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# INTERNAL STRUCTURE AND PSEUDOSTRATIGRAPHY OF THE DRAMALA PERIDOTITE MASSIF PINDOS MOUNTAINS, GREECE

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A B S T R A C T

The Dramala peridotite massif of the Pindos contains an internal pseudostratigraphy consistent with an up-section oriented to the east, across a gently-dipping, intact, petrologic moho. Chief structures are consistent with initial development of high temperature, 125/S dipping fabric (ridgecrest geometry) with rotation into, and new development of 040 fabric at lower temperatures. Both deformations continue into brittle field structures. These geometries constrain the position of the Vourinos and Dramala peridotite within a single obducting sheet: Vourinos is placed along a brittle-field leading edge, while Dramala is positioned at greater depth, along the trailing edge, where transform and decoupling deformation is well into the ductile field.

Σ Υ Ν Ο Ψ Η

Η περιδοτιτική μάζα της περιοχής Ντραμάλα της Πίνδου παρουσιάζεται μία εσωτερική στρωματογραφία με τα νεώτερα της μέλη προς ανατολάς, κατά μήκος μιας ελαφρώς κεκλιμένης πετρολογικής επαφής MOHO. Οι κυρίως δομές είναι συνεπείς με την αρχική ανάπτυξη δομών υψηλών θερμοκρασιών 125/νότια (γεωμετρία ωκεάνιας ράχης) με περιστροφή σε μία καινούργια δομή χαμηλών θερμοκρασιών 040/νότια. Και οι δύο παραπάνω παραμορφώσεις συνεχίζουν σε πεδίο ξηρών δομών. Η γεωμετρία μας αναγκάζει να δεχθούμε τις θέσεις του Βουρίνου και της Ντραμάλας στο ίδιο επωθημένο (OBDUCTION) τέμαχος.

## INTRODUCTION

The pindos Ophiolite comprises a series of deformed thrust sheets exposed over an area of 2,000 sq km (Figure 1). The highest thrust sheet consists of upper mantle peridotite that includes pyroxenite and gabbro dikes, large dunite bodies, and rare chromite occurrences (Brunn, 1956): These suggest a near-moho association of the peridotite.

Dramala is one of the largest peridotite massifs of the Pindos, with an area of 80 sq km and thickness of peridotite about 700 m. Dramala is exceptional for the Pindus in that its peridotite lacks serpentinization, and the transition

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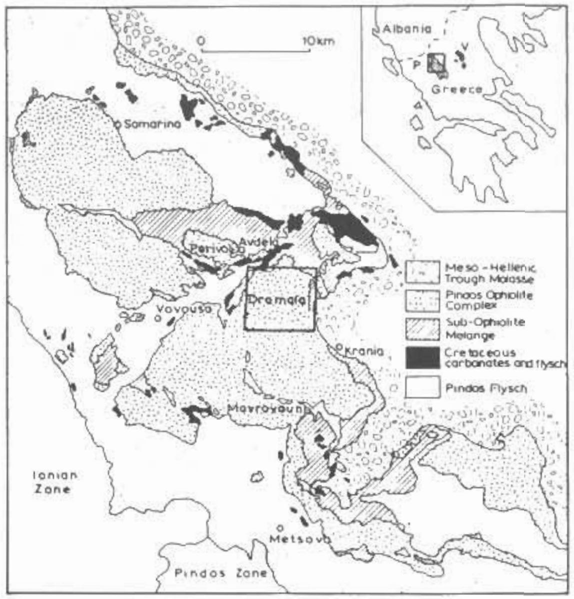


Fig. 1. Location of Dramala and general geology of the Pindos. Inset: Location of Pindos and Vourinos ophiolites.

zone through the petrologic moho is intact. Lavas representative of Triassic rifting, Jurassic ocean ridge and supra-subduction zone with island arc affinities occur in thrust sheets underlying the peridotite. Supra-subduction zone magmatics (boninites) intrude the crustal portion of the Dramala section, and more are immediately over-thrust by, and believed genetically related to, the Dramala peridotite (Kostopoulos, 1986). The full ophiolitic sequence, which includes the Dramala unit as oceanic layer 3 and 4 equivalent, is interpreted as a supra-subduction zone ophiolite (Pearce et al., 1984).

INTERNAL PSEUDOSTRATIGRAPHY OF THE DRAMALA UNIT

The north, west, and south boundaries of the map area (Figure 2) correspond to strike-slip faults (right-, right-, and left- lateral respectively) which cut through the peridotite into unerlying thrust sheets. The thrust boundary of the Dramala unit crops out on the west, north, and east margins of the area: Cumulates overide a lower cumulate imbricate along the SE margin. In situ amphibolite sole is exposed along the NW thrust boundary.

The following lithologic divisions are mapped over the massif:

a) Harzburgite with a moderate amount of dunite (0-10% of exposure) as layers or small pods crops out around the north, west, and southwest of [illegible]

b) Harzburgite similar to the afore-mentioned unit but with a small, pervasive



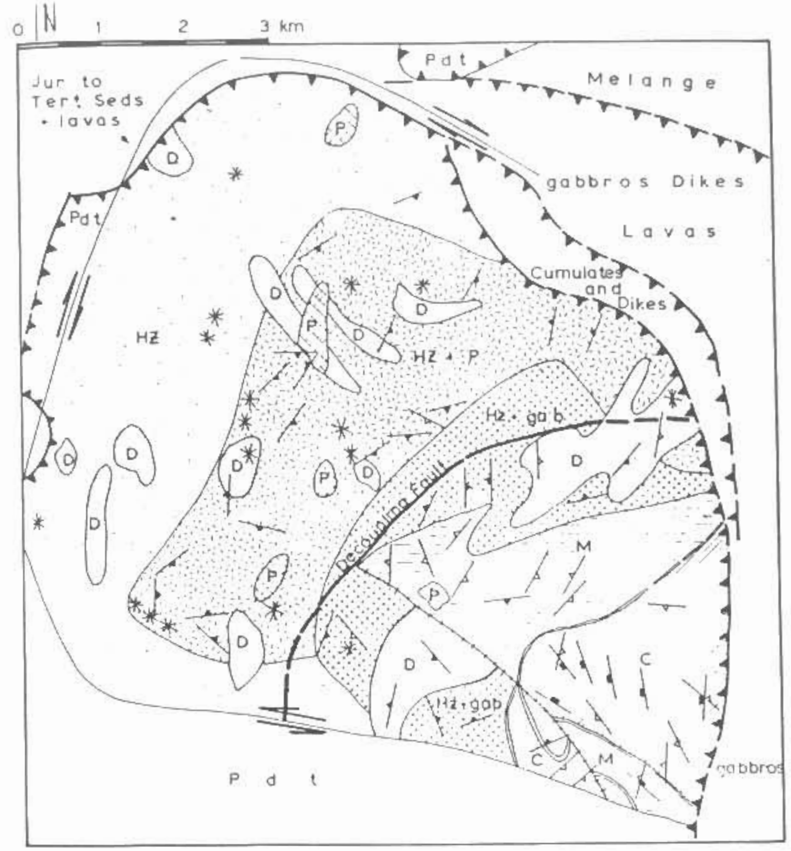


Fig. 2. Geology of the Dramala Peridotite. Legend: Pdt = undifferentiated peridotite. Hz = harzburgite. Hz+P = harzburgite with pyroxenite. Hz+gab = harzburgite with gabbro. Hz+D = harzburgite with dunite. P = massive pyroxenite. M = mixed unit. C = cumulates. * = chromite occurrence. Diagonal lines = underlying thrust sheets. Double line = limit of "petrologic moho". Arrow = strike-slip faults. Lines with triangles = thrust faults. Lines with hatchures = steep faults. Strike/dip with filled triangles = pyroxenite dikes. Strikie/dip with open triangles = gabbro dikes. Strike /dip with box = cumulate layers.

presence of pyroxenite (generally less than 1% of exposure) occurs in the center of the area, apparently overlying the "plain" harzburgite (a.,above). Most pyroxenite is present as 10 cm to 3 m wide dikes or boudins, but several massive pyroxenite bodies align NS across the area.

c) Harzburgite, as above, hosting gabbroic veins and dikes as well as pyroxenite occurs to the east and overlies the pyroxenite-harzburgite unit.

d) Harzburgite hosting a significant presence of dunite (greater than 20% of section) as deformed layers, pods, and moderate-sized dunite bodies is mapped throughout the area: A harzburgite-dunite "layer" including dunite bodies of large size crops out within the gabbro-harzburgite zone bordering the "mixed" zone (see below).

e) The "mixed" zone includes restite harzburgite and magmatic rocks with decreasing proportions of harzburgite to the east, comprising a petrologic transition between restite and magmatic sequences. The magmatic rocks consist chiefly of plagioclase dunite, pyroxenites, and gabbros, all with weakly oriented cumulate fabrics. Pyroxenite and gabbroic dikes cut the mixed zone, and a pyroxenite dike swarm (similar to that on the Aliakmon River in Vourinos, Moores, 1969) crops out within the zone. In areas with abundant magmatic rocks, the restite appears as remnant screens with sharp contacts against cumulates: Structural continuity between these screens implies no significant rotation or displacement by magmatic intrusion.

f) Cumulate magmatic rocks crop out in the SE of the map area. These include plagioclase dunite and oikocryst-bearing wehrlite, but are dominated by troctolite gabbro. In comparison to the layered cyclic-unit cumulates of Vourinos (Rassios, 1981, Rassios et al., 1983), the Pindos cumulates resemble a series of cumulate "sills", including abundant xenolithic material, finer-grained (chilled) layer margins, and magmatic flow-induced deformation structures.

The "mixed" zone is about 300-3000 m wide, and corresponds to the approximate position of the petrologic moho and transition zone of Vourinos (Jackson et al., 1975). At Vourinos, however, the "moho" contact is quite sharp, with restite inclusions only in the lower 10 m of the transition zone cumulates (harkins et al., 1980). The Pindos moho can be assumed to parallel the mixed zone/cumulate contact: This dips gently (?30 degrees) SE in the east and central parts of the area, in agreement with the orientation of major mappable units. The orientation of cumulate layers do not parallel this "moho", at least partly because of deformation (described below). The remnant of "moho" preserved may be marginal to, rather than directly below, the chief magmatic zone.

Outcrop patterns of the above units outline a synform with respect to the petrologic moho. Cumulate layers rotate into this fold. The fold axis parallels a NW-SE trending steep fault zone. The effect of deformation around this fault zone is severe: The mixed zone/cumulate contact becomes steep, and thickness of the mixed zone highly attenuated. The dunite-harzburgite layer below the mixed zone is not attenuated, but appears offset by as much as 1 km. How much of the change in structure within this area is due to the synformal deformation, the fault, or inherent lateral stratigraphic variation in the nature of the ophiolitic section (Rassios et al., 1983) cannot be estimated.

## PERIDOTITE FABRIC

The Dramala peridotite characteristically displays strongly defined mi-





Fig. 3. Peridotite fabrics of Dramala. 3a. Type 2 harzburgite (see text) hosting type 4 harzburgite. 3b. Type 3 harzurgite (white) hosting deformed dunite layer (grey). Elongate ribbons conform to 040/S dipping deformation, and dunite layer to older 120/S dipping geometry. From area of decoupling fault.

neral fabrics dominated in appearance by orthopyroxene foliation and lineation (Figure 3). By comparison, the fabric of the Vourinos harzburgite is blocky, and its orientation is difficult to measure.

Fabric Scale: One feature of peridotite mapped perhaps for the first time consists of an easily employed fabric "scale" applicable to harzburgite in outcrop, as follows: *0: No foliation observable in the field. *1: Weak foliation of blocky orthopyroxene. *2: Strong foliation of blocky orthopyroxene. *3: Plastic deformation of orthopyroxene into "augen" shapes or elongations up to 5:1. *4: Orthopyroxenes elongated in excess of 5:1, grading to sugar-grained textured mylonites.

Petrofabric evaluations crudely correlate fabric types to rock deformation mechanisms, as follows: Weak foliated fabrics represent high-temperature peridotite structures (1200 degrees, A. Nicolas, Pers. Obs.) corresponding to dia-

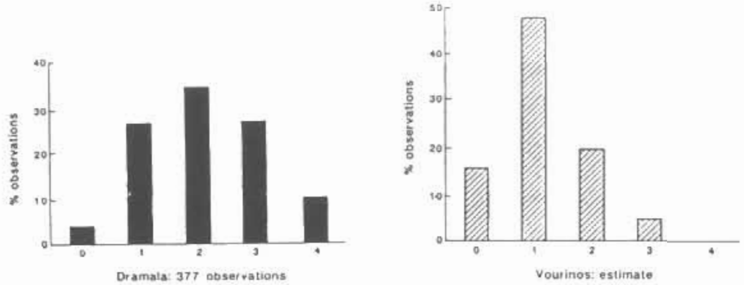


Fig. 4. Relative abundance of fabric type in Dramala Peridotite compared to the Vourinos upper mantle suite.

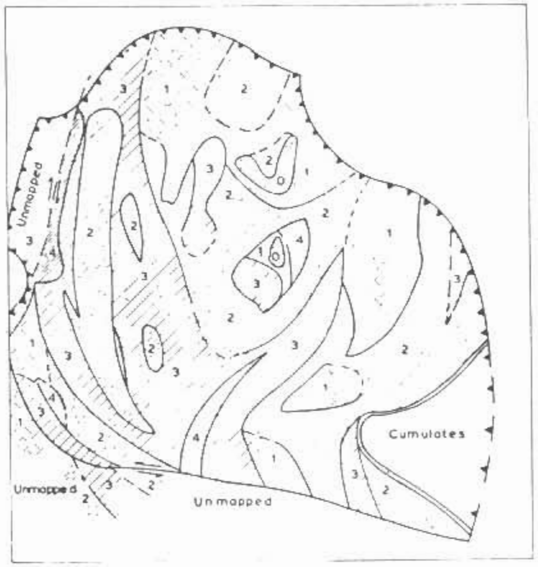


Fig. 5. Areal distribution of fabric types over the Dramala Peridotite.

piric and near-ridge fabrics of Vourinos (Ross et al., 1980, Nicolas, 1989, Nicolas et al., 1980, Nicolas and Poirier, 1976), while elongate orthopyroxene fabrics tend to lower temperature, sub-mylonitic deformation. The granulitic *4 fabric of the Pindus corresponds to mylonite development at 800-900 degrees (Ross and Zimmerman, 1982, A. Nicolas, pers. obs.). The mylonites of Vourinos (Ross et al., 1980) fall into the *3 fabric scale type (pers. obs.).

Figure 4 compares the relative abundance of these fabric types at 325 well-spaced stations over Dramala to an estimate of abundance of similar fabric types of Vourinos.

The distribution of these fabrics (Figure 5) delineate broadly north--south to N30E trending patterns. The fabric zones are not strictly gradational one into another: *3 zones contact *1 zones directly as often as they do *2 zones



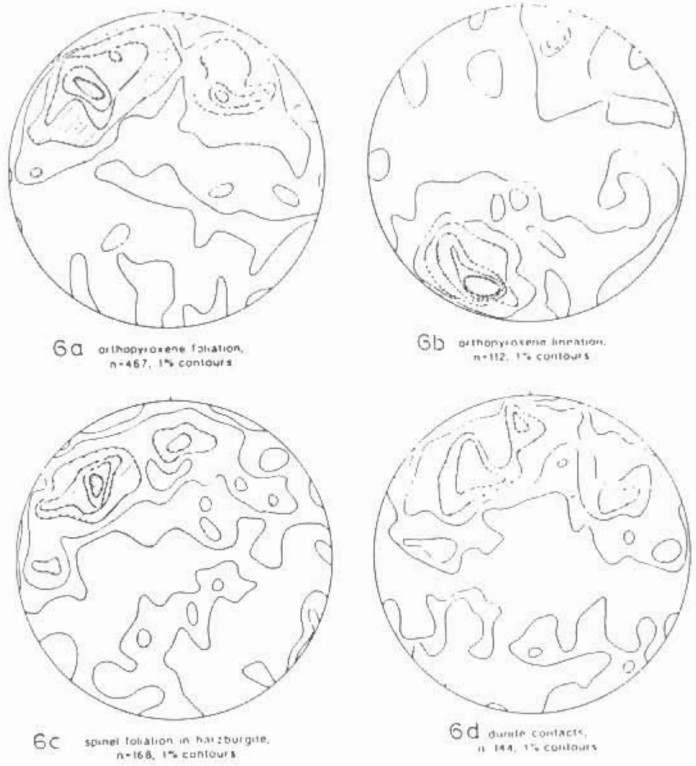


Fig. 6.

Mineral and Lithologic Fabrics: Orthopyroxene foliation measurements show two maxima (Figure 6a), one well-defined at 125/50-60S, and another with a spread around 040/50-60S. The strong concentration of orthopyroxene lineations at 020--20,30S (Figure 6b) corresponds in position to a possible intersection lineation between the two foliation maxima.

Spinel foliations in harzburgite show a strong 040 maximum (Figure 6c), and translation of the 125 maximum to nearly EW. The orientation of dunite contacts (Figure 6d) define a double maxima essentially the same in geometry as that of orthopyroxene. The foliation of spinels within the dunites (Figure 7a) show a stronger maximum at 125/50S. While spinels in harzburgite are strongly deformed in the 040 deformation, spinels in intruding dunites, mostly higher in the section, apparently retain the high-temperature foliation pattern.

The orientations of pyroxenite dikes display a pattern consistent to the orthopyroxene fabric (Figure 7b): A "spreading" maxima is centered about 040/S and a more constrained maxima at 125/S. Plots of gabbro dikes (Figure 7c) show two girdles, one with a maximum at 060/S, and the other about NS.

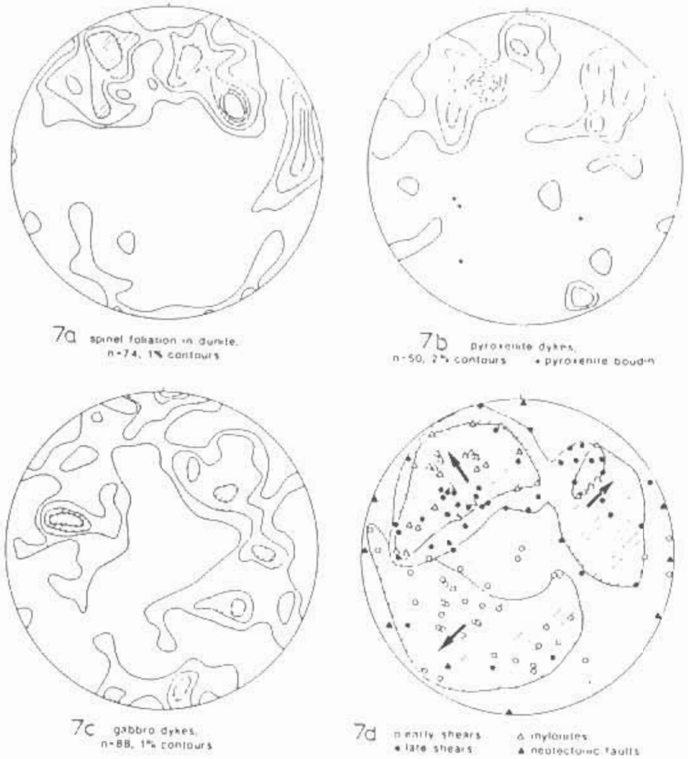


Fig. 7.

Figure 7d displays the range of mylonite and shear orientations in the Dramala massif: Mylonites and parallel brittle shears are associated with both the 125/south maximum and the 040/south maximum. Some of the mylonites within the extreme range of the 040 geometry appear to have been rotated from the 125 geometry. Others developed strictly parallel to the 040 geometry. That each set of mylonites is accompanied by shears implies that both formed at the beginning of a transition to a brittle environment, with no change in orientation of deformation. Rather than place the peridotite through two succeeding ductile/brittle episodes, both geometrical orientations of mylonites are postulated to have developed near--concurrently.

Mapped Fabrics: Across Dramala, the 040 foliation dominates the west, while the 125 foliation dominates the east. Where best represented, the 125 fabric resembles a typical but strong high-temperature peridotite fabric (types 1 and 2, above) while the 040 foliation represents a lower temperature granulation fabric (types 3 to 4, 900 degrees). At several places, a 125-oriented fabric can be traced into an 040 "zone", while elsewhere, the 040 deformation cross-cuts the 125



Fig. 8. Orthopyroxene form lines over the Dramala Peridotite. Dashed lines = 040/south dipping form lines. Solid lines = 125 form lines and 125 structures rotating to 040, with dips as indicated by boxes. Open boxes = Cumulate layering.

(Figure 3b). In the central part of the area, rocks with high-temperature fabric are cross-cut by the granulation texture.

Cumulate lamination and layering parallels the high-temperature 125 fabric, and thus preserves a "near ridgecrest" geometry. The 040 fabric can be discerned in the crustal section in several ways, including high- to low-temperature deformations, as follow: 1. Ductile deformation of mineral oikocrysts in dunite in the extreme NE of the cumulate area. 2. Intrusion of late gabbro dikes with 040/S geometry into minor ductile shear fold planes parallel to a late extension direction. 3. A weak "tectonite" fabric superposed onto cumulates (not parallel to layering or lamination). 4. Growth of amphiboles into the 040 geometry in altered gabbros. 5. A low-temperature kinking of pyroxene phenocrysts within a boninite intrusion in the cumulate section.

Figure 8 is a form line map of the two orthopyroxene fabrics. All measurements strictly parallel to the 040 and south dipping are represented as dashed lines. The remaining fabrics represent the 125/S fabric, and high-temperature fabrics rotating into the 040 fabric. The 125 fabric looks relatively undeformed in the east, apart from the area of the fault-parallel synformal axis. In the west, the form lines of the high-temperature foliation delineate shear and drag folds.

Neither form line fabric parallels the patterns displayed on Figure 5: The areal distribution of similarly deformed pyroxenes does not correspond to the major fabric trends. For demonstration, the elongate zone of highly deformed pyroxenes (type 3) in the west-center of the area (Figure 5) trends north-south, while pyroxene foliations cross the zone trending 040 or 125.

Comparison of figure 5 with the distribution of faults within the peridotite shows a surprisingly good correspondence (Figure 9): The highly deformed

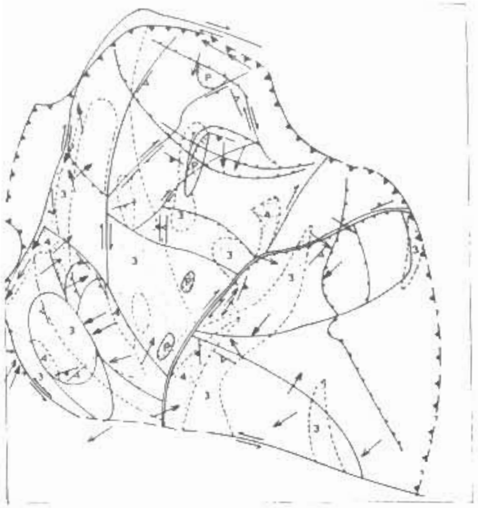

Fig. 9. Internal faults. Legend: Lines with large triangles = Thrust sheet. Lines with small triangles = Internal thrust faults. Double line = Complex decoupling fault. Single lines = Strike/slip faults. Plain lines = Complex faults. Arrows with open points = Movement as indicated by slickenslides and displacements. Arrows with solid points = Movements as indicated by ramping structures. Strike/dip symbols with filled triangles = mylonites. Strike/dip symbols with open triangles = shears. P = Massive pyroxenite. Zones labeled by numbers 3 and 4 are fabric types from figure 5.

type 3 and 4 harzburgite align with major internal thrust faults and (at the west edge of the thrust sheet) overlie the amphibolite sole. South-west over-riding internal thrusts lack corresponding zones of highly elongate pyroxenes.

The fault indicated by a double line on figure 9 parallels a major zone of *3- and *4-type fabric. Brittle movements within the fault zone offset dikes with right-lateral displacement, but ramp and slickenslide structures indicate movement to the east. Thus the fault trace is the limit of an internal thrust, the trace itself representing the trailing edge of the sheet. The correspondence of the fault trace with *3 and *4 harzburgite implies deformation initiated within the ductile field. The synform and axis-parallel fault contained in the over-riding part (to the east, Figure 2) cannot be traced into the footwall peridotites. Massive pyroxenite bodies in the footwall align as well with the fault expression. For these reasons, this fault is interpreted as a decoupling within the peridotite sheet that initiated in the ductile field.

SIGNIFICANCE

The pseudostratigraphy of Dramala, like the orientation of the petrologic moho, dips gently east, while Vourinos pseudostratigraphy is steeply west-dipping. The deformation geometry of Dramala parallels that of Vourinos, that is, Vourinos high-temperature harzburgite fabrics trend NNW and dip 50-60 degrees south (Roberts et al., 1988, Wright, 1986), and are paralleled by SW-dipping mylonite zones across which dunite bodies and chrome ores are displaced (Roberts et al., 1988, Vrahatis and Grivas, 1986). Mylonite offsets mimic ramping structures, defining overthrust to the NE. Tear fault systems at Vourinos and Dramala trend 040, but this deformation is dominantly ductile over Dramala, and brittle over Vourinos.



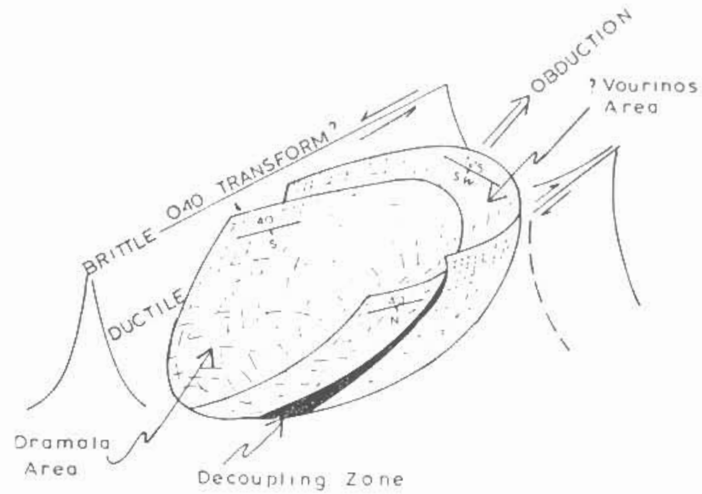


Fig. 10. Speculative model showing geometry and position of Dramala and Vourinos in a NE obducting thrust sheet.

Figure 10 is a cartoon reconstruction of the possible position of Vourinos and the Dramala peridotite within a single obducting sheet: Vourinos is placed along the leading edge, section turned near-vertical, and in an obduction environment in which tear faults are brittle field. Dramala is postioned at greater depth, along the trailing edge, where transform and decoupling deformation is well into the ductile field.

The timing of development of ductile-brittle faults coincides with transistion of the ophiolite from oceanic to obducting environments. Zones of similarly deformed peridotite (Figure 5) parallel these structures. The apparently similar geometry between deformation and the position of pyroxenite bodies, chromite occurrences, and dunite contacts suggests even a near-ridgecrest association for early compression.

The mapped trends of the fabric scale and parallel position of massive pyroxenites, chromites, and the decoupling fault imply variation in fluid content. Constant stress applied to zones with more or less fluid content might produce neighboring types 1 and 3 peridotites: High-strained zones suggest higher fluid content. Both lithologies require the presence of fluids (Dunlop and Fouillac, 1986, Johan et al., 1983). "Faster" cooling fluid-rich zones become the weak points for incipient faults. The decoupling zone would have been an appropriate weak zone for fluid circulation, or the occurrence of fluids might have facilitated development of a weak zone.

CONCLUSIONS

1. The lithologic distribution of Dramala can be equally well explained by proxi-

mity to a fluid-rich, ductile decoupling zone, or by an inherent upper mantle pseudo-stratigraphy.

2. All the structural net patterns are consistent with initial development of 120 maxima at high temperatures with rotation into, and new development of 040 fabric at lower temperatures, continuing into the field of brittle deformation.

3. The structures recognized within the Pindos ophiolitic peridotite describe the evolution of a mantle slab, magmatically active at least through early phases, through the processes of oceanic transport, obduction, and imbricate formation.

4. The implication is that emplacement strain geometry is established very early in the history of the ophiolite, and is difficult to distinguish from mantle fabrics formed at a spreading center. The same relation has been demonstrated at Vourinos (Roberts et al., 1988, Wright, in progress), and forms the structural basis of successful drilling programs targeting "blind" chrome ore bodies (Grivas pers. comm.).

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