. 1.00±0.30 respectively), suggesting lherzolite melting at deeper, nearly asthenospheric conditions, and harzburgite melting in shallower, oxidizing conditions, such as present in supra-subduction zone setting. Oxygen fugacity conditions for the plagioclase lherzolites are 1.00±0.50 log units above the QFM buffer, implying formation by melt impregnation at crustal levels (at the Moho). Partial melting estimated by spinel chemistry are about 11% for the lherzolites (13% for the plagioclase lherzolites) and 17% for the harzburgites.

Lava geochemistries represent diverse magmas and geotectonic settings. Lava blocks within the Mélange are typical within-plate (i.e. OIB to E-MORB) affinity, with melting predominantly within the stability field of spinel, and less commonly, of garnet. Basalts and basaltic andesites dominate, but trachytes have also been found. These lavas resemble the Permo-Triassic, rift-related, plume activity that preceded Neotethyan ophiolite generation in the region, especially the Mamonia complex of SW Cyprus. Lavas in the ophiolitic imbricates fall into two groups: back-arc basin basalts and boninites. The latter occur exclusively as dikes cross-cutting other lithologies,signifying the final supra-subduction zone stage before oceanic lithosphere obduction.


ROUTE MAP AND BASE GEOLOGY
SEPTEMBER 15, 2008
1 STEINMAN TRINITY
2 KOZIAKAS FAULT VIEWPOINT
3 SULPHIDE ORES
4 ANTILAXIMO IMBRICATION
5 KALONERI PERIDOTITE
6 VITOUMA CONVENT FAULT BRECCIA
7 MEGALI KERASEA OPHICALCITES
KALAMBAKA
To Sarakina
OPHIOLITIC IMBRICATES OF THE KOZIAKAS MOUNTAINS*
RECENT DEPOSITS
Alluvia and Shallow Cover
Fan Deposits
UPPER TRIASSIC TO EOCENE
Radiolarian and Pelitic Cherts
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Amphibolite Sole*
Thrust Fault
Reverse Fault
VITOMAS
GENESI
PRODROMOS
PRINOS
GORGORI
DILOFO
XILOPARIKO

Stop 1: Koziakas Ophiolite - Steinmann Trinity

WHAT IS AN OPHIOLITE?

Let us start with an exceptional roadcut that exposes an entire Steinmann’s Trinity: serpentine, lavas, and cherts cropping out within a twenty-meter distance. It is not that easy to make out the imbricated contacts. This stop is a reminder that an ophiolite is not a single rock type, but an assemblage of rock types derived from ocean lithosphere.

The roadcut section is representative of the tectonically-thinned imbricated Koziakas ophiolite. Where are the cumulates, the gabbros, the sheeted dikes? Question to consider: have these units been tectonically removed, or were they never present at all?

Stop 2: Koziakas Ophiolite - Fault Viewpoint

UP AGAINST THE WALL

From the viewpoint overlooking Xilopariko Village, towards the NW, the high ridge of the Koziakas Range consists of Jurassic limestone including imbricates of Triassic red limestones with chert layers: the steep relief gives the impression of a wall bordering this southern extension of the MHT. Further down slope, resistant limestone imbricates protrude from a matrix of Jurassic schistose dark clays, mudstones, and chert. The faulting of the ophiolite imbricate group against the clays and limestones is visible just beyond and below the village. An imbricate of highly sheared ophiolitic pillow lavas crops out across the road from the viewpoint.

Consider: How much imbrication affected the ophiolite while faulted against the Koziakas limestones, and how much before?

Stop 3: Koziakas Ophiolite - Sulphide Ores

HYDROTHERMAL ZONES

Sulphide mineralization here is typical of that found in ophiolitic lavas worldwide, and includes disseminated pyrite and pyrite-arsenopyrite-chalcopyrite (rare) concentrated in narrow channels, including clots of massive ore, within pillow lavas. Hyaloclastic and glauconitic sediments occur between sheared pillows. The imbricated outcrop may contain several hydrothermal channels, or tectonic repetitions of one mineralization pipe. These pipes may give a crude directionality within the sheared pillows.

Consider: No magmatic chamber cumulates or gabbros are exposed locally, and are rare in Koziakas. Does the existence of these hydrothermal pipes imply the existence of a cumulate section that hasn't been preserved?

Stop 4: Koziakas Ophiolite - Antilaximo Imbrication

WHICH WAY DID IT GO?

This roadcut exposes an imbricate of serpentinite that includes a rather significant fault zone on its western margin. This fault zone may be typical of those which accompanied imbricate emplacement onto the Koziakas limestone, but may also record movements coincidental with older nappe formation within the ophiolite such as undergone in the Othris ophiolite, and possibly original deformation accompanying brittle-field slab emplacement. The serpentinite is folded to the west of the outcrop. Pillow lavas are again exposed about 50 meters further.

Consider: The relative dating of structures are important to understanding all the deformation undergone by the Pindos Basin ophiolites.

Stop 5: Koziakas Ophiolite - Kaloneri Peridotite

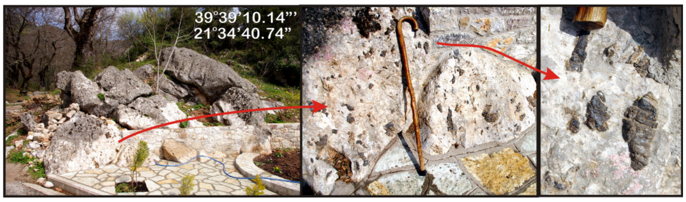
OLDER PERIDOTITE DEFORMATION

Imbrication within this exposure of harzburgite indicates an apparent eastern topping direction. The harzburgite contains a pervasive cataclastic fabric, and is the most accessible locality of its type. Elsewhere in Othris and the Pindos, areas of harzburgite and lherzolite in excess of several km area are cataclastites, and represent the final ductile motions of the slab. A fallen block at this locality (inset) displays folding, and even appears to be developing an axial planar foliation. Folding can be defined by analyses of foliations, but the folds themselves are rarely so well discerned in monochromatic peridotite.

Consider: While tempting, we must consider all the rotations undergone by the imbricates before we ascribe a ductile kinematic sense to the Koziakas ophiolite.

Stop 6: Koziakas Ophiolite - Vitouma Convent

OPHIOLITES ALONG FOR THE RIDE



This garden wall at the Vitouma Convent (left photo) is built upon a fault imbricate of Koziakas Limestone and Jurassic sediments against the ophiolite. This fault block is bordered to the west by well-broken chert fragments. Fault breccia (right photo) incorporates predominately ophiolitic clasts within a carbonate matrix. The clasts define a strong orientation (middle photo) that appears parallel to "mega-slickensides" in the upper part of the outcrop. Roadcuts below the convent include ophiolitic lavas and serpentinite fragments as well a a rare imbricate of upper level cumulate gabbro.

Consider: The youngest formations involved in this fault system appear to be Jurassic. MHT tectonism begins during the early Eocene. What is the date of this fault system, and what went on between the Jurassic and the Eocene?

Stop 7: Pindos Ophiolite - Megalo Kerasea Ophicalcites

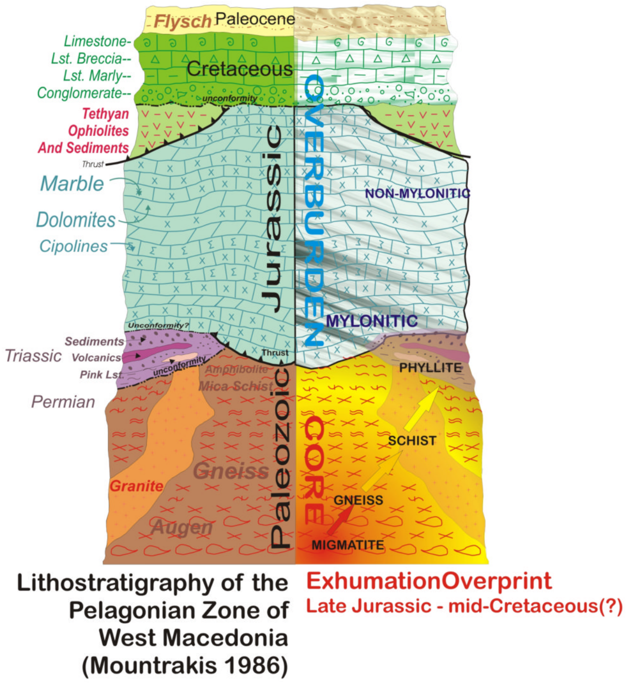
This tectonic melange crops out along strike of the Pelagonian - Ophiolite margin exposed along the Aliakmon River 20 km to the east, and the magnetically defined continuation of the Pelagonian-ophiolite margin beneath the Mesohellenic sediments. Imbricates are essentially serpentinite with highly deformed lavas and included pods of carbonate (white, age unknown). The kinematic sense varies from Koziakas, and the outcrop can be considered as a "hinge" between Koziakas and the Pindos ophiolites.

Consider: If this is a continuation of Vourinos - Pelagonian margin, could this represent the remnant of an ancient transform?

Day 2 -THE PELAGONIAN MARGIN

The western margin of the Pelagonian ribbon continent is encountered between the occluding Mesohellenic sediments of Meteora and the Vourinos ophiolite. A traverse across this margin exhibits the essential character of this continental terrane as well as the rocks affected by ophiolitic emplacement.

The Pelagonian itself is essentially a Hercynian continental block, once part of Pangaea, rifted apart with formation of the Tethys (~250 mya). It thus is host to the rift-drift system that, with time, gave birth to the Pindos Basin ophiolites (~170 mya). It is also the "footwall" continent to emplacement of the ophiolitic slab (~168mya). The Pelagonian thus shows evidence for the birth and destruction of the Pindos Basin. Its exhumation apparently followed emplacement of the ophiolitic slab (late Jurassic-mid-Cretaceous?), and only recently have exhumation models been applied to its interpretation as a core complex.



Classic lithostratigraphy and exhumation overprint of the west Pelagonian margin.

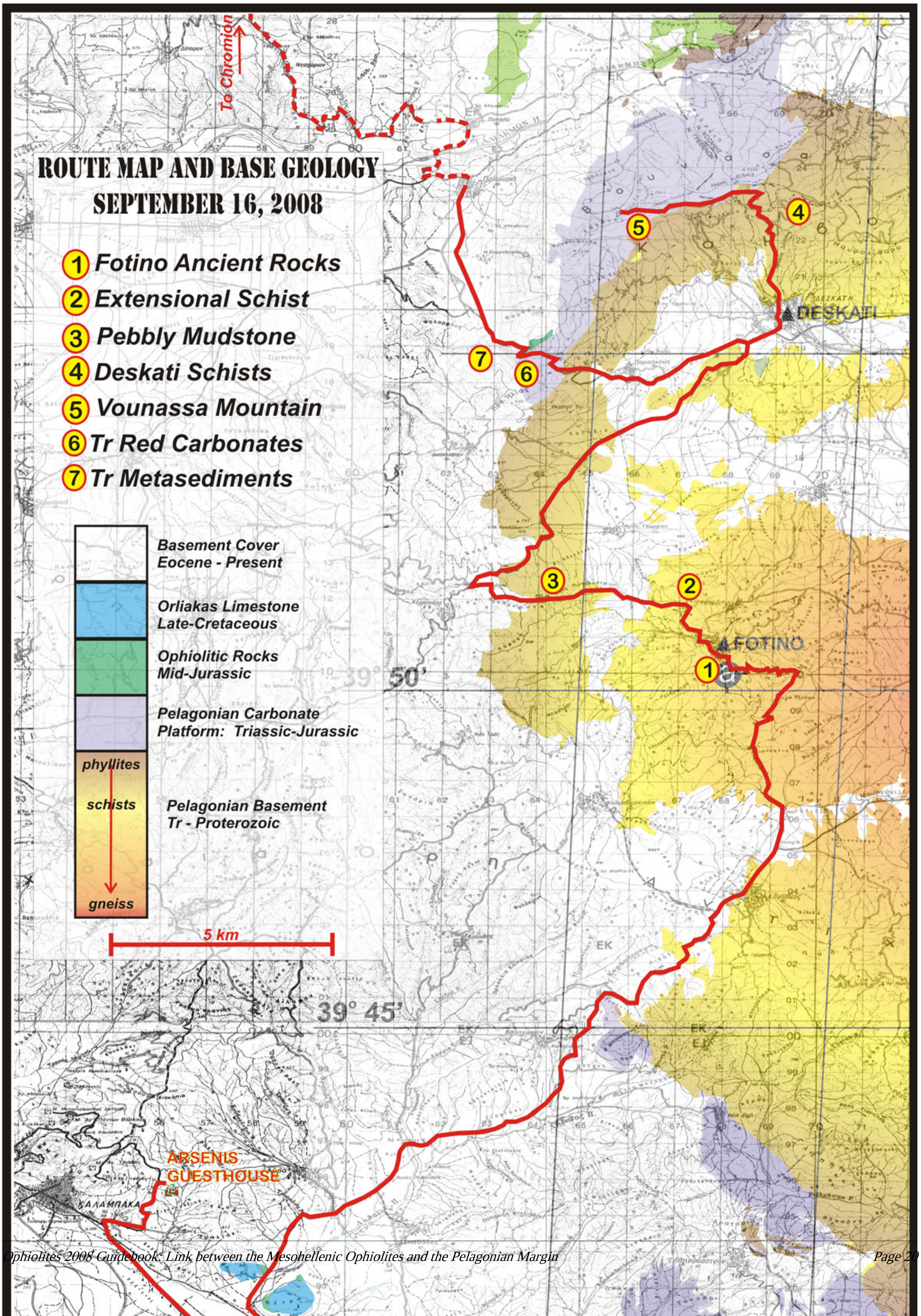
The nature of the Pelagonian continent is one of numerous late Precambrian to early Paleozoic terrane fragments welded in upper Paleozoic time to form part of Pangea. So far, the 700 my zircon age found in altered granodiorite at Fotino represents the oldest rocks of

Greece. These irregular terrane fragments, ranging in size from tens of m^2 to a few km^2, show a strong planar fabric presumably imprinted during Hercyian collision. Nearly all rocks in these areas are derived from intense deformation of the granodiorites. Old sedimentation on Hercynian-Pelagonian lands gave rise to quartzites and meta-greywackes, also highly metamorphosed. Some rocks of probable ocean crust affinity have been interpreted as Paleozoic ophiolites.

The rifting of Pangea split this older terrane: dikes of altered lava (now amphibolites) intrude schistose hosts; irregular bodies of highly deformed meta-basalts and acidic intrusions are rifting related. Stepping towards the rifting margin, towards Vourinos, more detail emerges with lessening metamorphism: sedimentation includes Triassic rocks, at least in part over a sedimentary unconformity with the Permian continent, compatible with origin in a rapidly deepening ocean basin: radiolarian cherts, red (ammonitico rosso) limestones, tuffaceous sediments, greywackes, and pebbly mudstones. These are, in turn, interpreted as overlain by a Triassic-Jurassic carbonate platform. The early Triassic sediments lack precise dating, and could include members synchronous to the platform carbonates.

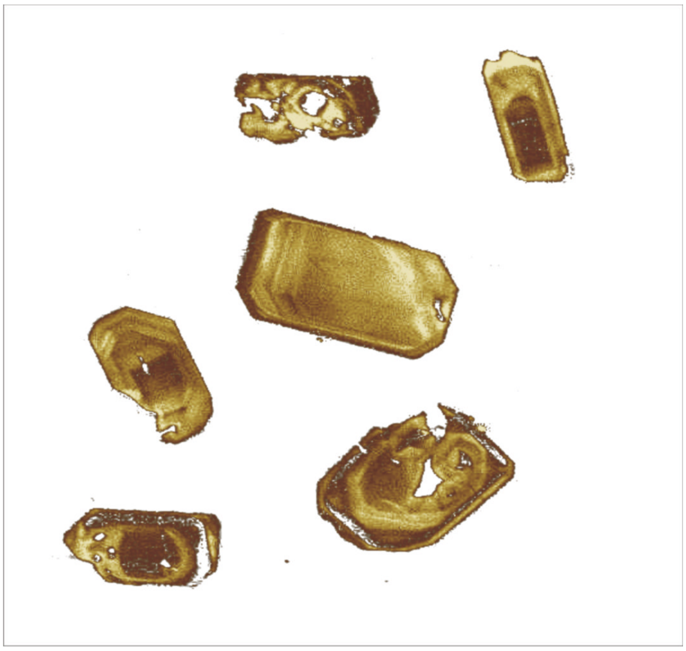
Initial exhumation of this margin shortly follows the emplacement of the Pindos Basin ophiolites. Close to the Vourinos margin, a deformation “footprint” from this slab may be observed. Elsewhere, strong exhumation phenomena either occludes this, or today's exposures represent greater “core complex” depths.

Exhumation structures are easily recognized in west Pelagonian terrane: they show great extensional movement synchronous to schistose metamorphism, and apparent lower-temperature gravity slippage in areas of higher paleo-topography. Such structures are lacking from Vourinos itself. Exhumation metamorphism and structure recedes near the Vourinos contact: the implication is that this represents the original Pelagonian rift margin, as well as the western exhumation limit.


ROUTE MAP AND BASE GEOLOGY
SEPTEMBER 16, 2008
1 Fotino Ancient Rocks
2 Extensional Schist
3 Pebbly Mudstone
4 Deskati Schists
5 Vounassa Mountain
6 Tr Red Carbonates
7 Tr Metasediments
Basement Cover
Eocene - Present
Orliakas Limestone
Late-Cretaceous
Ophiolitic Rocks
Mid-Jurassic
Pelagonian Carbonate
Platform: Triassic-Jurassic
phyllites
schists
gneiss
Pelagonian Basement
Tr - Proterozoic
5 km
To Chromion
DESKATI
FOTINO
39° 50'
39° 45'
ARSENIS
GUESTHOUSE
ΚΑΛΑΜΠΑΚΑ

Stop 1: Pelagonian Margin - Fotino Ancient Rocks

THE OLDEST ROCKS IN GREECE



Zircons from gneissic granites

Zircons from gneissic granites cropping out below the village of Fotino date to 700my, making these rocks the oldest known in Greece. The zircons and Nd-isotope characteristics suggest a Gondwanan origin, closely resembling the East Avalonian terrane. These muscovite granites served as the basement into which the later Permo-Carboniferous Pelagonian granites were intruded. Lower intercept zircon U-Pb ages of 177 - 178 my may indicate a disturbance due to ophiolite obduction onto the western Pelagonian margin.

Consider: How do we distinguish ophiolitic slab imprint from exhumation structures?

Stop 2: Pelagonian Margin - Extensional Schist

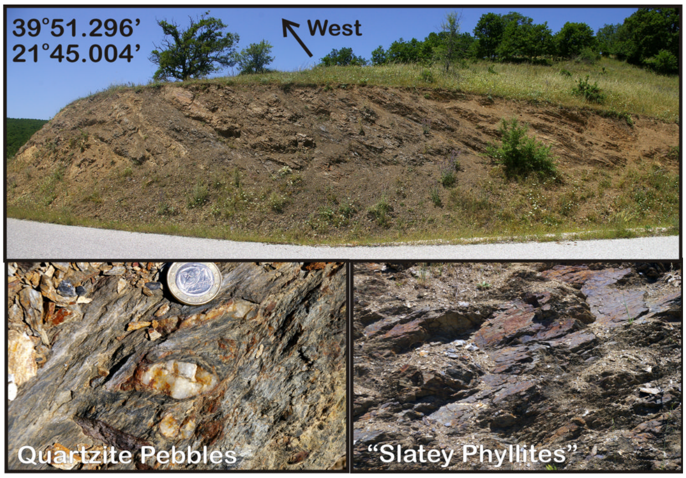
EXTENSIONAL DEFORMATION

Past Fotino driving N and NE, rocks cropping out along roadcuts exhibit strong extensional fabrics and a concurrent metamorphic gradation from near gneissic (Fotino) to amphibolite schists, phyllites and "slatey phyllites." The section appears to be transitional and intact, with no major Cenzoic displacement. The fieldtrip stop is within schist that includes metasediments as well as probable meta-intrusives (meta-diabasic amphibolites). White lenses consist of extremely altered felsic-quartz (altered acidic intrusives?), and deformed quartzite dikes and veins are common. Topping directions seem pervasively to the SW, and these presumably are related to exhumation of the Pelagonian.

Consider: Did a large ophiolitic nappe pass above these rocks, and what is the dating of this nappe movement relative to exhumation?

Stop 3: Pelagonian Margin - Pebbly Mudstone

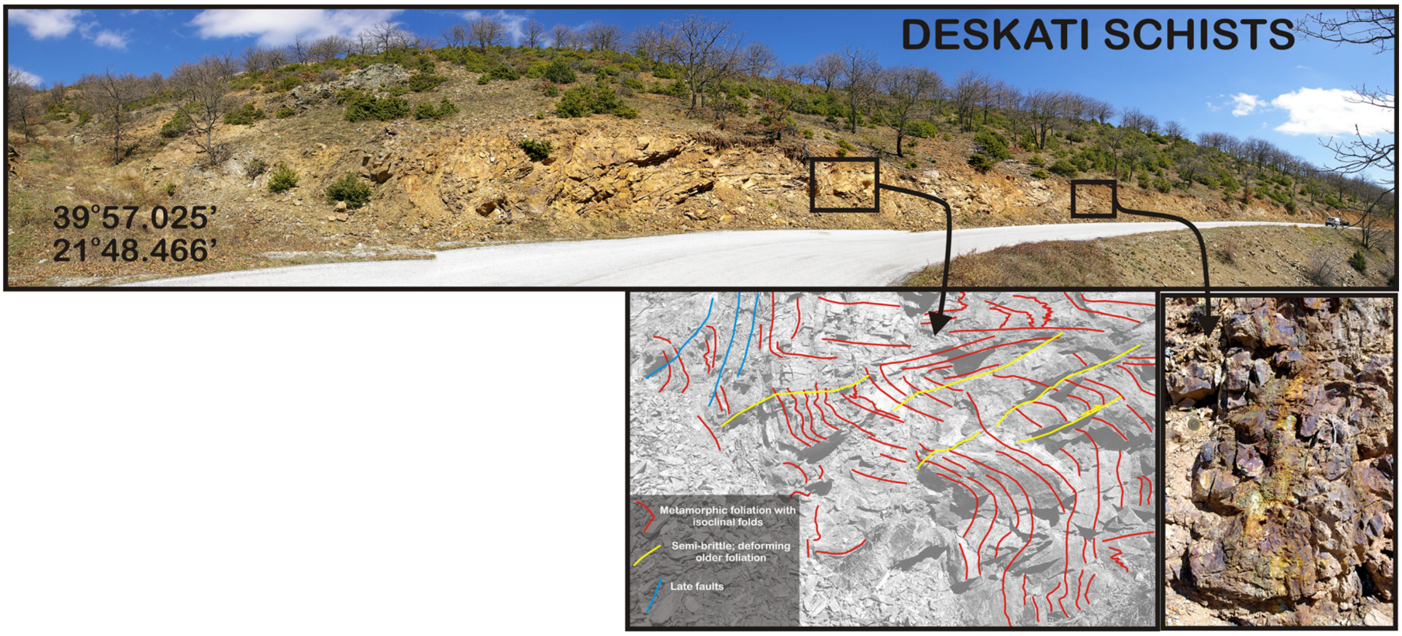
PEBBLY MUDSTONE



The western exposures of the Pelagonian basement formations are described as lower to mid-Triassic "semi-metamorphic" sediments including micaceous and calcareous shales (present site), red limestones, cipolines and micaceous quartzites. Dating of this entire margin is based on conodonts separated from the red limestones of upper Skythian-lower Anision ages. The present stop consists of phyllitic pebbly mudstones: their relative age compared to the red limestones is unclear. Pebbles are quartzite and schist at this locality, and the matrix consists of highly altered micas, clays (after feldspars) and rare biotite with strong metamorphic foliation and 0.5 cm scale layers. Veins of hydrothermal textured quartz with altered feldspars and pyrite grains strengthen the rock locally (silicified) and are also highly deformed. The kinematics at this site are more complicated than at previous stops, and seem to show both SE and NE topping directions.

Consider: A comparison between these pebbly mudstones (Tr?) with those beneath the sole of the Vourinos ophiolite (Jr?)

Stop 4: Pelagonian Margin - Vounassa Deformation



The schists of this site are considered neo-Paleozoic, and include multiply deformed metasediments and metabasic intrusives. The former includes cherts and greywackes; the latter at this site includes small pods of sulphide deposition in metabasite. Mica schists dominate, with actinolite schists after mafic protoliths; epidote and garnets occur among secondary minerals. Siliceous veins and dikes intrude all lithologies. The original stratigraphic lithologic distribution of ths assemblage is obscured by penetrative deformation imposing strong metamorphic foliation and microfolding. Deformed quartz veins best designate kinematics of late ductile deformation.

Metamorphic foliations are subsequently deformed into meter--scale folds apparently related to shear folds along shallow ramp systems. Most ramps in this outcrop top to the NE, and include several generations of brittle deformation. The latest deformation appears to be a set of minor but penetrative steep, narrow reverse faults.

Stop 5: Pelagonian Margin - Vounassa Mountain

VOUNASSA PEAK

Along the top of Vounassa Mountain, an unconformity marks the Permo-Triassic contact between the neo-Paleozoic Deskati schists (to the south and east) and Triassic-Jurassic Pelagonian platform carbonates. The latest ice age left glacial scars and high relief on the carbonates at an altitude within the Hellenic Alpine vegetation zone. The viewpoint spans from Mount Vourinos across the Mesohellenic Trough and to the Pindos. A foreground cover displays a "wormy" geomorphology over carbonate talus and Pleistocene deposits that may be due to karstic weathering (?).

Consider: The distances between Vourinos and the Pindos ophiolites, and whether these relate to their paleogeographic separation.

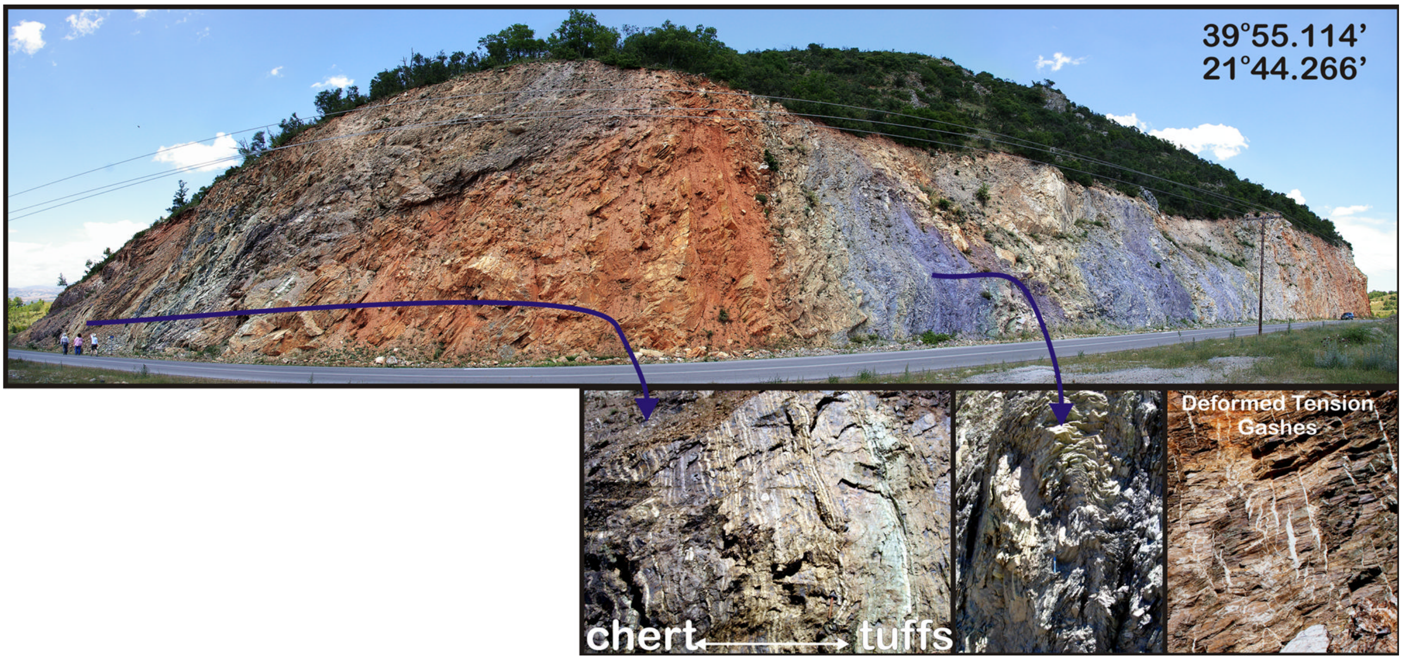
Stop 6: Pelagonian Margin - Triassic Red Carbonates

TR RED CARBONATES

The Triassic metasediment unit of the Pelagonian margin is dated by comparison to "Ammonitico Rosso" carbonates similar in appearance to these. Referenced as bearing Skythian-Anisian conodonts (in neighboring IGME Ayiofyllo sheet), it is not known where the original sampling locality is providing this date. Compared to nearby neo-Paleozoic schists, these sediments lack strong deformation, and appear to preserve in situ sedimentary brecciation and in-fill by clays. They appear to be the oldest sediments deposited above the Paleozoic schists, and represent an oceanic, moderately deep-water environment.

Consider: Are these part of early Tethyan Rifting?

Stop 7: Pelagonian Margin - Triassic Metasediments



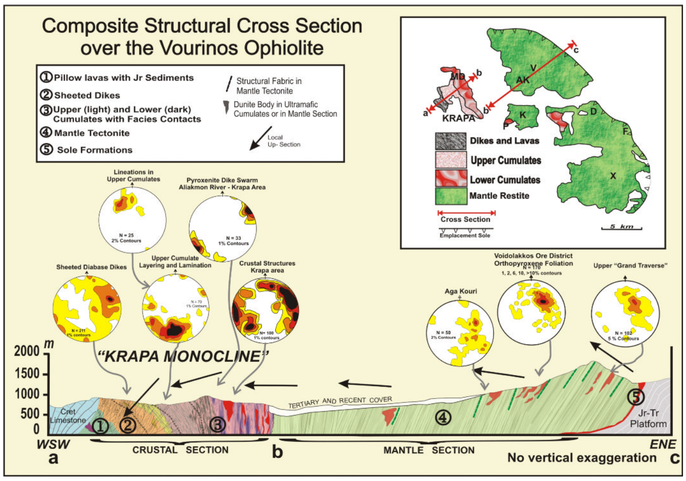
Called this due to their varied colors, the Triassic metasediments consist of radiolarian cherts (left of photo), tuffaceous sediments, quartzites, shales, mica schists, micaceous and siliceous carbonates. Folding is pervasive on the scale of the outcrop down to handspecimen size. The conventional interpretation is that these metasediments were deposited onto the red carbonates of the last stop, that is, in the same age range as Tethyan rifting. Both these and the neo-Paleozoic rocks are overlapped by the Pelagonian Tr-Jr platform carbonates.

Consider: Does the deformation mark the nearby lateral transport of the Vourinos ophiolite?

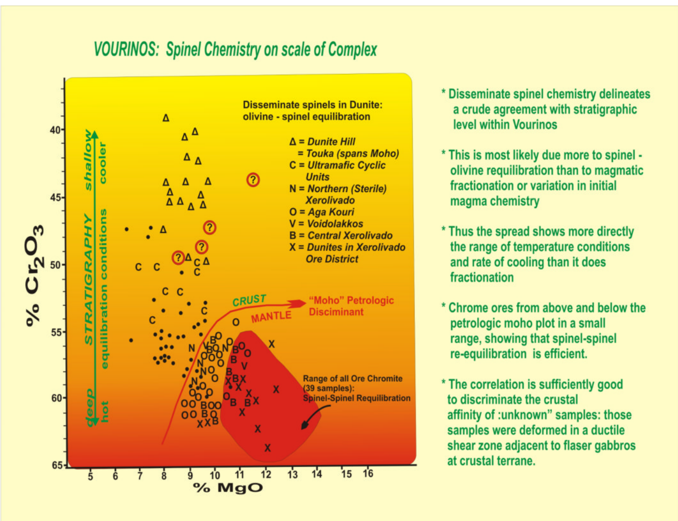
Day 3 -THE VOURINOS OPHIOLITE

The Vourinos ophiolite is an essentially unbroken remnant of oceanic lithosphere, intact from amphibolite sole at its base to deep water sediments at its top: this section is about 12 km thick, and oriented approximately vertically today, with uppermost rocks to the west. Vourinos highly influenced the Penrose Conference definition of an ophiolite, and its bias still dominates "idealized" models of ocean lithosphere. Our field symposium intends to display both the classic ophiolitic section and demonstrate its bias on interpretation of oceanic section.

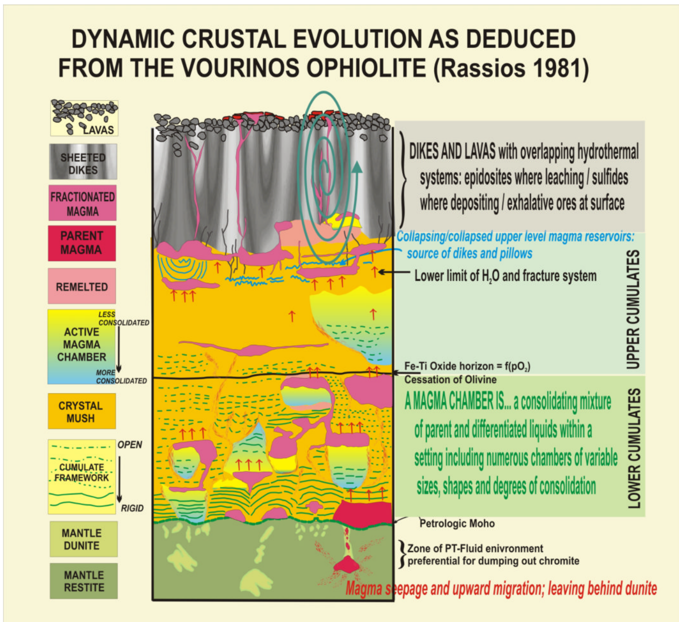
The section traversed today begins in unserpentinized harzburgite restite that retains a high-temperature mantle fabric: this fabric is seen as a weak shape-defined planar orientation of blocky-shaped orthopyroxene in a matrix of olivine grains of relatively large (~0.5 cm) grain size. Both minerals show an abundance of dislocation lamellae, kinking, and twinning, observable through a hand lens. In universal stage analyses, the planar fabric proves to be a strong intragranular deformation, referred to as a "diapiric" or simply as mantle fabric. The mineral orientation is presumed to form after partial melting by mantle flow or upwelling beneath a spreading center, and originates at temperatures of 1200ºC to 900ºC at 100 to 40 km. To unravel the "ophiolitic bias" from ocean lithospheric models based on these kinds of fabric one must question how this fabric survived transport from a depth of 100 km, susceptible to further ductile deformation down to temperatures ~700ºC, without any intervening deformation imprint or rotation. The presence of brittle ramp structures are pervasive to the complex, and even if each represents an extremely minor offset, collectively they are an effective mechanism for thinning and/or rotation of lithosphere.

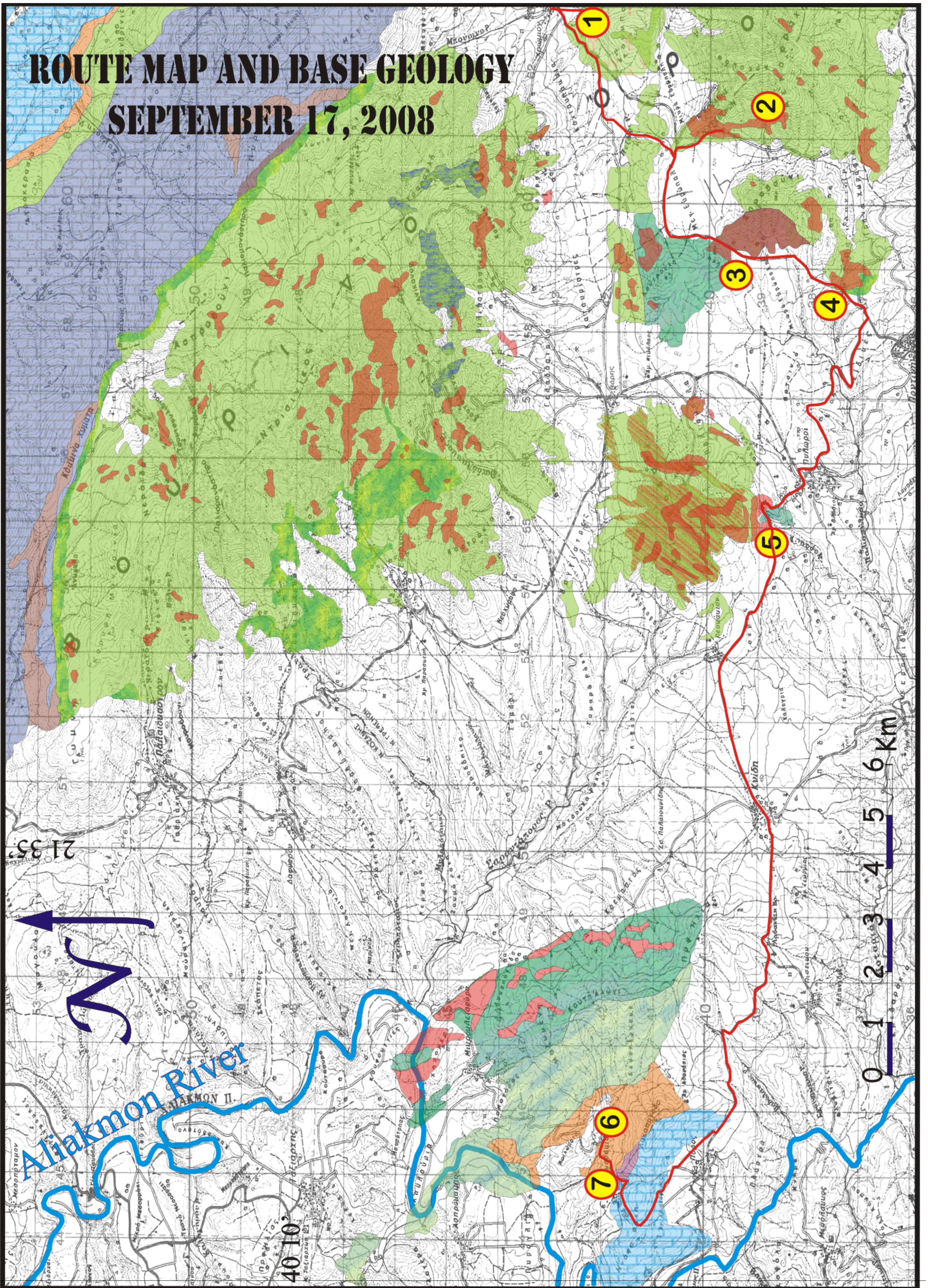


At relatively shallow sub-ridgecrest depths just below the petrologic moho (~1250ºC), high heat flow means that high-level mantle rocks will be among the earliest to cool below the solidus with drift away from the ridgecrest, thus freezing in ductile fabrics before significant spreading or additional ductile deformation occurs. At the Aetoraches locality, dunite hosting chrome deposits demonstrates near-pegmatitic fabric, with post-solidus crystal growth aligned to a planar imprinting ductile fabric: this fabric parallels fold planes on all scales, with original “S0” mantle fabrics highly attenuated and rotating into these fabrics. This secondary fabric is observed in dunites in the nearby cumulate dunite above the petrologic moho, but the higher-temperature tectonite mantle fabric is truncated at the moho. The petrologic moho at Vourinos was the first to be recognized, and is a sharp intrusive contact with irregular, m-scale, topography.



Lowermost cumulates and cumulates at the base of cyclic units are dunite, which then grade to wehrlite, pyroxenite and gabbronorite or troctolite. Adcumulate rocks (clinopyroxenites) examined in universal stage microscope show strong intragranular fabrics aligned with the later ductile overprint. The array of cyclic units and ultramafics document low-level magma chambers on the scale of hundreds of m^3 to km^3 volumes with possible up-welling structures. Further up-section, mafic cumulates tend to larger more continuous magma cells with synformal (slumping?) in-folding perpendicular to magmatic fabric. Within these structures, initial diabasic dikes intrude, increasing in proportions to form a 0.5 – 1.5 km thick sheeted dike complex (chiefly IAT with secondary boninite compositions). These sections cross low-amphibolite to greenschist facies metamorphism. Flows with zeolite facies and rare pillow lava occurrences overlie the section, but are truncated beneath an oceanic (upper Jurassic calpionellid limestone-radiolarian chert) unconformity. Hydrothermal systems cross these metamorphic facies, and in uppermost sections jaspers and metalliferous sediments have been identified. Both lavas and oceanic sediments are deeply eroded beneath the upper Cretaceous unconformity, overlain by rudistid-bearing reefy to nearly flysch-like limestone. Structures within the oceanic sediments not continuous into the Cretaceous are interpreted as probable emplacement deformation.





1 Doumaraki Peridotite

5 Pilori Roadcut

Stop 1: Vourinos Ophiolite - Doumaraki Peridotite

THE VOURINOS MANTLE SUITE

Top panorama: The mantle suite of Vourinos exposed at the Doumaraki Roadcut; Left inset: Outcrop appearance of ultra-fresh harzburgite.; Right inset: Petrographic view of harzburgite fabric.

The site is less than 200 m from the (locally covered) sole contact of Vourinos. Harzburgite with m-scale tabular dunite bodies at Doumaraki remain essentially unaltered with LOI < 1-1.5%. Blocky orthopyroxene grains (0.5 - 1 cm) and large irregular (>1 - 2 cm) dunite grains are representative of high TP (diapiric) fabric: dislocation lamellae in olivine can be discerned in hand-samples. Mineral foliation is best shown on weathered rock faces, and weak mineral lineation defined by Cr spinel. The outcrop is cut by brittle ramp structures topping approximately to the north. Consider: How did this unaltered mantle tectonite arrive at the surface with no serpentinization, and no apparent deformation imprint between high temperature ductile fabric and brittle field?

Stop 2: Vourinos Ophiolite - Aetoraches Mine

CHROME IN THE SHALLOW MANTLE

Top photo: Entrance to open-pit Aetoraches chrome mine. Lower photo: Large olivine crystals showing apparent sub-solidus growth into secondary tectonic foliation.

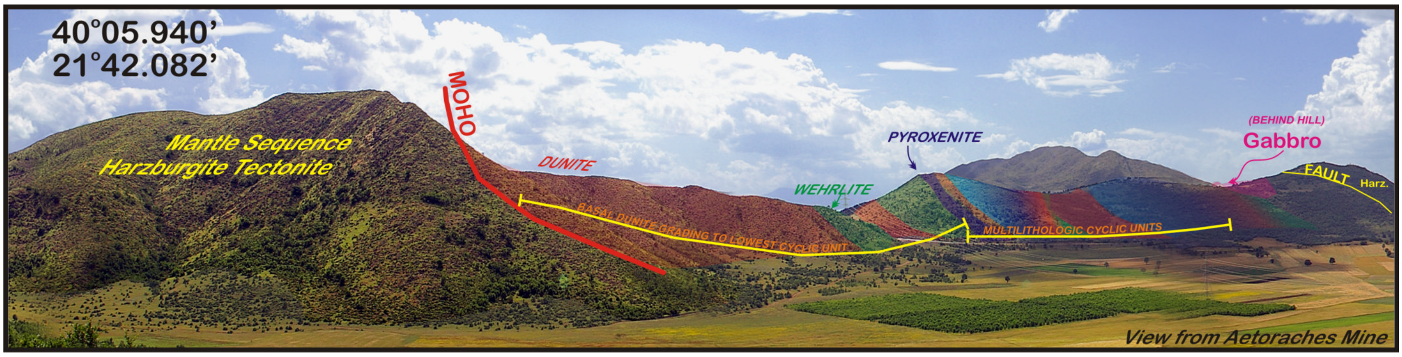
The Aetoraches Mine produced 200,000t of chrome ore before 1992, and was a primary exploration target: geologic estimations of reserves reach 2 mt. Ores crop out within a dunite body (>1 km length) located within harzburgite tectonite several hundred meters beneath the "petrologic moho." Mapping on 1:1000 scale emphasized high-temperature mantle fabric and delineated a synformal structure of host dunite, thus allowing modelling of ore continuation. Minor folding in ore layers exposed in the mine area conform with parasitic folds of the larger structure.

The area preserves sub-spreading center fabrics synchronous to ridgecrest magmatism, overprinted by a lower-temperature ductile fabric attributed to early emplacement-oriented strain. Chrome ores include layered types, folded and schlieren type. Subsolidus growth of olivine crystals across ore layers oriented with the late- stage ductile fabric creates a rare "flowering" or crescumulate appearance to some ores.

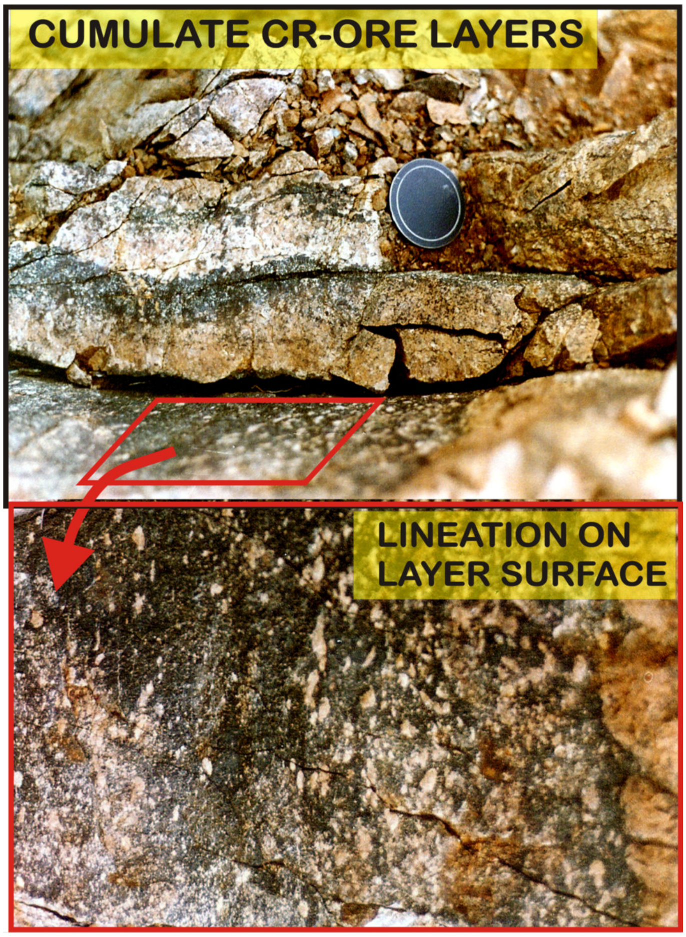
Consider: Does subsolidus olivine growth indicate the initiation of constrictive strain?

Stop 3: Vourinos Ophiolite - Petrologic Moho

THE “PETROLOGIC MOHO”



The “petrologic moho” contact with harzburgite tectonite to left of photo, and basal ultramafic cumulate complex to right.



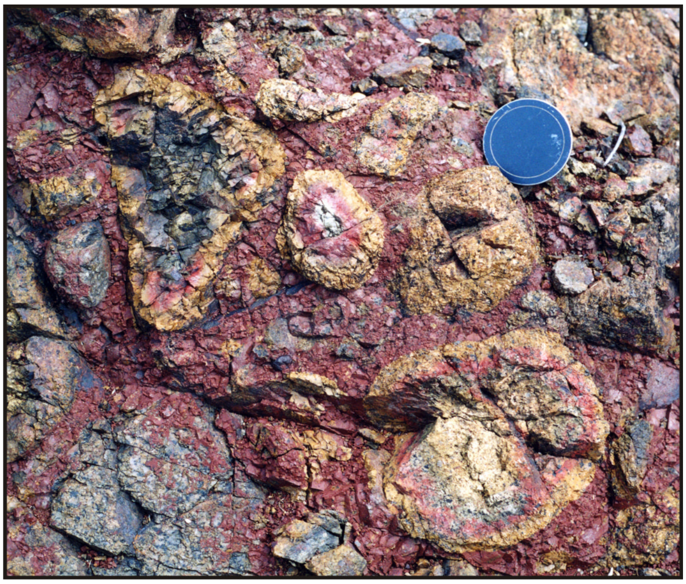
Cumulate chromite layer in basal dunite (top) and view on magmatic layering plane (bottom) demonstrating strong lineation.

The concept of a preserved contact between the oceanic mantle and crustal sequence, the petrologic moho, was first described at this locality of Vourinos. The contact between mantle harzburgite and a crustal section of cumulate dunite grading to adcumulate wehrlite, olivine clinopyroxenite, and ultimately gabbro and troctolite is sharp with m-scale intrusive topography. High-temperature intragranular deformation (diapiric fabric) is truncated at this contact, though lower temperature ductile fabric crosses the contact and is evident in folding of chrome ores, as well as strong lineations on cumulate chrome layers (photos). The basal dunite to "beheaded" top of the first cyclic cumulate unit is ~650m thick, overlain by multilithologic cyclic units (dunite to wehrlite to olivine clinopyroxenite to clinopyroxenite) ultimately evolving to a gabbro-troctolite sequence ~1.5 km above the "moho." Folds in Cr-ore occurrences within the basal dunite and lineations in adcumulate pyroxenites (optically defined) demonstrate a subsolidus fabric with 020 - 040 planar orientation.

Stop 4: Vourinos Ophiolite – Laterites

LATERITES ABOVE HARZBURGITE

Lateritic surface and redeposited laterite-rich sediments on serpentinized mantle harzburgite. The black layer is sedimentary serpentine.



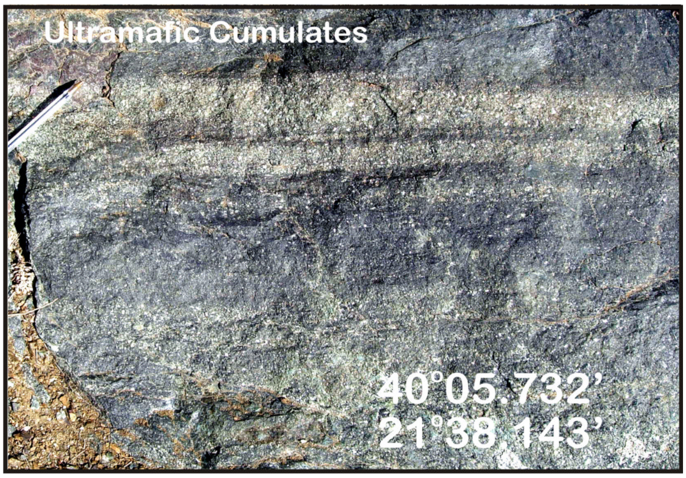
Cobbles of harzburgite in serpentine-jasperized laterite matrix.

Ni-laterites form from erosion of ultramafic rocks via leaching of mobile constituents, leaving behind resistant elements such as Ni, Fe and Si. These red layers, grading 0.5 - 1.5% NiO occur in situ above a Ni-rich weathering crust and eroded harzburgite. These mark the local base of Mesohellenic sedimentation. A gradation from constrictive structures upwards into Tertiary sediments and extensional jointing apparently transcends the compressive/extensional environment. A hydrothermal chimney crops out in harzburgite near the laterites, and has been suggested to be a late oceanic artifact. Serpentine cobbles with silicified rinds occur south of the laterites. Only peridotite cobbles occur in this conglomerate, though elsewhere other ophiolitic material is found; they do not include Pelagonian or Cretaceous material,found as clasts in the lowermost Tertiary. Possibly, the serpentine conglomerates belong to the oceanic period.

Consider: How much harzburgite (~0.2 - 0.4% NiO) must be eroded to produce a Ni-laterite (~1 - 2% NiO)?

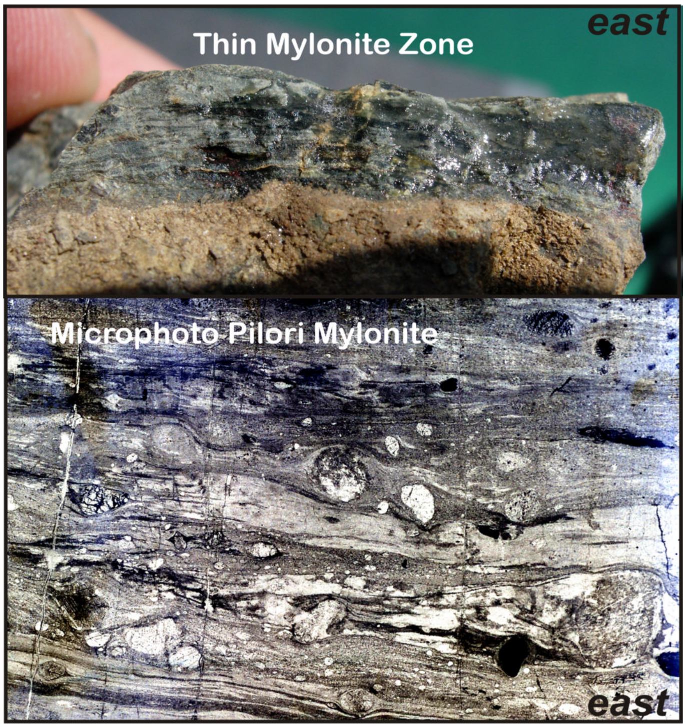
Stop 5: Vourinos Ophiolite - Pilori Roadcut

ULTRAMARIC CUMULATES



Magmatic layering in ultramafic cumulates (dunite-wehrlite-olivine clinopyroxenite).

Brittle structures imprinted on ultramafic section showing topping directions to the WSW.



Top photo in panel -- Outcrop appearance of thin mylonite zone in ultramafic cumulates. Lower photo in panel – appearance of mylonite zone in thin section. “Topping” direction of kinematic indicators is towards the ENE.

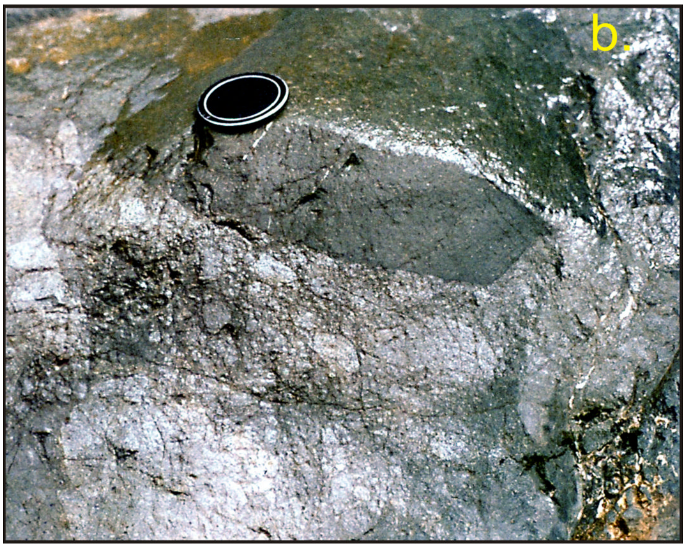
A fragment of crustal magmatic cumulates crops out at the base of Mt. Kissavos along the Knidi-Pilori road. The cumulates in this 800m long exposure show a petrologic continuity that demonstrates derivation from a single magmatic “cyclic unit” extending from dunite (now serpentine) at the base, through wehrlite and olivine clinopyroxenites, into two-pyroxene pyroxenites cut by minor gabbroic intrusions (now preserved only in the nearby streambed). This sequence defines a magmatic “upsection” to the west, in agreement with the directionality of the Krappa cumulates. Though less well preserved than Krappa, the cumulates here include several excellent examples of igneous lamination, layering, and igneous “sedimentary” structures. On the whole, the exposures are intensely sheared illustrating brittle deformation in a complex fault with a young EW strike-slip imprint (Cenozoic) topping to the SW in the same locality as an older tear fault. Thin mylonitic bands within the exposure date from older (ductile / ductile-brittle) episodes and show apparent kinematics towards the east.

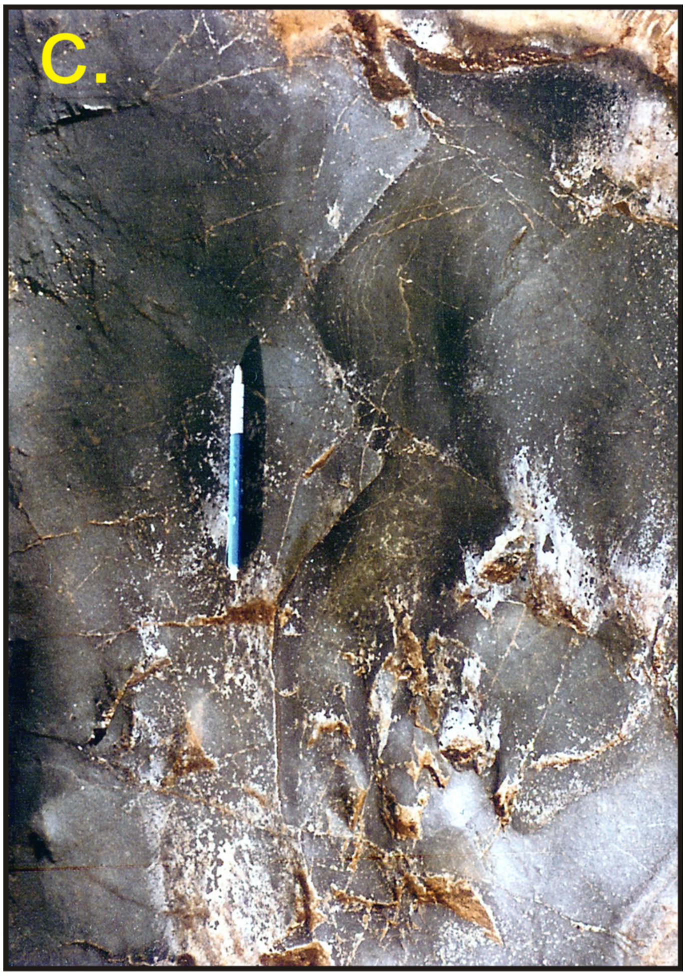
Consider: Slab emplacement tear systems provide convenient breaking points for all subsequent deformation.

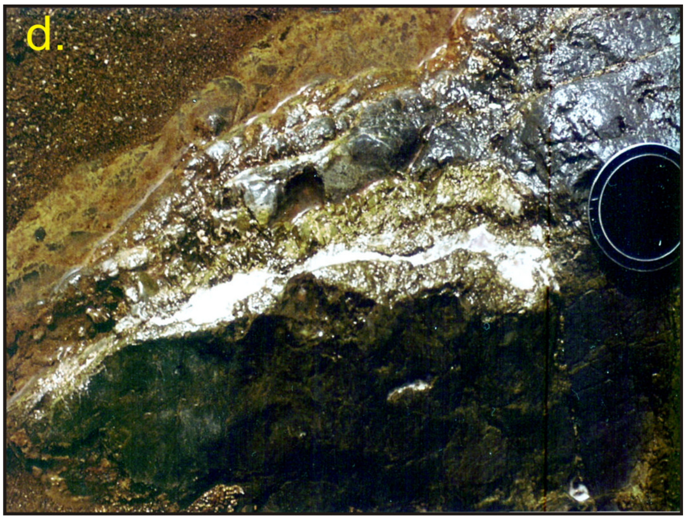
Stop 6: Vourinos Ophiolite - Sheeted Dikes

LANGADAKIA SHEETED DIKES

Sheeted dike complex at Langadakia. Photos explained in text.







The Vourinos Ophiolite includes a sheeted dike complex (a) of 1-2 km thickness in stratigraphic continuity within the crustal section. The general orientation of these dikes is NW striking with SW dip, perpendicular to the magmatic layering in contiguous cumulate rocks, that is, NW-striking, with steep (overturned) NE dips. At this stop, the water-polished dikes in the stream section show chilled margins and internal disruptions implying auto-brecciation (b), intrusion along pre-existing joint surfaces (c), epidosite deposition (d) and hydrothermal breccia pipes with minor sulphide precipitation.

Consider: The evidence for high-volatile conditions within the epidosite-bearing dikes as the "turn-around" point of hydrothermal circulation.

Stop 7: Vourinos Ophiolite - Oceanic Sediments

LANGADAKIA CALPIONELLID LIMESTONES

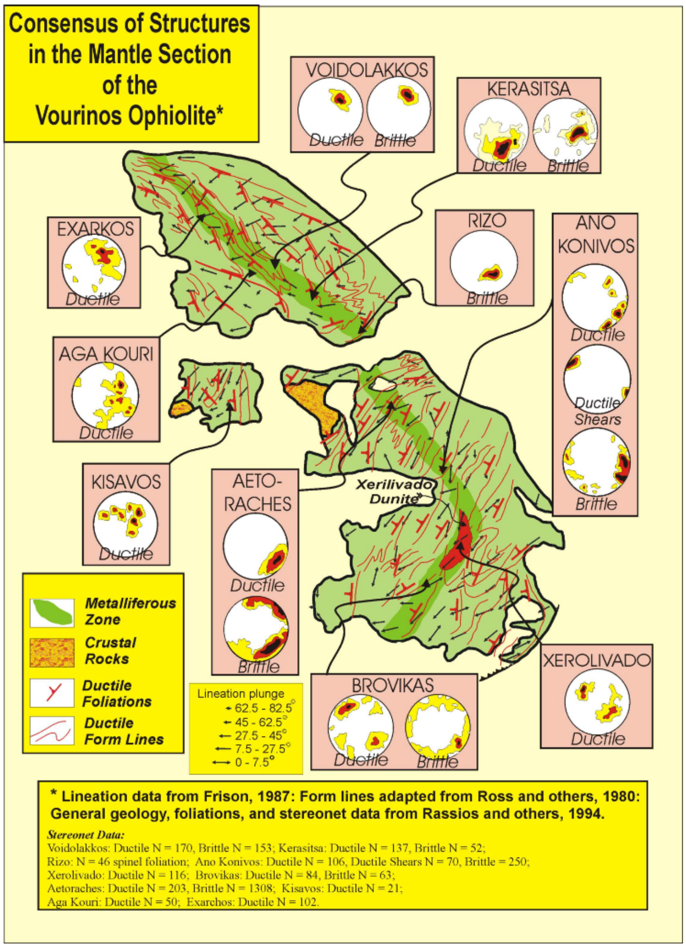
Langadakia Calpionellid Limestone. View from Ocean Layer 1 (right foreground) through ophiolite sequence and basal sole.

Jurassic oceanic sediments at Vourinos are deposited above an unconformity over zeolite-greenschist facies diabase dikes and flows: a thick pillow lava section is missing, with only several pillow lava outcrops within dikes preserved. The ocean layer one sediments include Calpionellid limestone with belemnite macrofossils (a), plus ribbon cherts. These sediments are overlain by a major angular unconformity by upper-Cretaceous rudistid-bearing limestone. The Jurassic sediments are thinned by erosion beneath much of this contact, and the basal Cretaceous consists of a layer of conglomerate including lava fragments (b). Folding in the Jurassic sediments is not penetrative into the Cretaceous (C).

Day 4 -THE VOURINOS OPHIOLITE

Traverse crossing Mantle and Sole

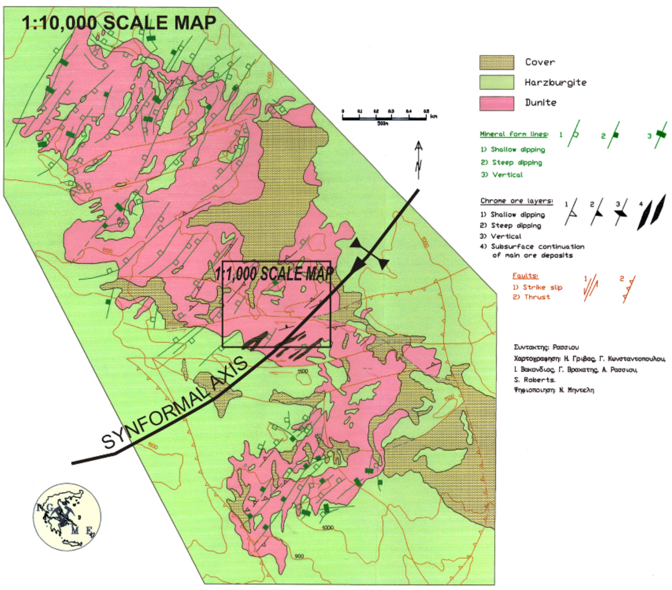
From the central area of Vourinos towards the SE, mantle fabrics rotate from NW with SW dip, to NE with steep dip (figure below); these form lines parallel the basal morphology of the ophiolite itself, implying a developmental relation between the turned orientation of ductile mantle fabric with that of emplacement. In a ductile nappe model, this would be predicted to reconcile lateral shear along the nappe margin.



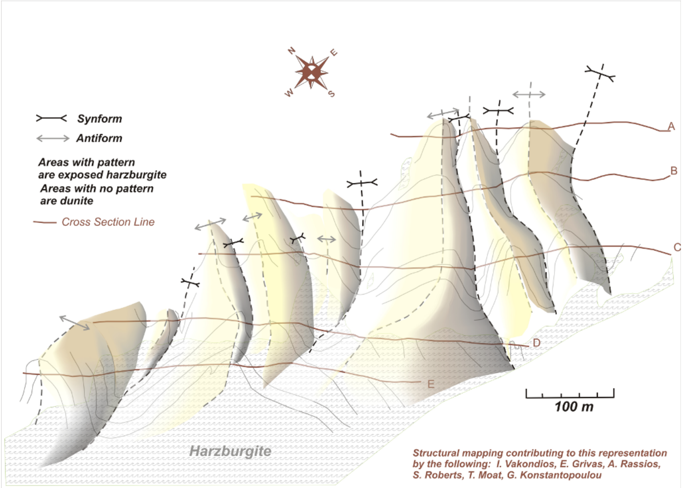
Structural analyses of the mantle peridotite of the Vourinos Ophiolite. Stereonet analyses document fabrics of individual ore districts.

Near the old entrance to the Xerolivado underground mine (now inaccessible), an open trench exposes NE-striking schlieren chrome ores in dunite. The mine operated from ~1954 until 1991, producing 2.25 mt of ore before closure due to a fall in Cr-ore prices. Despite the presence of 2.5 mt of estimated reserves, their depth complicates renewed exploitation. The ore within the trench site was sub-economic, and is not continuous to the major subsurface ore bodies. It is, however, characteristic of the morphology and geometry of “Xerolivado-type” ores. While outcrop layering suggests planar forms of the ores, they are better modeled as elongate, “snakey” shapes.

The host dunite crops out over a 3.5 x 1.5 km area that strikes ~NW and dips 10°-15° SW, continuing in the subsurface up to 10 km SW of the mine area. The dunite body has an unsymmetrical synformal shape, the axis trending NE with SE shallow plunge. The contact of the dunite with regional harzburgite is infolded, with parasitic fold axes on a wavelength of 10 – 50 m. Mineral foliations in dunite and harzburgite are parallel and define pervasive fold planes and axes. Chrome ores display small parasitic folds. Ore bodies coincide with synformal axes, with the largest bodies in the major synformal shape of the host dunite body. A morphological construction of this folding pattern defines probable sheath folds dating from late emplacement tectonism.



The Xerolivado Dunite Body, Vourinos Ophiolite, Greece.



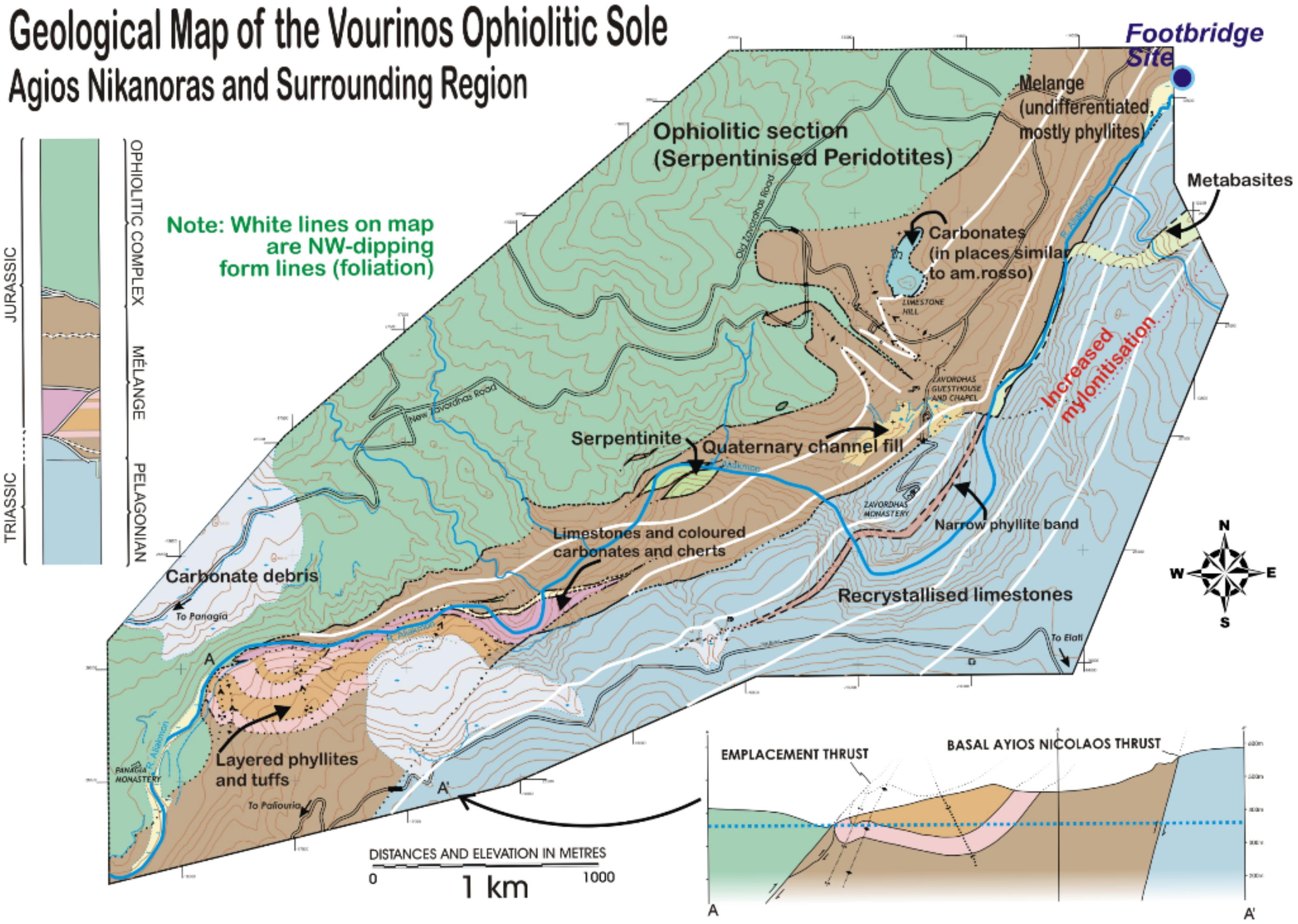
Fold topology of part of the Xerolivado ore district.

Remant ductile structures (orthopyroxene and spinel foliation, folded spinel bands) in serpentinised harzburgite immediately below the exposed sole on the Zavordas road are strongly imprinted by parallel brittle fabrics. These also parallel the orientation of the sole itself, here a ~1 m contact of serpentine against massive black amphibolite. Pebbly mudstone beneath the sole decreases from amphibolite-facies to phyllitic over a ~20m distance. Deformation of pebbles also decreases over this interval. Strong brittle ramping and duplex structures remain pervasive. Topping directions of all structures are NE.

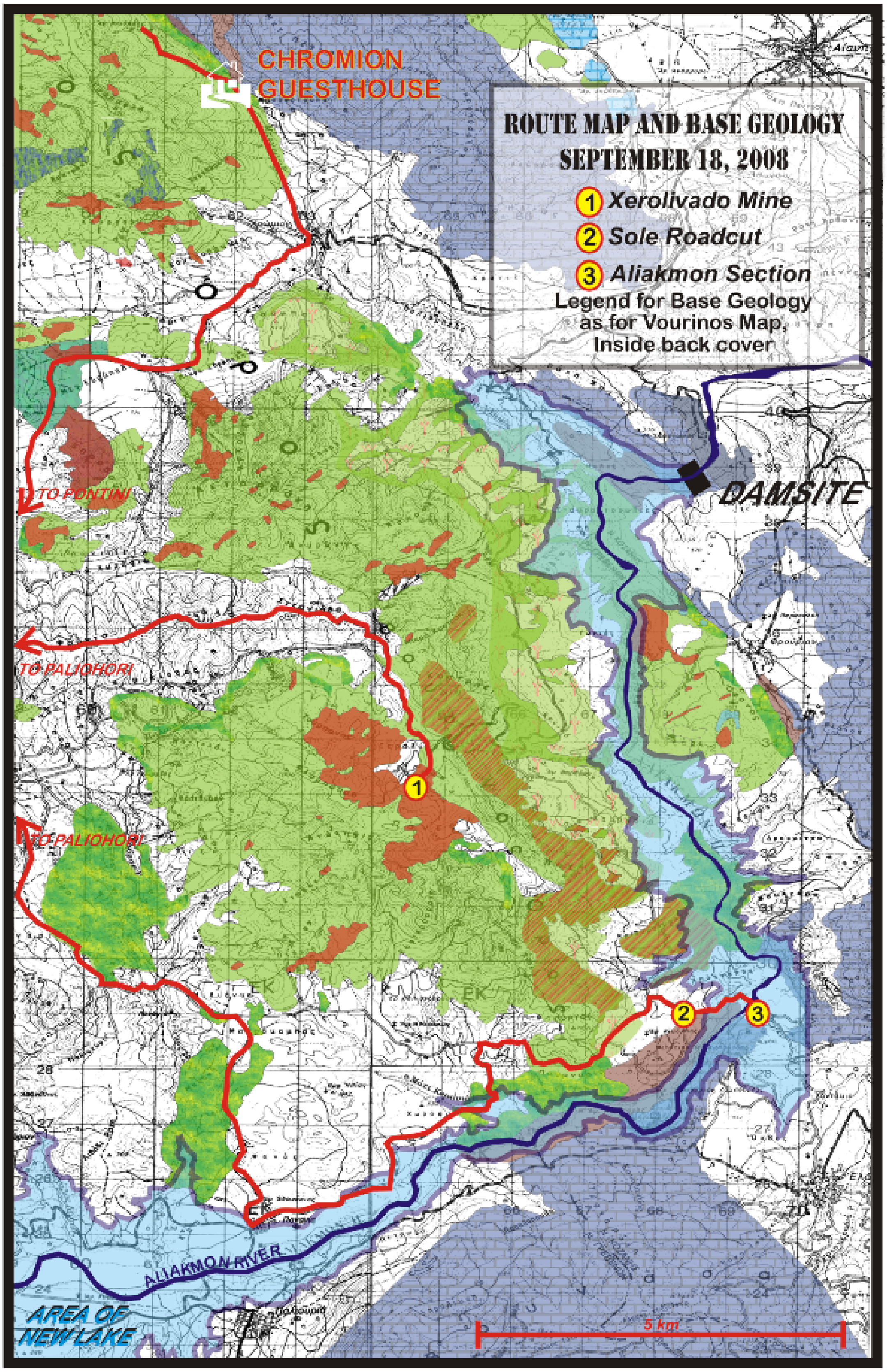
The sole is tectonically disrupted by ductile and brittle ramping structures, so that it over-rides itself along its outcrop pattern; once formed, the sole is not immune to continuing lower-temperature emplacement motion. Repetitive blocks of sole, including garnet amphibolite, crop out in the interval between the roadcut and Aliakmon River below Zavordas. The footwall, the Ayios Nikolas formation, has been dated as Jr, and certainly includes blocks of tectonically incorporated Jr ophiolitic debris (as in the Chromion Valley). All small pebbles examined to date appear to have provenance in the Pelagonian continent. The resemblance of the pebbly mudstone matrix of this formation to the Tr(?) pebbly mudstones west of Fotino questions their currently accepted ages, and suggests incorporation of a once broader mudstone unit as the matrix of a tectonic mélange formed during the emplacement of Vourinos.

The dextral rotation of ductile fabrics observed over the southern Vourinos massif continues into the formations beneath the sole. These include mylonitic limestones and sediments of the Tr-Jr platform series and another “mélange” consisting of a ~7km ribbon of magmatic rocks and oceanic sediments, 85m at its widest part. Within this ribbon, cherts, pillow lavas, sheeted dikes, diorites and metagabbros can be recognized, juxtaposed via ductile deformation on a scale varying from less than a m^2 to tens of m^2. No inherent original petrologic seqence seems preserved within the ribbon. Metamorphism of these rocks includes amphibolite facies, with garnets in some metagabbros. Sheeted dikes with fossil chilled margins include large epidosite masses.

Since the study of Brunn, the genetic association of this ribbon has been controversial: are these small remnants of Jr ophiolite over-ridden and incorprated into the Vourinos emplacement zone, or are they members of Pelagonian basement? Chemical analyses of lavas within this ribbon show WPB association, with the implication that these are from a rifting sequence. If so, then the Aliakmon Valley includes remnants of the birth of the Pindos Basin, plus its “demise” when emplaced onto the W Pelagonian margin.



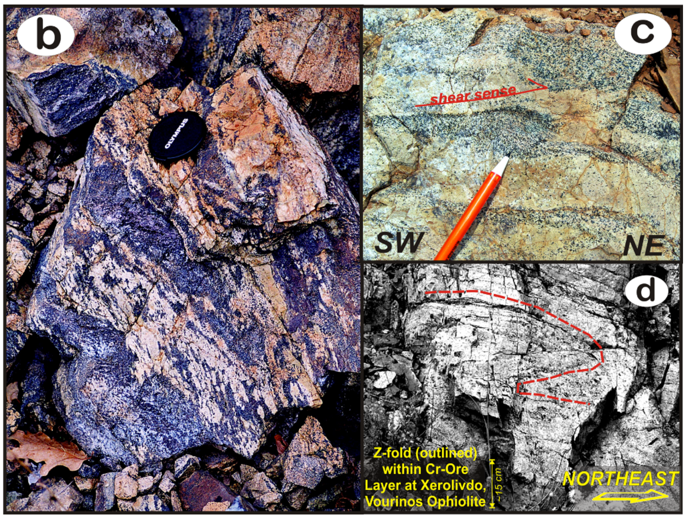
Geology of the Aliakmon Legacy Area. Map by Bob Myhill.



Stop 1: Vourinos Ophiolite - Xerolivado Mine

XEROLIVADO

Panorama of abandoned surficial ore trench.



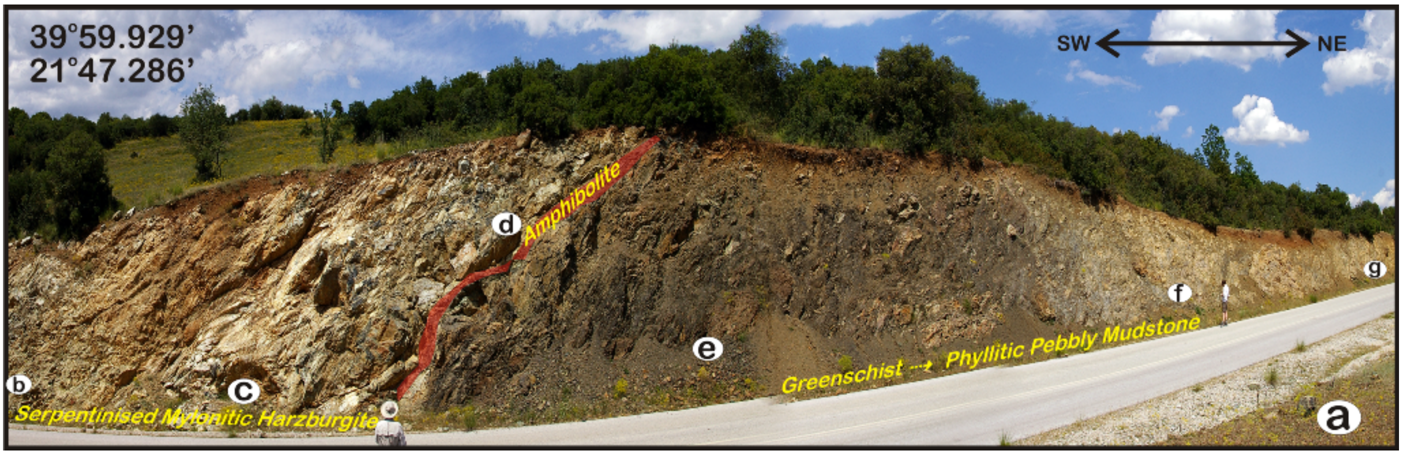
b. Ore in talus from underground mine demonstrating high-strain ductile deformation. c. NE topping kinematic indicator in ore seam. d. Dextral (NE topping) fold in ore layers above abandoned trench.

The underground chrome mine, more than 400 m beneath this site, is no longer accessible.Tailings around the old slant shaft entrance include schlieren ore, many samples of which demonstrate high-strain ductile deformation (photo b). The open trench (photo a), parallel to underground ore bodies, allows access into a subeconomic deposit of numerous ore ribbons. and displays brittle compressive structures along its walls: these allow kinematic assessment of ductile and brittle structures. Spinel foliation (photo c) parallels axial planes of parasitic folds that top to the NE, which align with regional fabric and folding. Unlike the SE-dipping structures of Doumaraki, Aetoraches and the Moho units, Xerolivado structures have been rotated 90ºCW and evidence dextral slip (as in Z-folds, photo d).

Consider: The greater apparent strain in these ores than at the near-Moho localities, and the coincidence of topping directions of ductile and brittle strain.

Stop 2: Vourinos Ophiolite - Sole Roadcut

SOLE EXPOSURE



Panorama of Vourinos Sole, or part of it anyway. Letters b through g are locations of photos below.

Figure b. Imbricated serpentinized harzburgite over the sole.

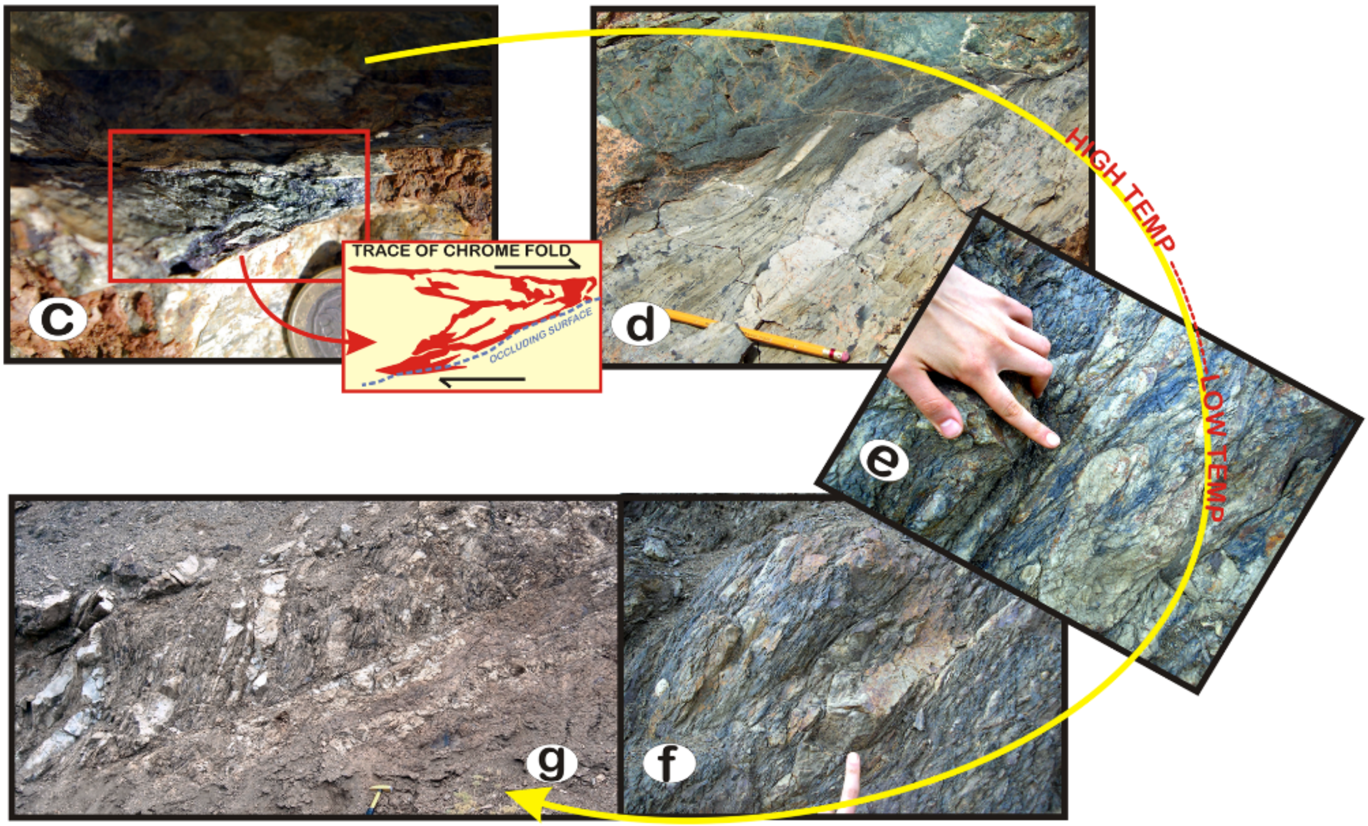


Figure c. Minor folded chromite band in serpentine immediately above the sole. This ductile deformation indicates topping relatively to the east. Figure d. Part of the sole itself: Black amphibolite over mylonitic deformed pebbly mudstone. Figure e. Greenschist facies pebbly mudstone with ductile kinematic indicators. Figure f. Ductile-brittle deformation in pebbly mudstone, lower greenschist facies with sense of topping relatively to east. Figure g. Brittle ramp in zeolitic facies pebbly mudstone topping to relative east.

Yellow arrow through photos c through g indicates relative direction of high to low temperature deformation among these localities on the roadcut.

Road building recently gave us this spectacular slice through the Vourinos sole (a). Serpentinized harzburgite to the west is emplaced over a high-temperature fault onto Ayios Nikolas Pebbly Mudstone and Triassic sediments and lavas further east. Photos along this outcrop detail specific kinematics: photo b shows NE-topping brittle imbricates in peridotite. Similar imbrication is found the length of the outcrop. Photo c is a dextral-topping, ductile-folded chrome ore band about two meters below the fault. Photo d shows constrictive movement of the massive amphibolite unit over light-colored altered and deformed footwall. Photo e shows folded pebbles and cobbles within the greenschist facies pebbly mudstone about three m east of the fault. Photo f shows phyllitic pebbly mudstone, with ductile-brittle kinematic indicators topping to the east. Photo g shows ductile to brittle ramping in the phyllitic mudstone ramping to the NE.

Consider: How representative of the sole is this particular outcrop?

Stop 3: Vourinos Ophiolite - Aliakmon Section

OPHIOLITE VS. PELAGONIAN MARGIN

Panorama of Aliakmon River in area of tectonic mélange. Photo by Dina Ghikas.

Driving below the Zavordas Monastery to the site of a footbridge over the Aliakmon, the section passes beneath the sole and pebbly mudstones into the Pelagonian footwall. Along the river this inclues Tr-Jr platform carbonates to the east and along the river itself a series of Triassic carbonates, gabbros, dikes, and cherts. All are strongly imprinted by ductile deformation and metamorphosed. Garnets have been located in remnants of amphibolite sole as well as within metagabbros. Carbonates and serpentinised harzburgite caught up in this deforming zone are mylonitic. Contrasting competency among the rock types has provided a unique display of kinematic indicators.

Consider: Zimmerman included the section as part of the sole assemblage, while Brunn classified the section, as well as the amphibolite units, as part of the basement. The spilites and lava chemistry within the highly deformed zone prove to be characteristic of rifting sequences. Did the site of initial Triassic rifting of the Pelagonian provide the ready-made framework to facilitate Jurassic ophiolite ramping onto the continental margin?

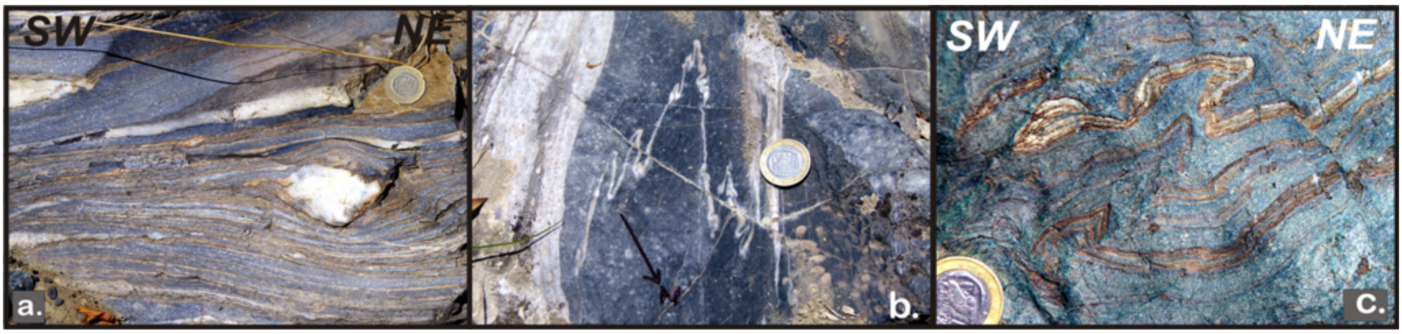


Figure a. Mylonitic carbonates from Aliakmon River section. Figure b. Mylonitic carbonates demonstrating fold. Figure c. Chert and pelitic sediments of tectonic mélange demonstrating complex folding and small ductile-brittle faults.

Exposures include a varied petrologic assemblage derived from members of the Pelagonian margin sedimentary cover, oceanic sediments, lavas, dikes, and gabbros of a rifting sequence, and shards of the ophiolitic slab and sole. Deeper parts of the Pelagonian are not included, though their deformation has been shown in exploratory boreholes placed for damsite planning. All are metamorphosed to some extent varying from amphibolitic to greenschist facies, and all are highly deformed. Deformation and kinematics demonstrate brittle to high temperature ductile conditions reconciling dextral shear between Vourinos and the Pelagonian margin. The rotation of internal ophiolitic structures (as at Xerolivado) exclude emplacement of the ophiolite onto pre-existing deformation; the lack of imprinting fabric common to Pelagonian basement and Vourinos precludes the interpretation as later exhumation fabric.

Figure d. Mylonitic pebbly mudstone metasediments. Figure e. Pillow lavas and chert of rifting sequence. Figure f. Deformation of gabbro from rifting sequence.

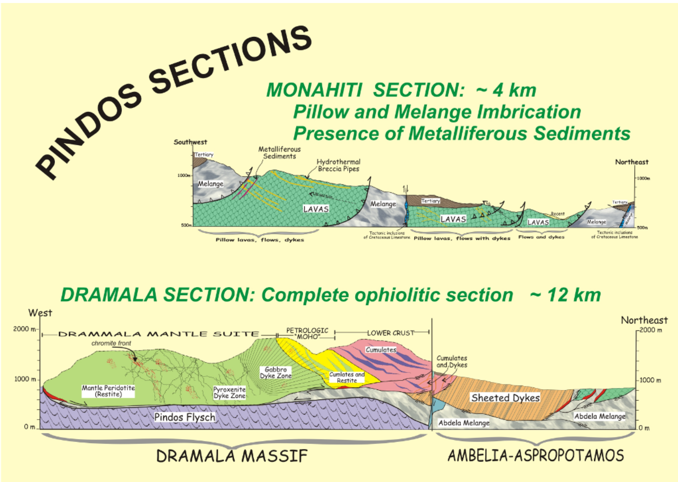
Day 5 -THE PINDOS NAPPE OPHIOLITE

Ophiolites of the high Pindos are parts of a >2000km^2 nappe complex emplaced over Eocene flysch: this emplacement is entirely brittle field, and its imprint is imposed on all pre-emplacement lithologies of the region. These SW-topping structures at places appear constrictive, in particular among the nappes themselves, while along the major contact of the nappe complex over the flysch, nappe-parallel brittle foliation appears to have formed at least in part from gravity sliding.

The precise geographic origin of the nappe complex is indeterminate: ophiolitic nappe margins in apparent continuation to ophiolitic units rooted in the Mesohellenic Trough (MHT) are obscured by deformation related to the origin and evolution of the MHT. The interior of the nappe complex retains a coherent strato-tectonic assemblage, giving the impression that the complex itself was not displaced any great distance. The orientations of ductile and ductile-brittle structures within the ophiolite parallel those of Vourinos and approximate those of the W Othris peridotite massifs: thus, displacements between these ophiolites apparently did not impose rotation. The sense of topping directions within the nappe, defined by ductile to ductile-brittle structures and brittle-emplacement ramps, show NE motion consistent in style to that of a large thrust sheet, that is, NE displacement facilitated by NE-striking lateral tear imbricates. Ramp stacking occurs along the eastern margin, and is largely responsible for the “inverted” ophiolite stratigraphy. Individual ramps overlap petrologically, thus breakage and shortening of the section appears less severe than for the disassociated Othris-Koziakas nappes: the mantle-cumulate Dramala imbricate overrides the cumulate-sheeted dike Ambelia imbricate, which in turn overrides a dike-pillow section.

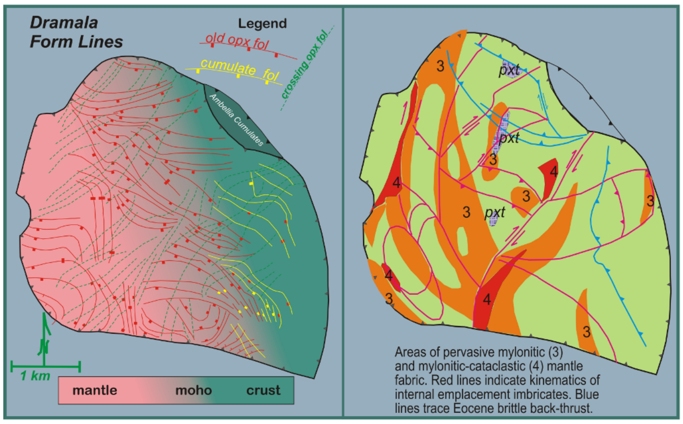
The high-temperature ophiolitic sole is intact at several localities. Banded amphibolite with rare garnet occurs between the basal ophiolitic rocks and the Avdella Mélange, a block-and-matrix accretionary complex. At the Liagouna locality, the amphibolite is about 100m thick, and emplacement metamorphism extends into the mélange for several hundred meters as a transition of amphibolite-greenschist-zeoloite facies. Amphibolite sole also occurs along the base of nappes of higher ophiolite units, such as the “near-moho” harzburgite and plagioclase dunites of Vasilitsa, gabbro cumulates of Orliakas, and as greenschist-facies banded sole rocks underlying lava units of the Monahiti area. Amphibolite dating of the sole constrains the emplacement age to between 169±5 and 165±3 Ma, while zircon dating of plagiogranite gives a crystallization age of 171±4my. The Eocene SW-topping back-thrust of the Pindos nappe ophiolite included the ophiolitic sequence itself, its immediate sole and host formations to obduction (Avdella Mélange), as well as the lower Cretaceous “first flysch” and upper Cretaceous limestone.

The glaciated mantle peridotite of the nappe complex allows spectacular viewing of mantle structure and melt phenomena. The continuity of deformation from ductile to brittle field , and the consistency of orientation of these structures within a NE obducting slab model, implies that these peridotites preserve the deformation mechanisms active during slab detachment and initial emplacement motions.



Cross sections through the Pindos nappe ophiolite. Upper section: imbricated pillow lava, dike, and Avdella mélange units at Monohiti. Lower section: composite section through entire ophiolitic nappe. The Dramala massif includes an coherent mantle – crustal cumulate section, over-riding imbricates of crustal cumulate units to lavas.

Cumulate rocks occur in continuous section with mantle rocks on Dramala, their transition comprising a “petrologic Moho.” Cumulates are also in continuous section with plagiogranites and sheeted dikes in the Ambelia imbricate. Lowermost cumulates are pods of plagioclase dunite within harzburgite in the Moho section, with gradual reduction of harzburgite upward, then as series of thin, lensing layers of dunite-wehrlite-troctolite (sills?) within the ultramafic cumulate section. Mafic cumulates above this consist of gabbro and troctolite, grading upsection to diorite and plagiogranite.

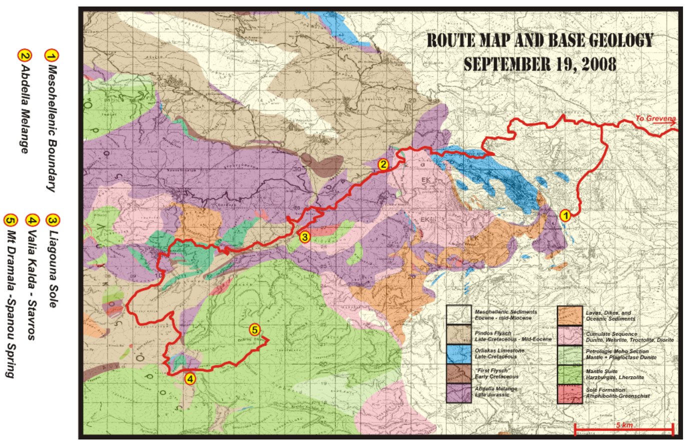


Left figure: Macrofabric map and position of “petrologic moho” over the Dramala massif. Right figure: Zones of mylonitic fabrics hosted by higher temperature mantle fabrics within the Dramala massif.

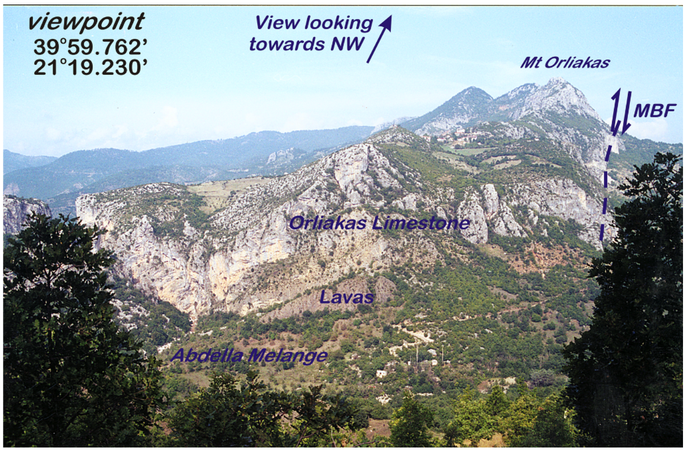
The Pindos nappe includes a thick imbricate including sheeted dikes, massive flows, and pillow lavas that straddle greenschist to zeolite metamorphic facies. Oceanic sediments are present within pillow lavas as interstitial material and isolated layers, but the ocean layer one interface (sediments over pillow lavas) accomodated thrust movement and is rarely intact.

In a geochemical sense, ophiolitic lithologies comprise two sequences of contrasting petrology and geochemical evolution, termed the Eastern Aspropotamos Complex and the Western Aspropotamos Complex. The Eastern Aspropotamos Complex is a 2-km thick polygenetic assemblage of diverse oceanic magma types. Its lowermost cumulate sequence consists of minor dunite–wehrlite–lherzolite layered intervals crystallized from a boninitic magma. These are overlain, but not intruded, by few dunite–troctolite–anorthosite–gabbro cyclic units, the latter exhibiting flaser structures, which, together with the overlying sheeted dikes and associated pillow lavas have crystallized from a Ti-rich normal mid-ocean ridge basalt (N-MORB) magma. Rare dikes, belonging to a Ti-poor N-MORB magma cut across the latter and feed overlying sparse pillow lavas. Both N-MORB units are, in turn, cut by dikes of transitional N-MORB/island-arc tholeiite (IAT) and primitive IAT character, the latter possibly parental to a seamount of differentiated IAT lavas built atop the pre-existing N-MORB crust. N-MORB and IAT lithologies are intersected by scarce dikes possessing a chemistry transitional between IAT and boninites (BSV). These, in turn, are cut by boninitic dikes proper, consanguineous with the lowermost ultramafic layered series of the complex. By contrast, the Western Aspropotamos Complex shows a much simpler volcanic stratigraphy, organized in two major magmatic episodes. The earlier episode is represented by lavas and dikes of IAT/BSV transitional chemistry, whereas the later episode is clearly of boninitic affinity. The thick plutonic and genetically related volcanic sections in the Western Aspropotamos Complex imply considerable melt storage before eruption.

Petrogenetic modelling indicates that at least three different sources are required to generate the Eastern Aspropotamos Complex units, whereas two different sources are required to generate the Western Aspropotamos Complex units at realistic degrees of mantle partial melting. These sources differ primarily in their clinopyroxene content, the latter being >8%, >6% and <7 wt.% for the MORB+MORB/IAT, IAT+IAT/BSV and BSV units respectively. All units appear to have been generated under 'open'-system conditions, characterized by very few replenishment cycles, low fractionation/eruption rates and low input rates. Moreover, the supra-subduction zone units show variable additions of rare-earth and high-field strength elements that can be explained by dynamic melting processes operating on source regions contaminated by oceanic island basalt-like and subducted oceanic sediment-derived melts. Field, geochemical and petrogenetic data support the interpretation that the Eastern Aspropotamos Complex was possibly formed near a trench-transform-ridge triple junction position similar to the southern termination of the Marianas Trench, whereas the Western Aspropotamos Complex was formed within the subduction fore-arc.



Stop 1. Pindos Ophiolite - Mesohellenic Boundary



View of Mt. Orliakas and Mesohellenic Boundary Fault.

The fieldtrip route crosses the Mesohellenic trough between Vourinos and the Pindos: magnetic and gravity maps confirm ophiolitic basement to a depth of at least 25 km as a keel-shaped structure. Mesohellenic sediments, including molasse and flysch, of late Eocene to mid-Miocene age fill the trough to near 5000 m thickness. Gentle west-dipping sediments towards Vourinos turn to east-dipping towards the Pindos and in the vicinity of NW-striking, Tertiary constrictional faults. Descending from the Mavronei Junction, the local Mesohellenic sediments include minor reverse faults and synsedimentary gravity faults.

The Mesohellenic Boundary Fault (MBF) is exposed along the extremely steep NE face of Mt Orliakas. The fault extends from this site to the NW into Albania and to the SE into the Koziakas area, a distance of 150 km. Our viewpoint of the MBF from Parorio exposes the fault of the Orliakas limestone (late Cretaceous, rudistid bearing) over a footwall including the Avdella melange and associated lava imbricates. The limestone is tectonically included as competent blocks within complex deformation zones hosted by less competent melange, flysch and serpentinite. Cretaceous blocks range in size from Orliakas itself, down to slender but prominent ribs on the scale of tens of meters. On the Portitsa side of the valley within the view, the limestone appears to be emplaced onto Tertiary Mesohellenic sediments.

Formation of the Mesohellenic trough was accompanied by steep fault sets parallel and perpendicular to the boundary fault that rotate ophiolitic terrane in the position of tectonic corridors.

Stop 2. Pindos Ophiolite - Avdella Melange

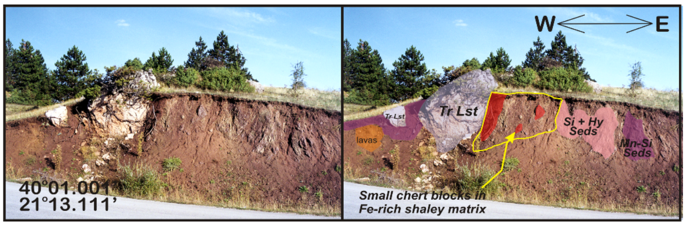
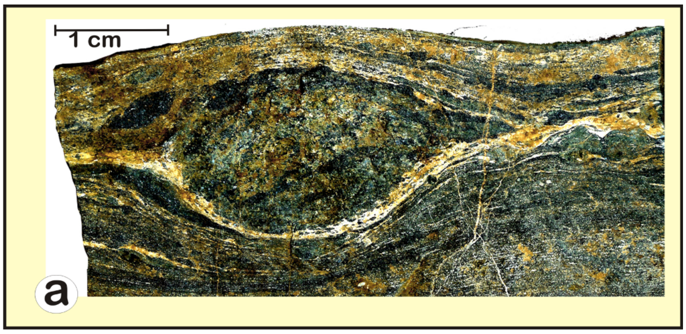


Photo of outcrop of Avdella Melange (left) and outcrop map of exposure on right.

The Avdella Mélange is a block and matrix accretionary sedimentary mélange that comprises the footwall formation to the Pindos ophiolite. In contrast to the Ayios Nikolas formation of Vourinos, it lacks Pelagonian continental fragments and the matrix is characteristically non-metamorphosed away from the sole. Blocks include Tr- to upper Jr-aged ribbon cherts, limestones, pillow lavas, and serpentinites.Their sizes range in scale from hand-sample to several km^2. The matrix is well-exposed and consists of mudstones and siltstones sometimes grading to chert, and hyaloclastic detritus. Blocks frequently show deformation that is not penetrative into the matrix in contrast to the Ayios Nikolas formation of Vourinos. Internal deformation in the matrix varies from weak schistosity to complex ramp structures. The Avdella Mélange south of Kranea includes fragments of sole amphibolite, and also appears to include a lower temperature sole along internal emplacement zones. The mélange is tectonically emplaced over early Cretaceous "first flysch" carbonates, and these in turn over the Cretaceous to Eocene Pindos Flysch. Younger Cretaceous limestones (Orliakas Group) crop out as tectonically included fragments of competent material within flysch, mélange, and serpentine dominated complex deformation zones.

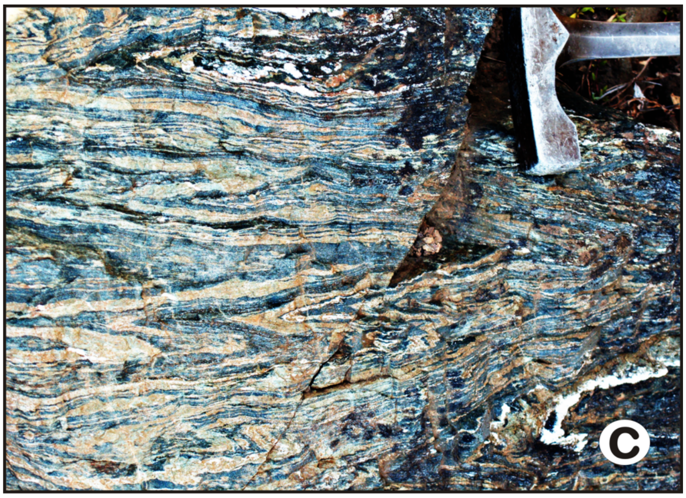
Stop 3. Pindos Ophiolite - Liagouna Sole

The Liagouna Sole at: 39°58.965' 21°10.591'



Garnet-bearing augen from Liagouna sole contact.

Serpentinized mylonitic harzburgite from above Liagouna sole.



Folded amphibolite within sole.

On Liagouna, the garnet-bearing amphibolite sole formation exceeds 100m thickness. Serpentinized harzburgites above the sole display primary mylonitic fabric with elongate orthopyroxenes. Metamorphism within and beneath the sole is gradational, extending several hundreds of meters into the Abdella Melange, decreasing through greenschist and zeolite facies. Sole amphibolite is banded, grey-white to black, with augen structures and complex folds. Garnet has been located at the sole contact itself within a δ structure.

The contact zone here is near vertical, rotated most likely during ductile-phase emplacement. Brittle structures crosscutting the sole zone, ramps and minor imbricates, show constrictional topping directions to the NE.

Stop 4. Pindos Ophiolite - Valia Kalda

VALIA KALDA – STAVROS

Panorama: Valia Kalda – View from Stavros locality. All visible terrane and mountain peaks are mantle peridotite.

Unaltered mantle harzburgite showing traces of ductile ramping structures showing topping to east.

Valia Kalda is a tectonic window through the peridotite nappe of the Pindos ophiolite (high peaks) exposing Pindos flysch and Cretaceous imbricates (valley floor). Other ophiolitic members and Abdella Melange are tectonically thinned out from here and to the SW.

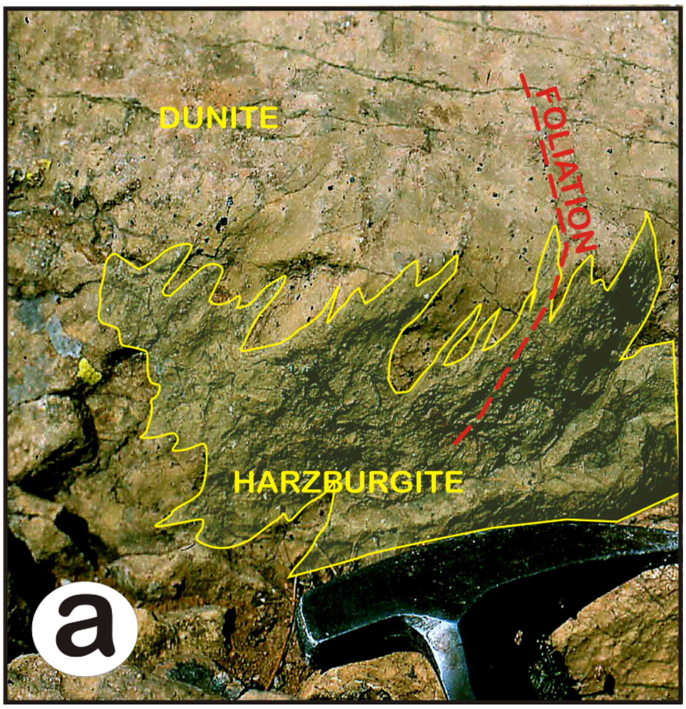
At Stavro, the peridotite is fresh: loss on ignition is lacking, and indeed, small positive gains on ignition are characteristic. This harzburgite/lherzolite is moderately strained, but not very mylonitic, demonstrating higher temperature intragranular deformation processes. Foliation of the tectonite dips SW, and defines a symmetrical imbricate-shaped fold on the scale of several hundred m^2 topping NE. Imprinting this are ~30o S-plunging lineations, ductile ramp structures (photo to right) topping to the NE, and younger brittle shears.

Several hundred meters up the road from Stavros towards the top of Dramala (Spanou Spring area), L-tectonite peridotite crops out.

Stop 5. Pindos Ophiolite - Mt Dramala

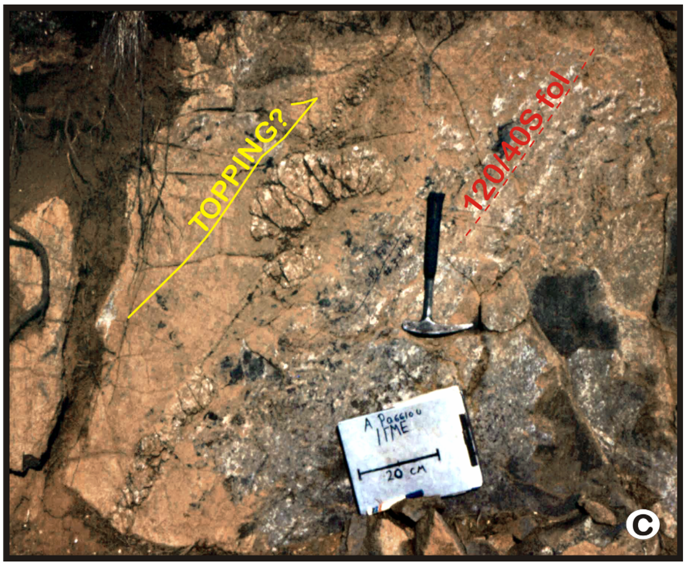
MT DRAMALA – SPANOU SPRING

Several of the ductile structures observed on Mount Dramala at or near: 39°56.489' / 21°09.816'



“Flame-style” irregular harzburgite/dunite contact.

L-Tectonite harzburgite on Dramala.



Pyroxenite boudin deformed along foliation / layering surface in mantle peridotite.

From Valia Kalda, the road ascends to the glaciated top of Dramala with a stop at the Spanou Spring site. Here, the harzburgite shows evidence of ductile kinematics synchronous to probable remelting in a hydrous environment allowing for intrusion of pyroxenite pegmatite dykes. Pyroxenites occur as irregular blebs and as meter-scale “boudins” deformed to δ-shapes by pervasive, continual kinematics. By comparison, ductile deformation of pyroxenite dikes at Vourinos is limited to several occurrences where the dikes are entrapped in emplacement-related mylonite zones.

Chrome spinel morphologies show deformation foliations and lineations within harzburgite and dunite, but individual grains are euhedral near and within pyroxenites, implying metasomatic growth.

Nearby, a single chromitite layer has been discovered that is ~10cm thick, traceable in outcrop for about 200 m, with probable continuations for over a 2 km distance. Ductile tectonic thinning is presumably responsible for this morphology.

Consider: The appearance of the peridotite suggests multiple phases of melting.

Day 6 -FINAL STOPS

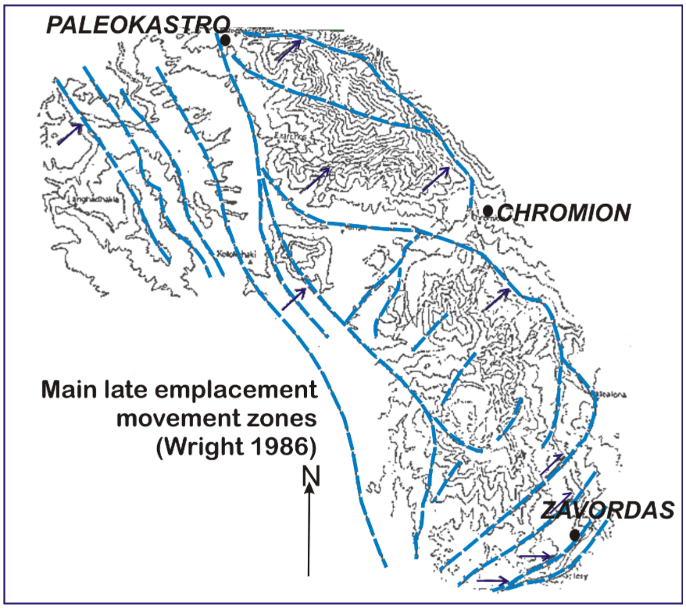
The northern margin of Vourinos displays unique outcrops and views. On the Aliakmon below Asprokambos, an exceptional exposure of upper cumulates (diorites, clinopyroxenites, entrapped magma) shows a range of structures consistent with a collapsing roof of a magma chamber: syn-tectonic folding, slumping, and channeling features accompany roof pendants and ductile faults in semi-consolidated magmatic rocks.

Our route passes a constrictional fault (photo below) of ophiolitic material with Mesohellenic sediments, and numerous angular unconformities within the sediments genetically related to movement on the fault zone. The fault zone exposed by highway construction, verifies a NE compressional environment into the mid-Tertiary as put forward by the late Theo Doutsos.

Road-cut exposure of Taxiarchis fault along Egnatia Highway.

The panorama from the north, in particular that from the original site photographed by Brunn in 1938, spans the entire oceanic lithosphere preserved over Vourinos. Brunn himself was the first to note that ophiolitic rocks, in particular the cumulates and diabasic rocks of Vourinos, were alike to those of the mid-Atlantic ridge described by Ewing et al in the mid 1950's.

From the village of Paleokastro, a route up to the valley of Mesiano Nero traces the northern emplacement zone of Vourinos. No other location along the Pelagonian margin gives a better feeling for "bulldozer" tectonics: pebbly mudstone hosts 1 - 10 m-scale blocks of serpentine, lavas, cherts, and limestone. Serpentine-rich fault breccia includes limestone fragments. Deformation within the pebbly mudstone, tectonically defined morphologies of melange blocks, and pervasive duplex and ramp structures indicate eastward topping. A ductile-fabric harzburgite crops out along the base of the ophiolite.

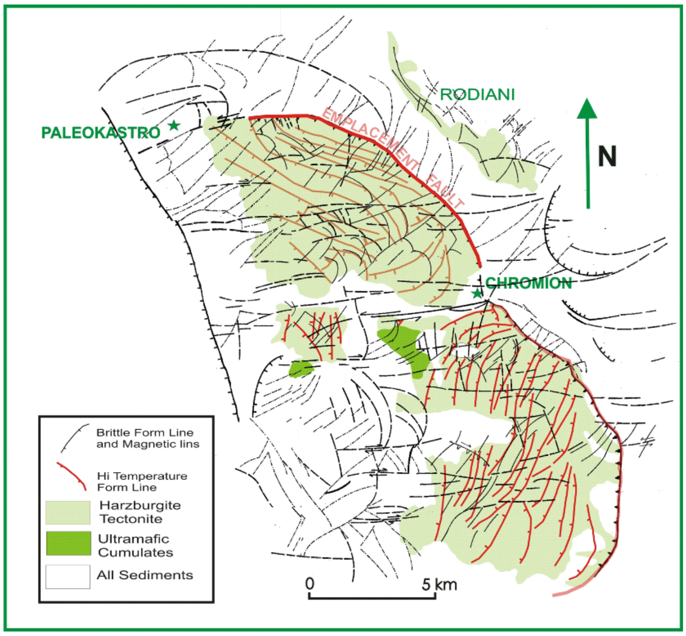


Late stage imbrication with emplacement vectors at Vourinos as determined by Wright 1986.

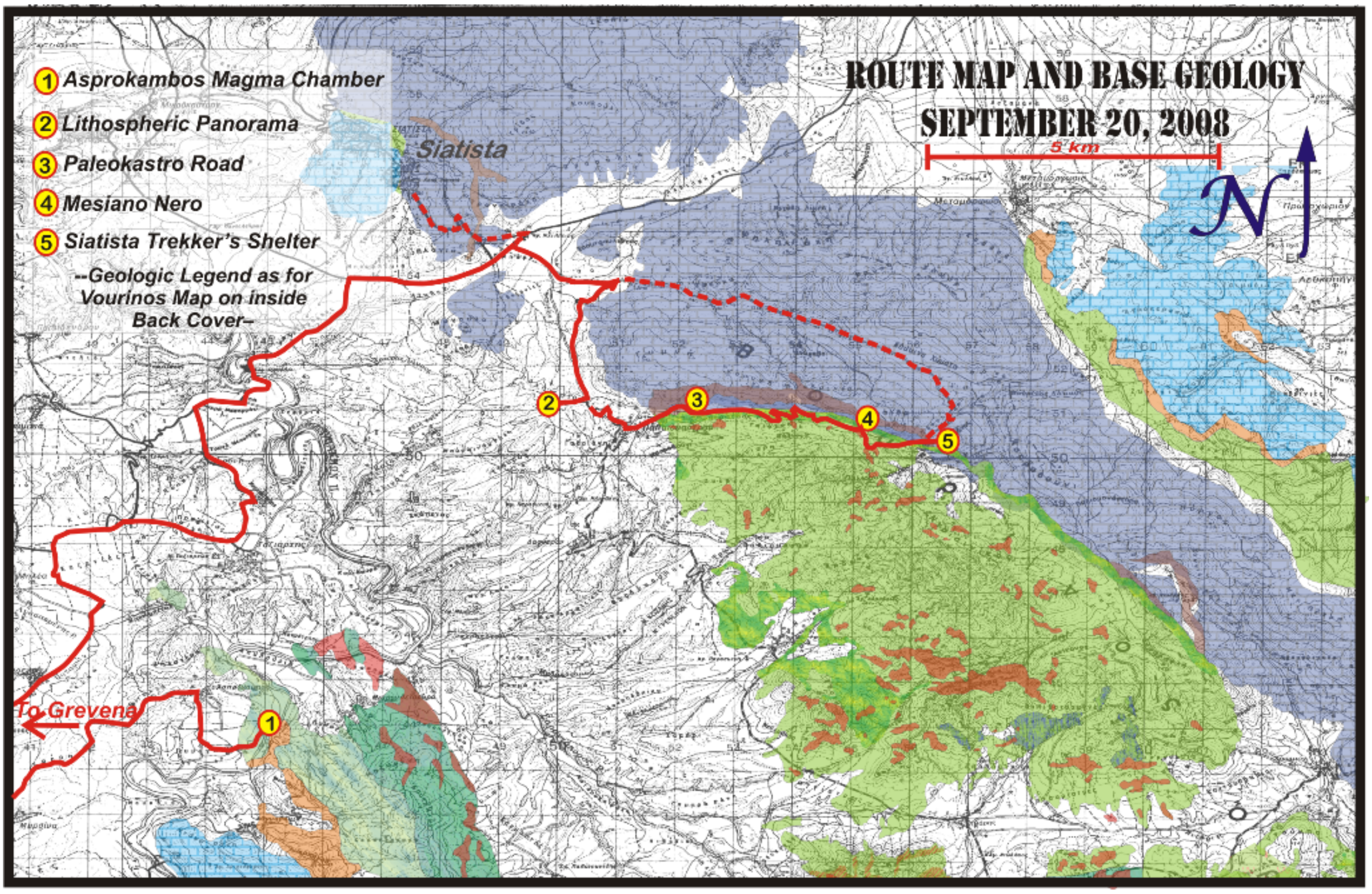
FINAL MOTIONS

The sketch maps below denote final brittle movements of the Vourinos peridotites. The upper sketch is based on field work by L. Wright: blue lines outline major imbricates uniquely associated with the ophiolite.

The lower map traces high-temperature form lines of mineral foliations (orthopyroxene and spinel) in red. Black lines are traces of magnetic lineaments: field checks show these to correlate to brittle shear zones. In particular, magnetite-rich serpentinized zones show up well under sedimentary cover. Horizontal black lines are mid-late Tertiary fault and shear systems, crossing into younger and older sediments.

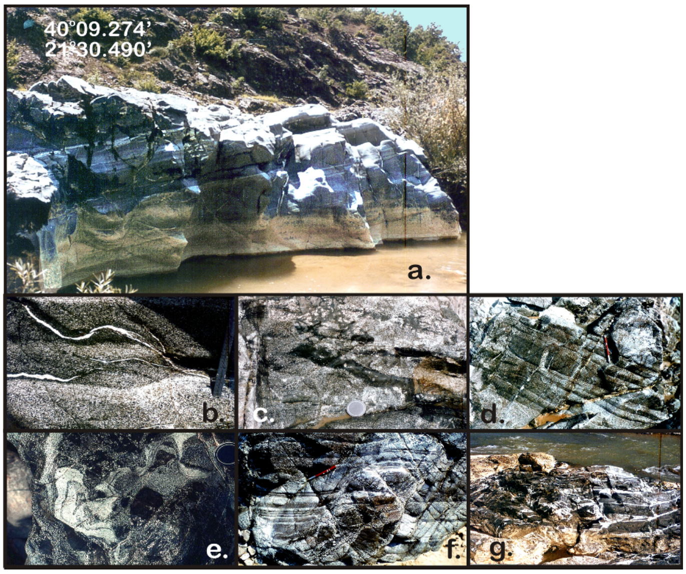


Brittle structures and magnetically determined subsurface shear patterns (obscured in outcrop by sediments) of Vourinos.



Stop 1. Vourinos Ophiolite - Asprokambos Magma Chamber

GABBRO – DIORITIC MAGMATIC CUMULATES



Magmatic cumulates in upper level chamber: a-g explained in text.

Along the Aliakmon River below Asprokambos, upper level cumulate gabbros and diorites display magmatic structures including igneous lamination and layering (photo a, b), mineral graded layers (photo b), entrapped magma (photo c), dioritic “diapirs” (photo d), igneous deformation structures such as slump folds (photo e) and igneous faults (photo f), and roof pendant structures. Further up-river, diabasic dikes penetrate and seem brecciated within felsic (noncumulate) rocks (photo g).

Consider: Unlike layered igneous intrusives (Bushveld type), ophiolitic cumulates form in an active tectonic environment. Are the features present in this exposure representative of spreading center magma chambers?

Stop 2. Vourinos Ophiolite - Lithospheric Panorama

Upper panorama of Vourinos Complex by Jan Brunn, 1938. Lower panorama by Rassios, 2008.

Jan Brunn first shot the panorama of the entirety of the ophiolite section in 1938 using a bellows camera with glass plates instead of film. This was ~40 years before the acceptance of ophiolites as representatives of oceanic lithosphere. The panorama spans 12 km, from the emplacement zone to the E, through mantle, “moho”, cumulates, dikes, lavas and sedimentary section in the west.

Stop 3. Vourinos Ophiolite - Paleokastro Road

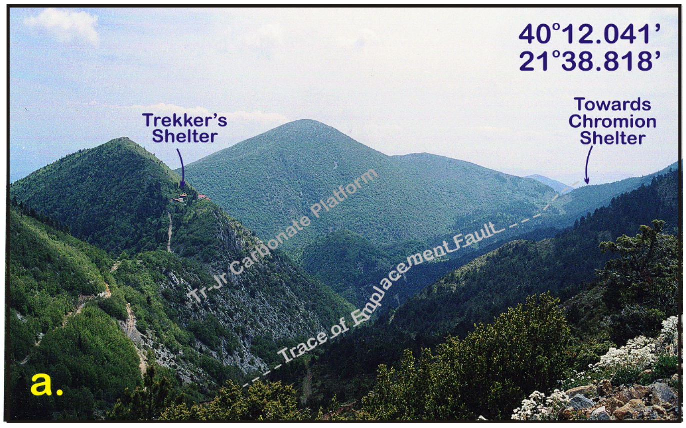
NORTHERN EMPLACEMENT ZONE

General view of track leading 4 km along Vourinos emplacement zone above Paleokastro.

Left: Limestone in mudstone mélange. Middle: Tectonically incorporated limestone block surrounded by serpentinite in melange. Lower: Banded appearance of deformed mélange.

Several stops can be made along the road from Paleokastro Village to the Mesiano Valley. The road parallels the northern continuation of the Vourinos emplacement fault for a distance of about five km. Pelagonian Tr-Jr platform carbonates crop out along the ridge to the east; mantle harzburgite crops out on a lower ridge to the west. Between these, the Ayios Nikolas Mélange (~0.5 km wide in map exposure) includes tectonically incorporated blocks of carbonates, lava, and cherts: parallel to the road is a slice of loferitic / mylonitic carbonate about 5000 by 200 m in area. Initial outcrops include pebbly mudstones hosting blocks of lavas and Tr-Jr carbonates. In addition to fault gauge in lower temperature emplacement parallel faults, slickensides along several carbonate faces could date to original emplacement deformation.

Stop 4. Vourinos Ophiolite - Mesiano Nero



View of emplacement zone within Mesiano Nero valley.

Basal harzburgite, Eldridge Moores, and deformed pyroxenite.

Boudins in mylonitic limestone.

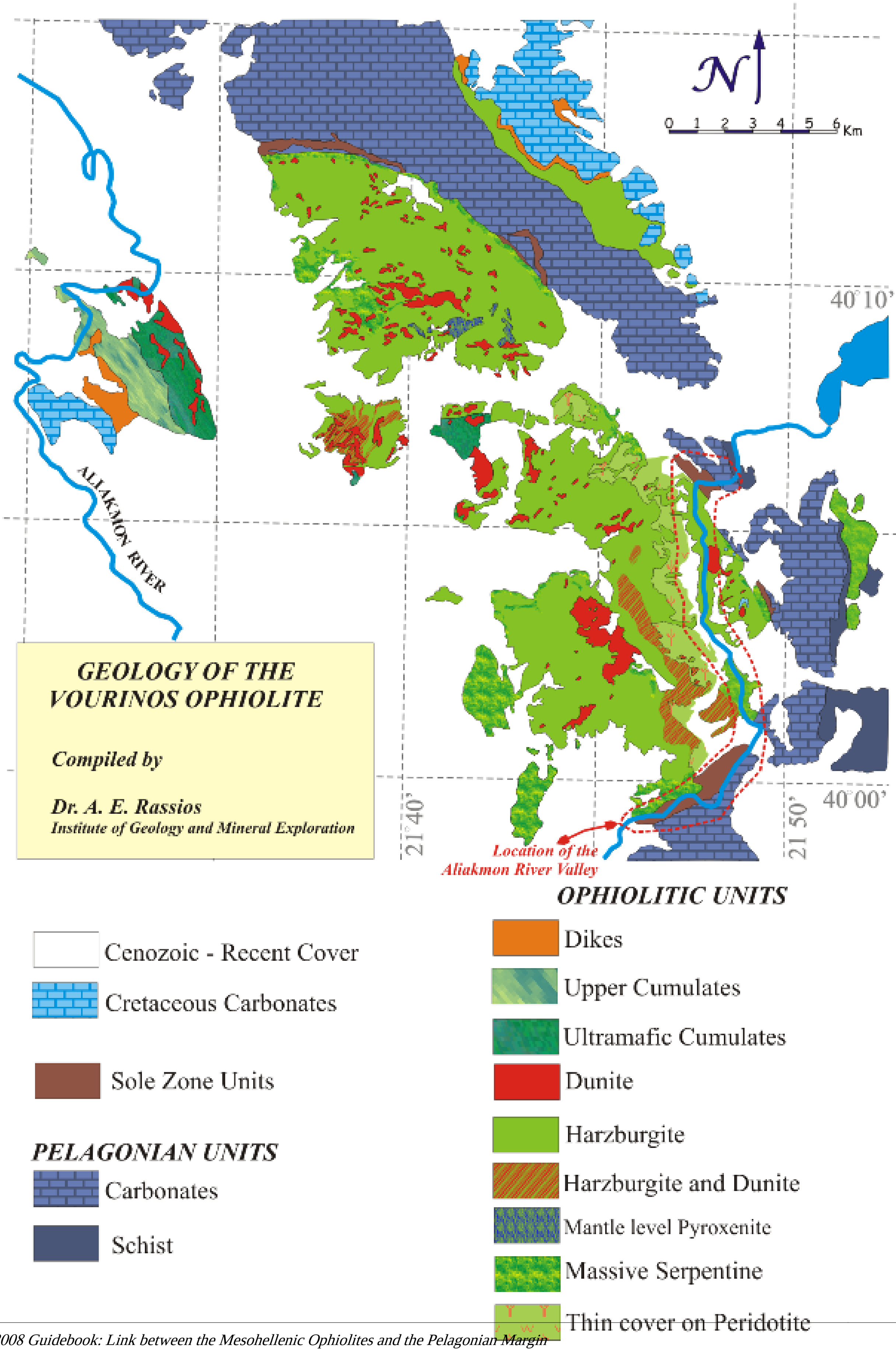
Mesiano Nero is a saddle where the ophiolite and Pelagonian basement are separated by <200 m of Ayios Nikolas Melange. The large included sliver of loferitic limestone becomes mylonitic with boudins indicative of lateral extension. The basal harzburgite is more mylonitic than elsewhere at Vourinos, and a thin mylonitic-cataclastic zone crops out along the base of the ophiolite.

Stop 5. Vourinos Ophiolite - Siatista Trekkers Shelter

View of Mount Vourinos from Siatista Trekker's Shelter.

Our final site gives us a chance to view the spectacular panorama of Vourinos and the valley tracing its emplacement. The area is an environmental preserve, and we'd like to point out the contribution the paleo-suture zone plays in this unique setting. Tr-Jr Pelagonian platform carbonates to the east provide soil constitutents of Ca, K, and not much else: note the lesser amount of vegetation there. Vourinos ultramafics generate Fe, Mg, and Si and a variety of trace soil nutrients, but lack essential constituents such as Ca and N: the harzburgite mountains are also relatively barren. However, where the soils mix along the base of the valley, the vegetation is rich, and includes several endemic plant species unique to the valley.

Back cover


N
0 1 2 3 4 5 6 Km
40°10'
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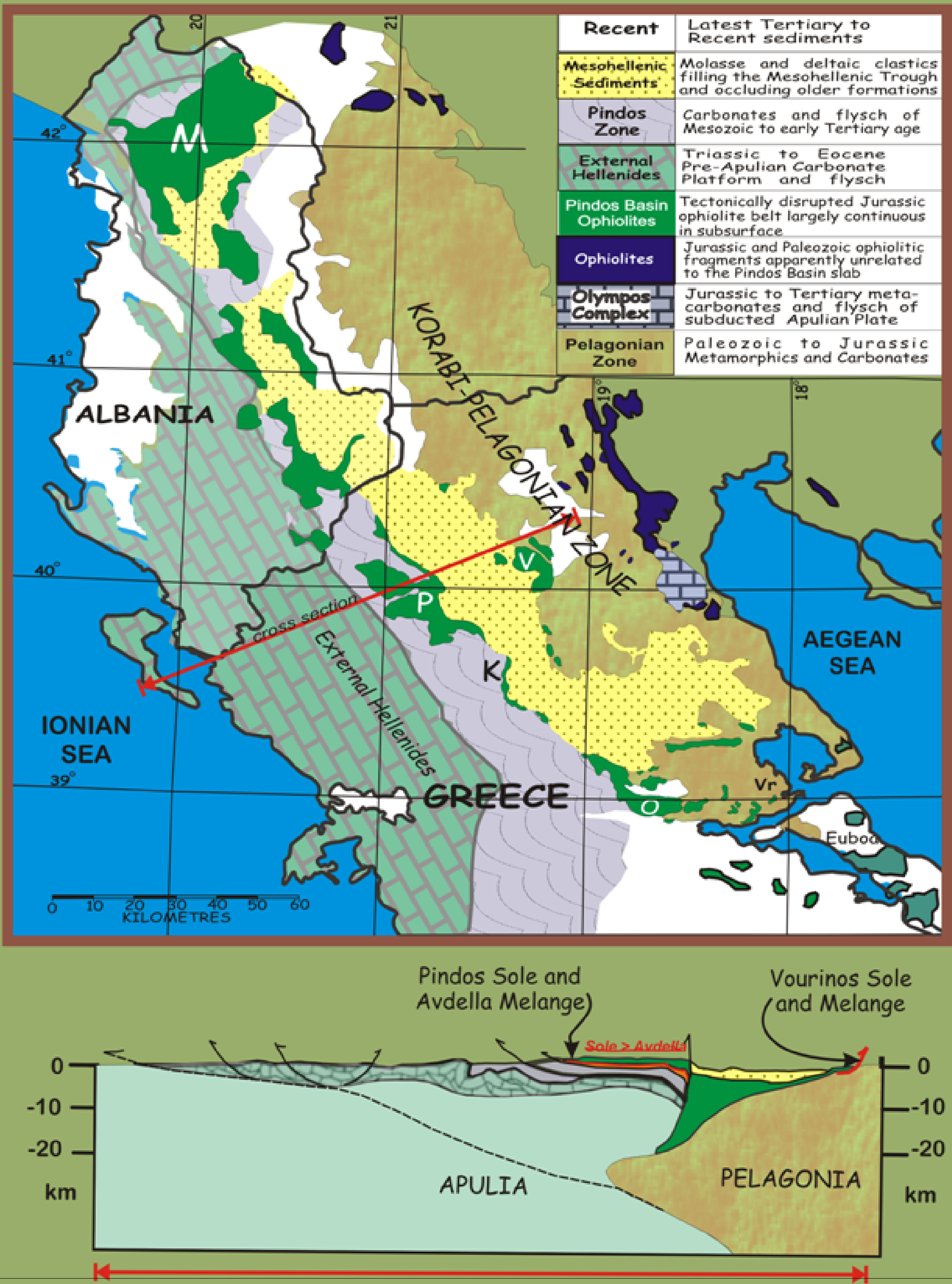
ALIAKMON RIVER
GEOLOGY OF THE
VOURINOS OPHIOLITE
Compiled by
Dr. A. E. Rassios
Institute of Geology and Mineral Exploration
Location of the
Aliakmon River Valley
OPHIOLITIC UNITS
Dikes
Upper Cumulates
Ultramafic Cumulates
Dunite
Harzburgite
Harzburgite and Dunite
Mantle level Pyroxenite
Massive Serpentine
Thin cover on Peridotite
Cenozoic - Recent Cover
Cretaceous Carbonates
Sole Zone Units
PELAGONIAN UNITS
Carbonates
Schist

OPHIOLITES OF THE PINDOS BASIN AND REGIONAL GEOLOGY



Acknowledgements

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No trip to the Vourinos Ophiolite would be complete without warm mention of Eldridge Moores and his dedication to the geology of Greece and ophiolites worldwide.

Members of the Organizing Committee: Ophiolites 2008
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Prof. Alastair Robertson, PhD
Prof. George Migiros, PhD
Asst. Prof. Dimitri Kostopoulos, PhD
Anne Ewing Rassios, PhD

We would also like to thank our Student Assistants:
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Robert Myhill, MSc, Cambridge University
Anna Mpatsi, Aristotelian University of Thessaloniki
Vagelis Moulas, University of Athens

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