Rotational deformation in the Jurassic Mesohellenic ophiolites, Greece, and its tectonic significance

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1. Introduction

The strain during displacement and subsequent emplacement of an ophiolitic slab onto a continental margin involves inhomogeneous simple shear both within a >10-km-thick thrust nappe and in the underlying tectonic basement. At the base of the emplacing oceanic slab, displacement is parallel to the shear plane marked by the metamorphic sole and an overlying zone of intensely mylonitic peridotite. Horizontal compression associated with the displacement and emplacement of such an oceanic slab, an originally vertical section gets tilted and rotated into an arc-shaped curve, concave towards the direction of shear.

This rotational deformation may result in an overturn of the crustal section in its upper portions (Twiss and Moores, 2007).

The recognition of such emplacement-related shear and deformation patterns within ophiolites is difficult because different lithological units with varying rheology and physical properties accommodate distributed shear quite differently in an internally heterogeneous ophiolite pseudostratigraphy. It is also difficult to sort out emplacement-related deformation features from those associated with both seafloor spreading-related extensional deformation and constrictional deformation in subduction-accretion settings. The paucity of structures that allow precise measurement of primary horizontality (S0) in oceanic lithosphere is also problematic. Pillow lavas approximate but are rarely strictly parallel to horizontality. Sheeted dikes are assumed to intrude originally along vertical planes, although sheeted dike intrusions with moderate dips have been observed in in-situ oceanic...
crust (Karson, 1998). Inherent $S_0$ mantle layering, depending on the degree and nature of ductile lithospheric overprint, is presumed to dip away from rift axes (Nicolas, 1989a). For structures that do approximate or can be used to reconstruct horizontality, rotational deformation resulting from imbrication during post-emplacement deformation imposes further complications and often cannot be

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**Fig. 1.** Simplified geological map of northern Greece showing the distribution of the Mesohellenic ophiolite belt and other major tectonic zones. Cross-section (modified after Doutsos et al., 2006) depicts the crustal architecture of the Apulia-Pelagonia collision zone and the root zone of the Mesohellenic ophiolites (here Pindos to the west and Vourinos to the east with their underlying mélangé units). Key to lettering: Vourinos (V) and Pindos ophiolites (P); Koukourello–Pindos locality (KP); Mirdita ophiolite-Albania (M); Othris Ophiolite (O); Ayios Stephanos locality (AS); Vrinena locality (VR); Koziakas Ophiolite (K).
distinguished from rotations dating back to the main ophiolite emplacement period itself.

The Jurassic Vourinos ophiolite in northwestern Greece (Fig. 1) provides an excellent opportunity to study its internal architecture that is an artifact of deformation postdating its igneous accretion. The Vourinos ophiolite is a typical Mediterranean-type suprasubduction zone ophiolite (Dilek, 2003), displaying seafloor spreading-generated extensional structures and crustal units, heterogeneous mantle sequences, and underlying metamorphic sole and mélangé units (Zimmerman 1968, 1972). It rests tectonically on the passive margin and rift assemblages of the Pelagonian microcontinent (Moores 1969; Naylor and Harle 1976; Smith and Rassios 2003; Ghikas et al., 2007), and it is unconformably overlain by the Cenozoic clastic rocks of the Mesohellenic Trough (Vamvaka et al., 2006). Earlier studies by Rassios and Smith (2000) and Smith and Rassios (2003) have evaluated various models on the igneous environment of formation and tectonic emplacement of the Western Hellenide ophiolites. The recent paper by Rassios and Moores (2006) has presented field-based structural observations pertaining to the crustal and upper mantle processes involved during the igneous accretion of the Pindos–Vourinos oceanic slab in an extensional environment and subsequently during its obduction onto the continental margin.

The Vourinos ophiolite is rotated ~90° such that an E–W cross-section along its entire width presents an excellent geotraverse from its mantle sequence and the underlying metamorphic sole up to the upper crustal units and the sedimentary cover. This rotation of the ophiolite, as originally documented by Moores (1969), poses a significant question regarding its tectonic evolution and for ophiolite geology in general.

Rassios (1981) and Beccaluva et al. (1984) described a monoclinal overturn of the upper crustal section in Vourinos that was relatively dated back to the oceanic spreading period. However, our studies have shown that the internal structure of Vourinos is, to a large extent, a result of progressive non-coaxial deformation following its magmatic evolution. In this paper, we describe the internal architecture and the rotational deformation of Vourinos as an imprint of inhomogeneous shear associated with the initial displacement of the ophiolite from its igneous environment of formation and subsequent emplacement onto the Pelagonian continental margin. We document the occurrence, geometry and kinematics of mesoscopic and macroscopic ductile to brittle structures that developed during this progressive heterogeneous deformation in the upper mantle and crustal sections of the Vourinos ophiolite. This study has important implications for interpreting the internal structural architecture of ophiolites in general. Our results suggest that differential rotational deformation within ophiolites is not always associated with extensional tectonics during seafloor spreading of ancient oceanic crust, and hence caution should be exercised when structural and paleomagnetic studies are undertaken in those ophiolites, which appear to have experienced widespread heterogeneous deformation and rotation.

2. Geology of the Mesohellenic ophiolites

The Vourinos and Pindos ophiolites are part of the Jurassic ophiolite belt exposed along the margins of the Mesohellenic Trough crossing much of Greece and Albania (Fig. 1; Smith, 1993). The Vourinos ophiolite is analogous to the Penrose-type oceanic lithosphere (Fig. 2; Moores, 1993; Smith, 1993).}

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**Fig. 2.** Comparison of the pseudostratigraphy of a Penrose-type complete oceanic lithosphere with that of the Vourinos and Pindos ophiolites (modified after Rassios and Moores, 2006). Reconstructed Vourinos pseudostratigraphy is analogous to the Penrose-type oceanic lithosphere in terms of its inferred thickness and internal structure. Pindos ophiolite has been highly deformed and tectonically imbricated. The Pindos Flysch underlies the ophiolite and its mélangé (Avdella).
mapped at the surface, have their origin in this peridotite keel, and hence they likely represent bidivergent ophiolitic thrust sheets derived from the same ophiolitic root zone underneath the Mesohellenic Trough. Both Pindos and Vourinos have similar crystallization ages (168.5–171 Ma; Liatı et al., 2004), and near-contemporaneous metamorphic sole ages (~162–167 Ma; Roddick et al., 1979; Spray and Roddick, 1980; Thuziat et al., 1981; Spray et al., 1984), supporting their genetic relationship.

3. Internal deformation in the Vourinos ophiolite

Detailed structural analyses within the Mesohellenic ophiolites were produced during reconnaissance studies for chromite ores (Economou et al., 1986) and delineation of tectonic criteria for exploration drilling strategies of chrome ore districts over a 12-year period (1984–1996). The results of these reconnaissance studies have been reported mostly in internal reports of the Institute of Geology and Mineral Exploration of Greece (IGME), and in some peer reviewed papers (i.e. Rassios et al., 1986; Roberts et al., 1988; Rassios and Kostopoulos, 1990; Rassios, 1991; Rassios et al., 1991; Rassios and Konstantopoulou, 1992; Konstantopoulou, 1992; Grivas et al., 1993; Rassios, 1994; Rassios and Grivas, 1999, 2001). Compilation of this massive data resource, in synthesis with new research observations and paradigms, continues to provide new insights for the structural architecture of the Mesohellenic ophiolites, particularly for those structures associated with their displacement and emplacement kinematics. In this section, we document and discuss the nature of heterogeneous deformation within the lower, ductile portions and in the higher, crustal sections of the Vourinos and Pindos ophiolites.

3.1. Rheology and deformation of ophiolitic mantle rocks

An ophiolitic–oceanic slab should record strain in a heterogeneous fashion, as each oceanic layer (Fig. 2a) differs in its degree of competency and rheological properties. Competency varies within oceanic layers, as well; a pillow lava outcrop with abundant hyaloclastic sediment interlayers is less competent than pillow lavas lacking significant sediments within pillow interstices. In many well-preserved ophiolite complexes around the world, the majority (~80%) of a complete pseudotachylite consists of various serpentinized upper mantle peridotites (Coleman, 1977). Original mantle lithologies, essentially a mixture of harzburgite or lherzolite with minor dunite, provide a further source of heterogeneous rheology as demonstrated in rock deformation experiments (Avé Lallemant and Carter, 1970; Nicolas et al., 1973; Avé Lallemant et al., 1980; Chopra and Paterson, 1981). Peridotite deforms via plastic intracrystalline mechanisms (dislocation creep) that initiate at temperatures of about 1200 °C (referred to as “asthenospheric” or “diapiric” fabric) and continue in cooling conditions through about 900 °C (Mercier and Nicolas, 1975; Nicolas and Poirier, 1976; Watts et al., 1980; Calmant, 1987; Kohlsedt et al., 1995); it then deforms as a ductile material via intercrystalline mechanisms (disruption creep) down to about 700 °C, at which point it enters the brittle field (Calmant, 1987). Peridotites beneath the rift axis at a typical seafloor-spreadin spreading center experience high-enough temperatures to record ductile deformation. Mantle layering (Nicolas, 1989a) is considered as the most primitive sub-ridgecrest mantle lithology preserved in ophiolitic mantle sections, and is generally utilized as an “S0” fabric for tectonic analysis of mantle peridotites in ophiolite complexes. As the newly formed oceanic lithosphere is translated away from the spreading center, it cools down and the ductile-brittle transition is depressed to successively greater depths (Harper, 1985). The first and quickest parts of the slab to cool are the shallowest sections; thus, the highest temperature (near magmatic condition) fabrics within a preserved ophiolite are commonly located near the petrological Moho. In many cases, these “frozen-in” fabrics record shallow mantle processes occurring synchronously with ridgecrest activities, such as deformation of magmatically growing chromitite ores (Christensen and Roberts, 1986), and are affected to a
lesser degree by continuing ductile deformation still occurring at deeper levels in the slab.

Rassios and Smith (2000) modeled the time span and distance over which an off-axis and passively spreading oceanic crust is capable of undergoing ductile deformation. With greater depth, the slab remains in ductile conditions for a longer time span, and higher-temperature deformation is gradationally overprinted by cooler but still ductile deformation in the off-axis environment. Thus, “S₀” structures such as mantle layering and lithological contacts are deformed in a gradationally evolving tectonic environment. For an ophiolite of the thickness of Vourinos, ductile deformation would be recorded for a period of about four million years in succeedingly deeper levels (Rassios and Smith, 2000), at which point it crosses entirely into the brittle field. The near-contemporaneous crystallization and metamorphic sole dates of the Vourinos and Pindos ophiolites, that is, within ~4 million years, essentially forces us to consider that the ductile imprint on the spreading slab coincides with ductile-field emplacement motions. Thus, plastic mantle fabrics preserve a spectrum of deformation dating from the asthenospheric diapiric flow beneath the ridgecrest into homogeneous, spreading-related mantle flow away from the ridgecrest and displacement-emplacement processes.

Fig. 3. Aeromagnetic anomaly map showing the distribution of a high-magnetic slab beneath the Cenozoic sedimentary units of the Mesohellenic Trough (modified from Memou and Skianis, 1991). The surface outline of the Pindos, Vourinos and Koziakas ophiolites is shown in green. High-magnetic anomaly between the Pindos and Vourinos ophiolites indicates the continuity of the mafic-ultramafic rocks at depth beneath the Mesohellenic sedimentary overburden.
Within even relatively simple mantle peridotite suites such as in Vourinos, the difference in competency is such that chromite-rich lithologies (chromitite or olivine chromitite) are the most competent at all temperatures, and have been suggested to provide the “breaking point” for initial brittle behavior (Grivas et al., 1993). Massive harzburgite is more competent than pure dunite (Nicolas et al., 1980; Moat, 1986; Roberts et al., 1988). Once ductile deformation has initiated, producing inter-crystalline and essentially mylonitic forms of strain, early fine-grained neoblastic-crushed zones preferentially accommodate later strain via dynamic recrystallization (Nicolas, 1989a). When subsequent serpentinization of peridotite occurs in brittle field conditions, these differences in competency are further accentuated, as, for example, between easily deforming totally serpentinized dunite and partially serpentinized harzburgite. By viewing deformation within mantle peridotites as an example of the accommodation of continuous strain associated with coaxial deformation in a heterogeneous medium, kinematics of deformation and direction of tectonic translation can be deciphered (Ceuleneer and Nicolas, 1985; Holtzman, 2000).

During this ductile interval, shallow-level peridotite above the ductile-brittle transition zone deforms in a brittle mode synchronously with ductile deformation at depth. Thus, peridotites at both shallow and deeper structural levels record the same orientation of shear strain but by different mechanisms. As the oceanic lithosphere
becomes older and cools further, the ductile-brittle boundary gets pushed down and brittle structures overprint older ductile structures (Harper, 1985); however, both ductile and brittle structures record a similar orientation of shear strain and kinematic direction.

The constrictional fabric within an ophiolitic mantle sequence provides an abundance of structures that show displacement directions within the slab. Intra-slab imbrication, ramps and brittle shearing phenomena are pervasive to all structural levels in the slab and demonstrate “over-riding” emplacement directions. The deformation of earlier formed high-temperature peridotite structures by later stage lower-temperature but still ductile shearing creates folds, which occur on a range of scale from the size of an entire ophiolite massif (at Vourinos, by the bowing of structures parallel to the sole zone described in the following sections), to the kilometer-scale synformal shape of the Xerilivado dunite body delineated by its petrologic contact, and to sheath folds tens of meters in scale defined by form lines within this synform. Fold vergence of these and even more minor parasitic folds, as well as ductile shear features such as “δ” and “σ” structures, shear boudins, and tectonic “fish” structures are widespread to demonstrate internal vorticity (Passchier and Trouw, 1996; Twiss and Moores, 2007). Lineations showing preferred alignment (as dragged, or over-riding trains of chrome spinel, for example) can be observed directly, or measured as “stretching” lineations coinciding geometrically with fold axes of verging fold systems, used for interpreting the sense of shearing and the direction of tectonic transport.

Some examples of these structures have been described previously (Rassios and Smith, 2000; Rassios and Moores, 2006) and several more are represented in Fig. 4. Fig. 4a shows a typical spinel foliation (vertical) in dunite: most spinel grains are aligned in trains and some individual grains display asymmetrical “heads” and “tails.” The largest grain (upper right corner) shows minor shortening, overriding along the foliation trace toward the top of the photo. Fig. 4b and c show mylonitic fabrics that demonstrate E–NE-directed sense of shearing. Fig. 4b is from a mylonitic band several cm thick and traced over ten meters within lower cumulates at Vourinos, and Fig. 4c is a mylonite zone from Voidolakkos (Ross et al., 1980; Grivas et al., 1993) including over-riding ductile imbricates.

Observing folds directly within mantle peridotites is difficult since the host petrology is uniform in appearance. However, as shown in Fig. 4d, moderate-scale folds can be seen within chrome-ore bearing areas, and can be useful in indicating local kinematics (here verging to the northeast in the direction of ophiolite emplacement). Elsewhere, folding is delineated by careful studies of mineral foliation (for example, Ayrton, 1968; Rassios et al., 1994). Mineral lineations, where observed within massive lithologies (spinel lineations in dunite or chrome ore, spinel and pyroxene lineations in harzburgite) correspond to the geometrically determined position of fold axes defined by foliations. Some brittle structures, such as those depicted in Fig. 4e, can be circumscribed to specific tectonic environments based on whether or not they continue into younger Cretaceous to recent formations, and

**Fig. 5.** Composite structural cross section of the Vourinos ophiolite. The Krapa Monocline with an overturned crustal section is shown at the WSW extreme of the section. Contour diagrams depict various intra-oceanic structural elements in the ophiolite (structural data are taken from Rassios, 1981; Rassios et al., 1991; Mavrides and Kelepertzis, 1994, and this study). Inset map (upper right) shows the general map of Vourinos with major ophiolitic subunits, and localities mentioned in text. Cross section line (a–b–c) is also shown. Key to lettering: X = Xerolivado; V = Voidolakkos; K = Kissavos; P = Plitori Section; D = Doumaraki; F = Frouro; AK = Aga Kouri; MD = Mikroklisoura pyroxenite dike swarm; KRAPA = Krapa Hills area.
whether or not they reconcile with the regional direction of emplacement. Brittle ramp shears are commonly oriented in the general direction of emplacement override. In Fig. 4g, these brittle shears are imprinted on peridotites with a high-temperature “diapiric” fabric that are lacking those structures originated from intervening temperature conditions. This observation demonstrates the need for envisioning a mechanism for displacing mantle rocks from high-temperature ductile conditions into brittle field conditions without undergoing intermediate deformation.

3.2. Rotational deformation in the crustal sequence

The crustal structure and the upper contact of Vourinos are well exposed within the Krapa Hill locality in the northwestern part of the ophiolite (Fig. 5; some lithological characteristics of the uppermost section are shown in Fig. 6). Layering in the ultramafic to gabbronoritic and dioritic cumulates is nearly vertical with an “up-section” direction to the west. Cumulate layers are rotated into slightly overturned (to the east) orientations near the contact with the overlying sheeted dike complex. Diabasic dikes (Fig. 6a) first occur in a transition zone made of mixed dike-cumulate screen zones in the east, and then grade into sheeted dikes toward the west over an interval of about 0.5 km. These subhorizontal sheeted dikes run parallel to the strike of cumulate layering, but dip perpendicular to it. The uppermost volcanic member of the ophiolite includes a minor screen (~5 m in outcrop) of small pillow lavas within mixed dikes and flows and hydrothermal jaspers (exhalative sediments) in the uppermost 200 m of the section. Metamorphic zoning, typical of crustal units in other ophiolites (Coleman, 1977) is consistent with the observed up-section trend such that amphibolite-facies mineral assemblages occur at deeper structural levels mainly within the mafic cumulates. Greenschist-facies assemblages are encountered at the level of dike-screen units and grade upward into a zeolite-facies within the uppermost sheeted dike complex and in the lowermost extrusive sequence.

Part of the upper contact of the ophiolite is overlain by a Jurassic Calpionellid-bearing limestone (Fig. 6b; Brunn, 1956; Moores, 1969; Mavrides et al., 1979; Mavrides, 1980), as also found within parts of the Pindos ophiolite (Jones, 1990; Jones and Robertson, 1991). Red “ribbon” chert-limestone units also appear within this unit at Vourinos. These sedimentary rocks are interpreted as the “Layer 1” member of the Vourinos oceanic crust. At their thickest (northward) outcrop, these limestones appear to have been deposited directly onto an eroded surface of greenschist-facies dikes and lava flows. The thickness of this sedimentary unit decreases to the south beneath the Cretaceous unconformity (Fig. 6c, d), and the southernmost outcrops are seen to rest on higher igneous stratigraphic levels, containing zeolite-facies dikes and lava flows. Using the horizon of the zeolite-facies metamorphic zone as a rough indication of the original stratigraphy, we estimate that at least 250 m of volcanic rocks were eroded prior to Calpionellid limestone deposition.

Bedding within the Calpionellid limestone is oriented ~N–NW with dips (~85°) to the east. The best estimation of original horizontality

![Image of various lithologic units within the uppermost part of and overlying the Vourinos ophiolite.](https://example.com/image6.png)
within the upper parts of the volcanic unit of the ophiolite (lava flows, metalliferous sediment horizons) shows that the uppermost volcanic rocks were rotated ∼10°–12° in a counter-clockwise sense about a horizontal axis before the deposition of the overlying Calpionellid unit. In addition, the Calpionellid unit exposes sub-meter scale folds verging to the east (Fig. 6e); this deformation fabric is not seen in the overlying Cretaceous carbonates. Timing of this folding is thus synchronous with the ophiolite emplacement in the late Jurassic.

Layering in the Cretaceous limestone defines a 40°–60° counter-clockwise rotation about a N–NW horizontal axis, apparently a continuation of the rotation observed in the Jurassic sediments. It is not possible to date the timing of formation of the unconformity at the base of the Cretaceous more accurately than to say that it would appear to be coeval with the late emplacement period.

A section through the entire Vourinos ophiolite and its sedimentary cover, from the amphibolite sole at the bottom to the east into the Cretaceous limestone on top to the west (Figs. 5 and 7) demonstrate the structural continuity and allows documentation of a gradual steepening of $S_0$ fabrics. Above the basal sole, these fabrics dip moderately to the west (Fig. 5), rotate towards verticality around the position of the petrological Moho, and then overturn within the cumulate section to dip about 60° to the east. To attain this flexing structural pattern, it is not necessary to invoke any other mode of deformation other than inhomogeneous shear (Fig. 7) consistent with a deforming nappe sheet. The “topping” direction would imply this shear to be generated by an eastward motion along the base of the ophiolite, with a westward lag at the top surface and creating an apparent monoclinal fold of the Krapa Hills. At the time of the deposition of the Cretaceous limestone, the ophiolite was oriented as a mafic-ultramafic slab with a vertical pole plunging about 30–40° eastward, and “original horizontality” dipping to the west. The further rotation of the obducted ophiolite was probably due to post-Cretaceous subsidence and shortening of the Mesohellenic Trough.

Occurring in the center of the Krapa Hills monocline is an exposure of pegmatitic pyroxenite dike swarms between the upper mantle peridotites and the highest cumulate gabbros (Fig. 8; Rassios, 1981; Rassios et al., 1983a). This dike swarm crops out along the Aliakmon River section of the Krapa Hills as a ∼250 m thick exposure (Rassios et al., 1983b). Pyroxenite dikes of 20 cm to 2.5 m thickness (Fig. 8a–c) constitute as much as 75% of the exposed outcrop made of serpentinitized dunite, which is the host rock of the dike intrusions. The dikes are composed of websterite and clinopyroxenite that show a typical pegmatitic fabric where the largest pyroxenes, up to meter scale, grew perpendicular to the dike walls; smaller pyroxene crystals, 1 to 20 cm long, occur with more random orientation in the central parts of the dikes (Fig. 8d–e). Pyroxenite dikes with this pegmatitic fabric run N–NW with steep dips to the E. In general, these dikes are tabular in appearance and do not display any evidence of ductile deformation as in the underlying mantle peridotites. They crosscut older brittle structures in the peridotites and are deformed by late brittle structures such as minor pre-Tertiary strike-slip faults and neotectonic features. The exception to this structural “rule” seems to be the deformation of some pyroxenite dikes within ductile mylonite zones such as at Voidolakkos (see inset map in Fig. 5 for location; Ross

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**Fig. 7.** Cartoon demonstrating the flexure of an idealized oceanic lithosphere via simple inhomogeneous shear and its resemblance to the composite structural section of Vourinos as seen in the Krapa Monocline. The modern oceanic lithosphere is presumed to include a heterogeneous competency due to its diverse lithology and temperature gradient beneath the ridgecrest. The attitude of mantle layering in the modern lithosphere implies that the ridgecrest lies to the left relative to this representation. Deformation style and geometry in upper levels of the “flexed” ocean lithosphere are similar in orientation to the structures observed in the Krapa Monocline. A continuity in the observed direction toward “up section” within the composite structural section of Vourinos (Fig. 5) delineates a pattern parallel to that of the flexed idealized section.
et al., 1980; Grivas et al., 1993) and within mylonitic harzburgite immediately above the basal sole. The relative timing of the intrusion of these dikes can hence be constrained as sometime between on-axis crustal construction of the Jurassic oceanic crust and late stage ductile deformation associated with the initial displacement of the ophiolite from its igneous tectonic setting. Therefore, these pegmatitic pyroxenite dikes may have formed as a result of precipitation of late-stage fluids within shear fractures that opened up during inhomogeneous shearing associated with the eastward displacement of the Vourinos lithosphere in a suprasubduction zone environment in intraoceanic conditions.

Fig. 8. Pegmatitic pyroxenite dike swarms in Vourinos along the Aliakmon River. a. Intersecting pyroxenite pegmatite dikes surrounding a “Λ” shape dunite inclusion in the dike swarm. b. Single pyroxenite dike, approximately 2 m wide and 200 m in length (surface exposure) continuing across the Aliakmon River. c. Single, relatively narrow pyroxenite dike within serpentinized dunite. Even in this smaller dike, pyroxene crystals are blocky and several cm in size. The dunite in contact with dikes shows a blackened serpentine envelope. d. Single orthopyroxene crystal above hammer. Optically continuous pyroxene crystals range in size from about a cm to nearly a meter. While both ortho- and clinopyroxenes have been observed (Rassios, 1981), their size range precludes statistical analyses of modal proportions and chemical composition. e. Typical pegmatitic fabric in pyroxenite dikes. Hand is set on dark serpentinized dunite margin. Along margin, large pyroxene crystals grow perpendicular to the dike contact, while smaller and more random orientations occur within the central portions of the dike.

Fig. 9. Examples of structures within the Mesohellenic ophiolites depicting intra-slab rotation. a. Upper map (a1) shows the emplacement movement directions (arrows) observed along the “bowed” basal thrust zone of Vourinos (by Wright, 1986). Green lines outline major imbricate structures associated with the ophiolite. Lower map (a2) shows high-temperature form lines of orthopyroxene and spinel mineral foliations in red and traces of magnetic lineaments in black. Magnetite-rich serpentinized zones show up well under the sedimentary cover. Nearly E–W-trending strike-slip faults and shear zones (locally dashed) are mid-late Tertiary brittle structures, crosscutting the younger sedimentary rocks as well as the ophiolitic units. b. Synformal-antiformal composite structure of the Dramala imbricate group of the Pindos nappe. Synforms in the overridden Avdella Mélange coincide in position with bowed antiforms delineated in mineral form lines in the Dramal peridotite, and antiforms in the mélange occur below “tear” systems delineated by bowed synforms in the peridotite. Elongate arrows in the peridotite in the diagram at left indicate differential movement within the nappe. The diagram at right is a cross section; scale on the order of 7 km. c. Bowing of structures at Ayios Stephanos (Othris) synchronous to “hot” nappe emplacement (see text for explanation). d. “Ductile Rafting” of high-temperature peridotite fabric at the Aga Kouri ore district. Mylonitic and ductile-shear zones transport a “diapiric” fabric terrane towards the east and into a deeper part of the mantle section. The shear sense kinematics around this core zone is shown by folding along ductile margins, the bowed shape of the eastern major ore body, and smaller scale kinematic indicators. e. The Koukourelo “Ductile Highway” of the Pindos ophiolite nappe. A zone of mylonitic-cataclastic fabric peridotite extends to the northeast where it is covered by the Mesohellenic sedimentary units. The fabric strikes NE, and a parallel magnetic lineament possibly is continuous with the southern emplacement margin of Vourinos.
**b** Peridotite Form Lines

**Mélange Form Lines**

**c**

Geology and Location of "Hot" Nappe at the Ayios Stephanos Chrome Mine

1. Brittle Thrust Surface
2. Ductile-Brittle Thrust
3. Brittle Strike-Slip Fault

Mineral Form Lines

Chrome Ore Pods

Mine Pit

PHOTO: Massive Chromite Ore from zone entrapped within peridotite thrust zone. Gabbro dike includes deformed pods of ore and xenoliths of peridotite.
3.3. **Rotational deformation as evidenced by the mantle suite**

Structural observations presented here apply to all mantle rocks studied within the Mesohellenic ophiolites, with an emphasis on Vourinos due to its relatively intact section. A common method of study of mantle structures is to draw “form lines,” continuations of high-temperature foliation measurements, across the peridotite suite (Ross et al., 1980; Frison, 1987; Rassios and Moores, 2006). On a broad scale, major ophiolitic imbricates display “bowed” structural distributions of mantle form lines and outcrop patterns. Vourinos itself provides the strongest example of this phenomenon: the basal sole, over 40 km along outcrop, is arcuate in shape (Fig. 9a, upper map), and the general trend of high-temperature form lines in the overlying mantle section parallels the sole (Fig. 9a, lower map), as pointed out by Wright (1986), Grivas et al. (1993), Rassios (1994), and Gikas et al. (2007). The chrome-ore rich metalliferous zone (Grivas et al., 1993) within the mantle suite, about 5 km structurally higher than the basal sole, spans the length of Vourinos and also parallels this arcuate synformal geometry of the ophiolite.

A bowed shape is also shown by form lines in the ∼20 km² Dramala imbricate of the Pindos ophiolite above an amphibolite sole (Rassios, 1991) where the form lines delineate an antiform structure verging to the NE in the peridotite massif. Based on the morphology of folds in the sedimentary units of the Avdella Mélange underlying the ophiolite, Jones (1990) deduced a synformal structure for the identical area. Fig. 9b is a cartoon showing the coexistence of these structures, antiforms in the Dramala peridotite above the sole and a synform in the Avdella Mélange immediately below the ophiolite nappe.

Smaller scale imbricates within the Othris ophiolite to the south also show bowing structures of form lines such as those in the area of the Ayios Stephanos Chrome Mine (Fig. 9c). This area displays bowed deformation of orthopyroxene form lines within a plagioclase hedenstolite nappe overriding a harzburgite nappe. Plastic fabric elements (mainly mylonitic) are observed around and parallel to the contact zone between the nappes, suggesting that still “hot,” plastic conditions existed within the peridotite at the time of peridotite nappe imbrication. The thrust itself apparently was accommodated along a chrome-bearing dunite body that was extensively attenuated during this deformation (very little remnant dunite remaining in outcrop), concentrating chrome ores into massive boudins and facilitating a weak zone for intrusion of gabbroic dikes. In this case, the bowing phenomenon and nappe formation can be relatively dated as an off-axis deformational event in intraoceanic conditions.

Such “bowing,” including the coexistence of synformal-antiformal composites, is characteristic of many thrust nappes, and is by no means unique to emplaced oceanic lithosphere. Rock masses within such nappes are rotated in semi-circular fashion around apparent vertical axes. “Bowing” of primary structures within oceanic slabs, such as in Vourinos and in some areas of the Pindos and Othris described above, is a mode of vertical rotation affecting the internal parts of ophiolitic slabs undergoing thrusting.

3.3.1. **Rafted diapiric fabric domains**

Several research groups identified diapiric fabrics in the mantle section of the Mesohellenic ophiolites (Ross et al., 1980; Frison, 1987; Nicolas, 1989b; Rassios and Moores, 2006). Small areas dominated by blocky-shaped pyroxene fabrics, interpreted (Nicolas, 1989a) as having initiated beneath a seafloor spreading rift axis, lack overprinting by younger ductile structures (i.e. elongated pyroxene fabric or significant intergranular deformation fabrics). These domains are locally cut by brittle emplacement features such as thrust ramps and shear zones shown in Fig. 4. They range up to several km² in size within the Vourinos mantle section and down to about 0.5 km² in the Pindos. How could these rocks be translated from conditions such as those described by Ross et al. (1980) at ~120 km depth and temperatures of ~1200 °C to shallow crustal conditions without having acquired deformation structures expected to develop at intermediate depths?

Diapiric fabrics and planar mylonite zones were first documented in ophiolites within the Voidokilakos Chrome Mining District (Ross et al., 1980), Grivas et al. (1993) demonstrated that these mylonite zones, each on meter-scale thickness and traceable for distances of several hundreds of meters, serve as ductile ramp structures that cause dislocation (overriding to the NE) of dunite–harzburgite lithological contacts. Dunite bodies (including chrome ore deposits) are deformed within these mylonitic ramps at temperatures of ~900 °C (Ross et al., 1980). Harzburgites hosting these mylonite zones show no evidence of this lower temperature ductile imprint. Mineral foliations show them to be passively folded. Rassios et al. (1994) describe “tongue-shaped” folds at Voidokilakos analogous in geometry to ductile condition imbrication phenomena.

In the nearby Aga Kouri district (see inset map in Fig. 5 for location), we observe a kilometer-scale area showing a “high temperature” core, that is, a diapiric fabric zone, retaining undeformed chrome spinels. The high-temperature core zone has been translated to the NE by lateral ductile ramps with rotation of its internal fabric (Fig. 9d): these ramps are accompanied by folding of lithological contacts between the dunite and harzburgite, and by the formation of mineral stretching due to lower-temperature ductile deformation. In the case of Aga Kouri, we estimate a minimum translation distance of this hot core zone of one km, that is, from the nearest diapiric terrain following the lateral ramping structures towards the west. The translation of early high-temperature diapiric fabrics by lower-temperature ductile ramp structures can explain the lack of intermediate deformation within the core zone area. The translation of these core zones shows additional rotation due to differential lateral shear that gives the appearance of vertical rotation within small areas inside an ophiolitic slab.

3.3.2. **Mylonitic shear zones as ‘ductile highways’**

Rassios (1991) described mylonitic domains cropping out over areas 0.2–1 km-wide and up to 10 km-long within the Pindos mantle unit (Fig. 8d); similar mylonitic rocks occur even in larger areas within western Othris. These domains consist of peridotites that exhibit mineral fabrics that range from mylonitic in appearance (that is, formed at ~900 °C–700 °C), to deformation fabrics in which individual mineral grains of pyroxene are elongated to strain ratios of 5–10:1. These rocks appear in microscopic examination as long ribbons of highly strained orthopyroxene haloed by pyroxene neoblasts in a matrix of primarily olivine neoblasts. The distinctive appearance of these fabrics allows us to map them as described in Rassios and Smith (2000). The conditions of formation of these highly elongated mineral fabric domains may reach temperatures nearing the ductile-brittle boundary around 700 °C. We have traced individual mylonitic fabric domains in the Pindos for distances up to 3 km (Rassios, 1991; Rassios and Moores, 2006) and for 10 km in the Kedron area of Othris (Rassios, 1994) before they are occluded by younger sedimentary rocks or displaced by younger imbrication structures.

Mylonitic peridotite zones on the order of fifty to a few-hundred meters in thickness are common features of ophiolites immediately above their metamorphic soles (Nicolas, 1989a), as in the basal mylonites documented above the Dramala (Pindos) and the Vourinos soles (Rassios, 1991; Rassios et al., 1994). However, within the Dramala nappe pervasive mylonitic fabric zones extend from the sole upward into higher parts of the mantle section. Their outcrop pattern does not always agree with the orientation of mineral foliation form lines as shown in Rassios and Moores (2006), who hypothesized that volatile-rich zones within the mantle rocks could locally affect mechanisms of peridotite deformation. These volatiles would promote a more pronounced elongation fabric (as if at cooler temperatures), while regional temperature-pressure conditions are uniform. In general, pervasive mylonitic zones in Dramala trend N70E, although several appear to cross towards the NW, perhaps outlining incipient ductile thrust patterns.

South of the Dramala imbricate, several contiguous areas of the Pindos mantle section contain similar pervasive mylonitic fabric
domains as described above. In the Koukourello area (Fig. 9e), these mylonitic fabrics grade into complete cataclasites resulting in a fine-grained rock comprised entirely of neoblasts. This zone trends about 050° with a width of 1 km and is exposed over a distance of 8 km. Both extremities are occluded by imbrication and younger sedimentary cover, and hence the entire length of this feature cannot be determined. Using elongation of pyroxene grains (averaging about 8:1) as way to make a rough estimate, we determine the original pre-deformed length of the preserved section on the order of a kilometer or less. Zones of this nature clearly translate material within an oceanic slab undergoing ductile to brittle deformation for significant distances.

We interpret these zones of pervasive late-ductile mylonitic fabric as broad lateral ramp phenomena, informally referred to as ‘ductile highways’. These shear zones likely played a major role in lateral transport of the mantle section during the initial displacement of the Jurassic oceanic crust. As such, they have contributed to the rotation of the mantle section while still in ductile conditions.

4. Tectonic implications

Accretion of ophiolites into continental margins is a first-order tectonic phenomenon causing significant internal deformation within the ancient oceanic crust. The mode and nature of this internal deformation have been rarely documented in the literature, and generally are only considered as secondary in emphasis to primary seafloor spreading processes responsible for the igneous accretion of oceanic crust.

We constructed a composite cartoon (Fig. 10) to show the potential effect of displacement-emplacement related shear deformation within the mantle peridotites in higher levels of an oceanic slab, and in the distribution of magnetic anomalies on the seafloor as recorded by the striped patterns. Detached over a basal thrust, internal nappe deformation via formation of a “bowing” structure should result in deformation of the magnetic-stripes in a similar fashion and geometry (Fig. 10a). Ductile rafting as recognized at Aga Kouri requires that high-

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**Fig. 10.** Cartoon model suggesting the effect of ductile deformation at depth in the oceanic lithosphere-ophiolitic slab on surface pattern of magnetic stripes. At left, a block diagram of an idealized complete oceanic lithosphere with frozen igneous (pillows, dikes, cumulates) and high temperature mantle structures. Lower in the mantle section, peridotite remains in ductile field, with higher temperatures toward the base. a. “Bowing” of structures in displaced oceanic lithosphere. b. Ductile rafting as recognized at Aga Kouri. c. A “Ductile Highway” shear zone in displaced oceanic lithosphere. See text for further discussion.
temperature asthenospheric fabric is translated down-section, thus resulting in this “fossil diapiric” fabric surrounded by lower temperature ductile deformation structures (Fig. 10b). In this cartoon, the slab has been rotated to a position to allow such movement via mylonite zones as in Aga Kouri. This inferred rotation agrees in a broad sense with the pre-Cretaceous orientation of the Vourinos slab. A “Ductile Highway”, a pervasively mylonitic-cataclastic shear zone, may deflect magnetic stripes on the seafloor to a transform fault-looking pattern (Fig. 10c). Distinguishing between an ancient oceanic transform fault and a displacement-emplacement related ductile shear zone would be difficult if the two systems are parallel in orientation.

Our study of the internal structural fabric of the Mesohellenic ophiolites, particularly Vourinos, suggests that differential rotational deformation as recorded in their crustal and mantle rocks is not always related to extensional or transform fault tectonics during seafloor spreading of ancient oceanic crust. The time gap between the igneous construction of oceanic crust and its emplacement into a continental margin appears to be less than 10 million years in the case of many Tethyan ophiolites (Dilek and Moores, 1990; Robertson et al., 1991; Hacker and Gnos, 1997; Dilek et al., 1999; Robertson 2004; Dilek et al., 2005; Warren et al., 2005; Çelik et al., 2006; Dilek et al., 2008), and hence age constraints on the timing of formation of some of the brittle and ductile structures in these ophiolites are not reliable unless they are well documented by the occurrence of carefully dated crosscutting dikes and plutons. Some of the well documented rotations of normal fault blocks around ridge-parallel, subhorizontal axes or vertical axis rotations in the vicinity of fossil transform faults in the Troodos ophiolite (Morris, 1996, and references therein) are likely to hold true; however, in some other cases the cause of horizontal and vertical rotations in some ophiolites have been potentially misinterpreted within the context of paleomagnetic studies, resulting in incorrect regional scale tectonic reconstructions (Morris et al., 2002). Therefore, caution should be exercised when structural and paleomagnetic studies are undertaken in those ophiolites, which appear to have experienced widespread heterogeneous deformation and rotation during their original displacement and subsequent tectonic incorporation into continental margins.

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