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EMPLACEMENT TECTONISM AND THE POSITION OF CHROME ORES IN THE MEGA ISOMA PERIDOTITES, SW OTHRIS, GREECE

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ABSTRACT

Petrogenetic criteria fail to predict an economic chrome potential in the Othris ophiolite; neverless, several mines contain deposits of Al-rich chrome ore nearing three million tons combined potential. Structural mapping in the Mega Isoma massif reconciles this dilemma as follows: (i) Chrome ores originated within a harzburgite nappe now largely occluded by an over-riding nappe of plagioclase lherzolite; (ii) Emplacement of the lherzolite tectonically thinned the ore-bearing section around the petrologic moho, entrapping massive ore pods along the thrust surface; (iii) Primary oceanic structures are overprinted by ductile cataclasis that preferentially affects ore sites, and in turn by brittle emplacement structures, so that all structures appear to reconcile a single "emplacement strain" orientation. Potential ore "traps" are located along the thinned "moho" surface where mylonitic form lines rotate from the NW into conjugate shear zones.

INTRODUCTION

The peridotites of Othris crop out over an area of 900 sq km (figure 1) and host the Tsangli, Domokos, and Ayios Stefanos chromite mines (Economou and others, 1986). Less than a dozen additional chrome occurrences are known in the region. By comparison, over 750 chromite occurrences have been mapped over the 400 sq km Vourinos ophiolite (Vrahatis and Grivas, 1980), with combined chrome resources estimated at over 8 million tons of ore. In part, the dearth of occurrences in Othris follows exploration criteria for chrome in ophiolites, to whit: (i) Host ophiolites to chrome ores are usually supra-subduction zone type ophiolites like Vourinos (Pearce and others, 1984, Roberts, 1986, 1988), while

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Othris is generally recognized as a mid-ocean ridge (MORB) type ophiolite (Hynes, 1972, Courtin, 1979, Ferriere, 1982); (ii) Chrome ores are generally hosted by very depleted mantle harzburgite (Dick, 1977, Sinton, 1980, Dick and Fisher, 1984, Pearce and others, 1984, Roberts, 1986, 1988) such as is present at Vourinos (Moores, 1969), while Othris is characterized by an abundance of fertile lherzolite (Menzies and Allen, 1974); (iii) Chrome ores are restricted to ophiolitic sections originating near the position of the petrologic moho (Brown, 1980, Christensen, 1982, Evans and Hawkins, 1989, Nicolas 1989), which outcrops at Vourinos (Jackson and others, 1975), but has not been preserved within the Othris ophiolite. Neverless, the three million tons of ore represented in the Othris mines comprise significant economic interest. Having mapped the peridotites in detail, we have been able to reconstruct a tectonic sequence that explains the limited presence of chrome ores; herein we present results from the Mega Isoma massif, the most extensive lherzolite nappe of Othris in which is included the Ayios Stefanos mine and several minor chrome occurrences.

REGIONAL GEOLOGY

The Othris mountains of central Greece (figure 1) comprise inter-deformed thrust sheets emplaced over Paleozoic-Jurassic continental rocks, and overlain by Cretaceous conglomerates and limestones, flysch and Tertiary molasse sediments (Smith and others, 1975, Courtin, 1979, Ferriere, 1982). The thrust complex includes the following units: i. A volcano-sedimentary unit consisting of pelagic limestones with lavas, cherts, and gabbros of a rifting sequence (the Agrilia formation of Smith and others, 1974); ii. The Othris ophiolite complex, including dismembered upper mantle and crustal section rocks (Hynes, 1972, Menzies, 1974); iii. Locally, Cretaceous limestone and flysch formations are deformed within the nappe pile and along its margins; elsewhere, the Cretaceous is deposited over an unconformity that severely thins the nappe section, and the nappe complex as a whole has been thrust over flysch to the southwest.

The amphibolite sole of the ophiolitic unit dates to about 177 my at temperatures of 860 C at 7 kbar (Spray and Roddick, 1980). Radiolarian cherts associated with crustal levels of the ophiolite are lower Jurassic (about 200 my, Ferriere, 1982), thus constraining the time period between extension and sole formation to at least 25 my.

Ophiolitic members have been emplaced in reverse stratigraphic order, that is, from lowest to highest in the nappe pile as follows: first cherts and pillow lavas; then sheeted dikes and gabbroic cumulates; ultramafic cumulates and near-moho mantle rocks; and finally fertile mantle rocks (plagioclase lherzolite). Amphibolite sole is associated only with the ultramafic nappes; a lower temperature amphibolitic assemblage is associated with late imbrication of the nappe pile concurrent to obduction.

Based on the geometry of folding in the nappe pile, Smith and others (1974) deduced emplacement to the east to northeast. Imbricate formation and internal ophiolitic deformation of lavas of central and eastern Othris agree with this obduction direction (Rassios, 1990, 1989, Konstantopoulou and others, 1989). Eocene thrusting emplaced the nappe complex over flysch sequence rocks to

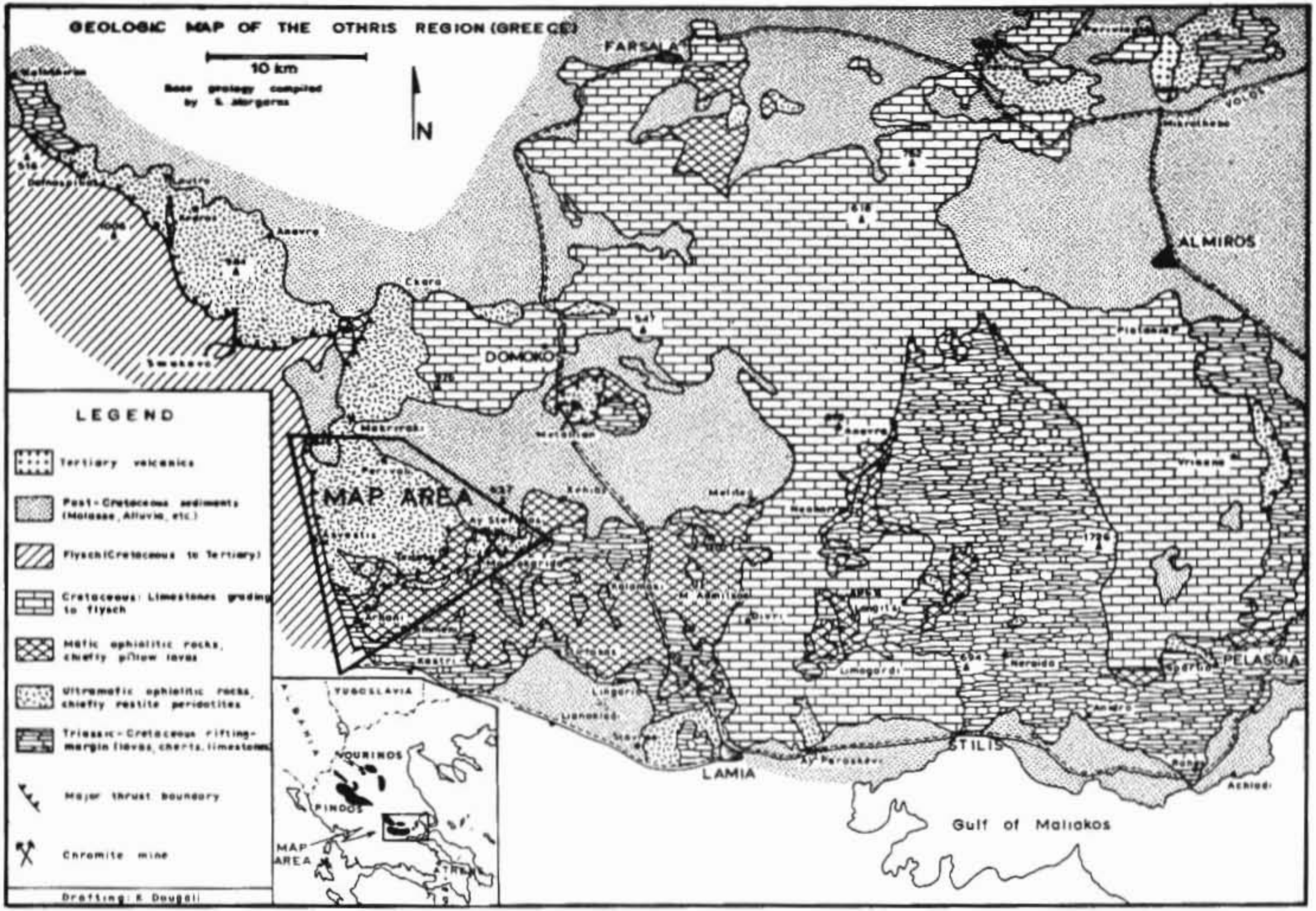

FIGURE 1. Location of study area within the Othris Ophiolite, Greece.

the west and southwest. Later tectonism includes normal faulting and synformal warping contemperaneous to sedimentary basin formation and east-west strike-slip fault systems.

LITHOLOGIC-TECTONIC UNITS OF MEGA ISOMA

In the Mega Isoma area (figure 2), we map six units (underlined, below), each corresponding to (i) a separate thrust sheet or unique tectonic position and (ii) a distinct lithologic assemblage, as follows:

Upper nappe: Plagioclase lherzolite with strong to weak preferred planar orientation of minerals dominates the highest ophiolitic thrust. Modal content of plagioclase varies between 3 and 15%. Chrome diopside-bearing lherzolite crops out within this thrust sheet near Perivoli Village, where are also found "impregnated" feldspars, segregatory gabbros and gabbroic veinlets characteristic of a "near-moho" original position (Menzies, 1974, Nicolas, 1989).

Intermediate nappe: This unit is chiefly harzburgite with moderately well-defined mineral foliations, and the pervasive presence of dunite layers 0.2 - 3m thick. Shows of chrome spinel have been located within this unit, but no promising occurrences.

Lower ophiolite nappe:

a. Mixed zone units consist of tabular dunite, gabbro, and plagioclase lherzolite bodies, 0.3-5 m thick, crudely conformable to mineral foliation. Gabbro, in addition, crops out as cross-cutting dikes and irregular "podiform" bodies. No cyclic units have been observed.

b. Gabbroic units consist of troctolite cumulates with weak lamination and layering; most of the gabbro has been overprinted by strong tectonic mineral foliations.

Nappe pile imbricate margins: Amphibolite units one to fifty meters thick and extending up to 10 km along strike outline imbricate drag folds. Constituent metamorphosed lithologies include gabbro, dunite, and diabase containing deformed jaspers and copper mineralization.

Basement ophiolitic nappes: Undifferentiated crustal sequence rocks comprise the basement formation in the area. These are chiefly higher ophiolitic members such as pillow lavas of the Mirna group (Hynes, 1972) and deformed ribbon cherts and gabbros.

All contacts between the above units are thrust faults (figure 2), and the thrust packet as a whole is cut by two sets of later faults, as follow: north-south to northeast-striking tear faults date from northeast emplacement of the thrust stacks; the second set consists of younger east-west striking wrench faults with left-lateral displacement.

STRUCTURAL EVOLUTION OF THE SW OTHRIS PERIDOTITE

Following Menzies (1974), we presume that all ophiolitic peridotite in the southwest Othis area is genetically related. Assuming an original ophiolitic stratigraphy corresponding to generally accepted oceanic models (Colemam, 1977, Nicolas, 1989), the dismemberment and imbrication of the peridotite stack proceeds (in overlapping stages) as follows:

The initial state begins at the cessation of ridgecrest extension; by this time, oceanic mantle layering parallels mineral foliation (Nicolas, 1989).

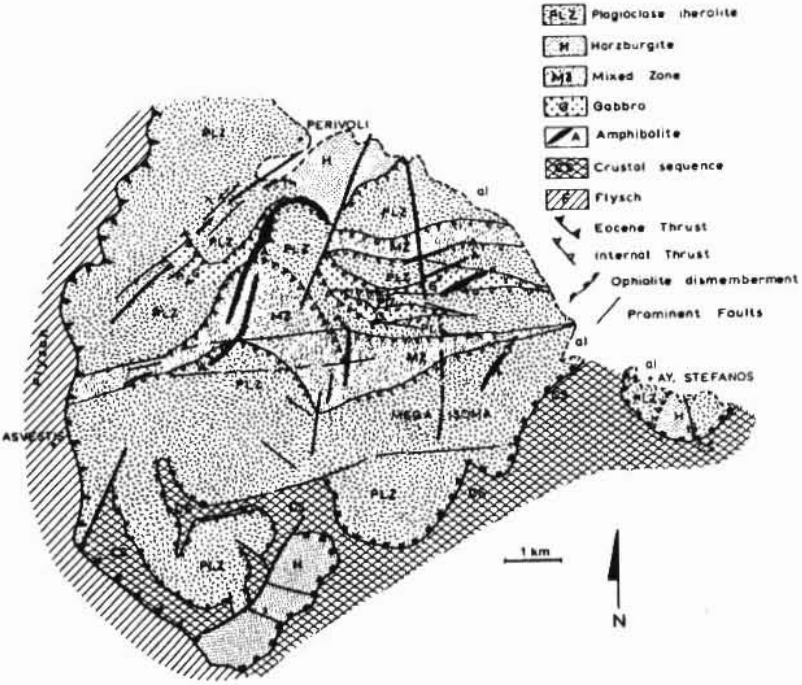

FIGURE 2. General lithologies and structures of the Mega Isoma Massif.

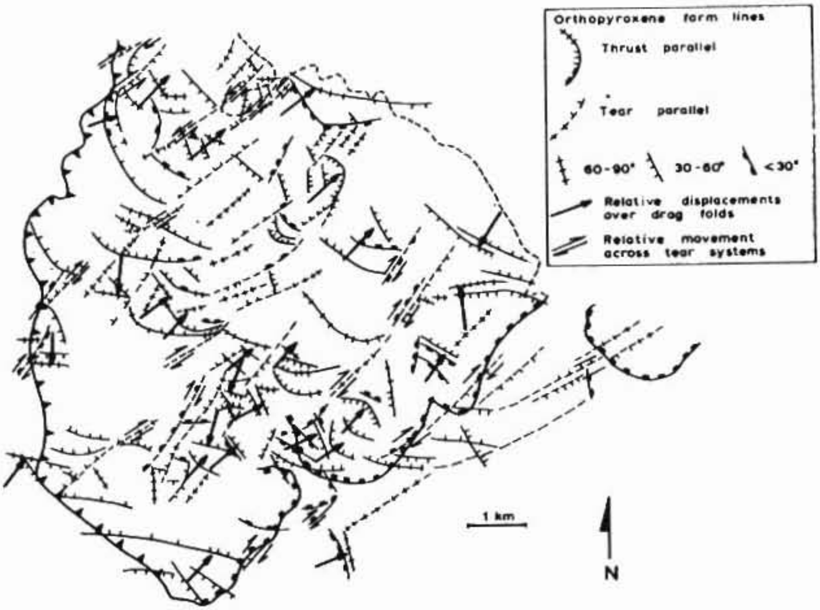

FIGURE 3. Orthopyroxene (high temperature fabric) form line map of Mega Isoma.

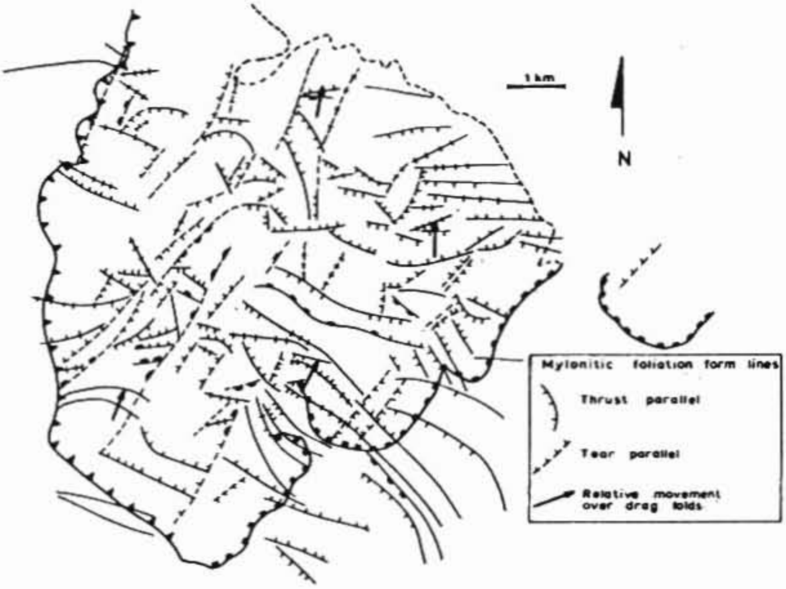

FIGURE 4. Mylonitic (intermediate temperature near ductile/brittle boundary) form line map of Mega Isoma.

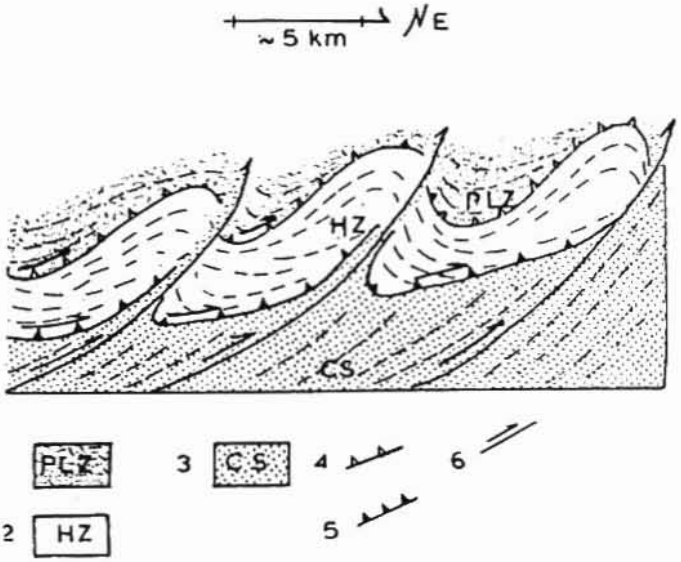

FIGURE 5. Schematic diagram of formation of amphibolite-lined imbricates. Legend: 1 = plagioclase lherzolite nappe; 2 = Harzburgite nappe; 3 = Ophiolitic crustal sequence "basement"; 4 = Thrust of lherzolite over harzburgite; 5 = Thrust of peridotite nappes over crustal sequence; 6 = Amphibolite-lined imbricates. Dashed lines trace conformable ophiolitic structures (peridotite form lines, sedimentary layering, etc.)

I. The earliest disruption to ridgecrest geometry occurs at high temperatures as layering and foliation rotate, before actual rupture, to orientations parallel to the obduction geometry: This deformation (figure 3) reconciles shear via (i) drag folds with axial foliation "ramping" towards the northeast, and (ii) ductile conjugate shear systems.

II. As temperatures fall, deformation grades to ductile cataclasis (figure 4) of similar strain geometry to the high temperature deformation.

III. Actual ophiolitic detachment within the oceanic section is accompanied by formation of amphibolitic sole; elsewhere (e.g. Oman, Nicolas, 1989, Pindos, Rassios, 1990) sole parallel cataclasis imprints peridotites in a thin zone above the sole. Neither amphibolite sole nor sole-parallel cataclasis are preserved in the Mega Isoma area.

IV. The detached slab undergoes dismemberment, creating a reverse stratigraphic order to the ophiolitic section. In the case of Mega Isoma, dismemberment initiated in semi-ductile conditions as indicated by the following: (i) remnant ductile structures (folds and cataclastic fabrics) are abundant along the contact between lherzolite and harzburgite nappes, and (ii) gabbro has been intruded into and around the position of the lherzolite/harzburgite nappe contact, and plastically deformed between these nappes.

V. The nappe pile is itself imbricated, each imbricate cutting from the crustal unit nappe at the base of the pile into the over-riding near-moho and mantle peridotite nappes. These imbricates are lined by amphibolite units containing a mix of low-amphibolite facies ophiolitic material: the metamorphic grade indicates relatively high temperatures in the area of the imbricate fronts. The nappe pile imbricates initiate from northeast to southwest, such that succeeding over-riding imbricates deform the trailing end of north-easterly imbricates (figure 5). By the time of formation of the amphibolite units, the ophiolitic rocks have passed entirely into brittle field.

VI. Amphibolite-lined imbricates are themselves parts of greater-sized brittle imbricates, traced by brittle shear zones (figure 6), and accompanied by southwest dipping ramp structures.

VII. The nappe pile is thrust to the southwest over flysch, generating younger sets of northeast-dipping ramps, with much internal displacement accomodated by parasitic movement along pre-existing tear systems through the nappe pile.

VIII. Following thrusting over flysch, the ophiolitic nappes deform as a coherent block along with the flysch and regional basement (figure 7).

CHROME ORES OF MEGA ISOMA

Chromite shows are pervasive to the harzburgite unit, but ores crop out at only two localities, Ayios Stefanos and Arhani, each along the base of the lherzolite nappe (figure 6).

Chromite shows crop out in dunite layers within the harzburgite unit; they consist of disseminated euhedral chromites in layers less than 0.5 m thick, and minor schlieren occurrences including fist-sized lumps of massive ores at fold axes. All shows occur in the northwest of the area where the host harzburgite nappe

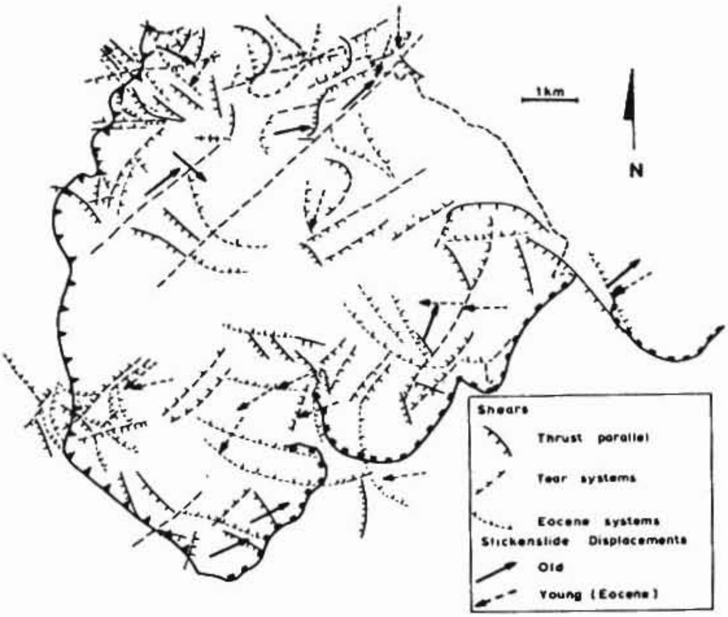

FIGURE 6. Shear systems and slickenslide directions of brittle movement over the Mega Isoma massif.

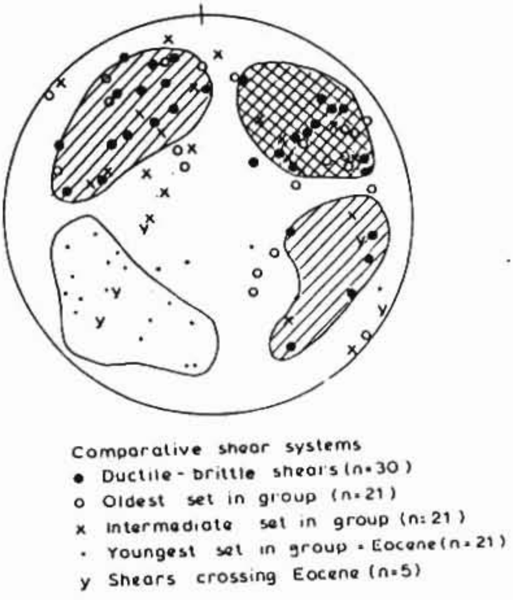

FIGURE 7. Comparative shear systems of Mega Isoma. Ductile shears are assumed to by oldest wherever measured. 21 shear sets were measured in which cross-cutting relations clearly define three generations of shears.

is best preserved and in close proximity to the thrust contact with over-riding plagioclase lherzolite.

The Arhani occurrence consists of small pods of massive ores exploited along the thrust contact of harzburgite with a crustal sequence imbricate where structures turn into a major tear system: No remnants of host dunites have been preserved.

Ayios Stefanos massive ore pods are as large as 4 m diameter, and crossed by irregular gabbro dikes and veins: Xenoliths in these gabbros include dunite and lherzolite pods. The hanging wall to the ore zone consists of plagioclase lherzolite, and the footwall is harzburgite. Gabbro is found only within the ore zone, and apparently intruded the thrust contact itself. Mylonitic fabrics within the ore pods and along the nappe contact suggest that the ore zone accomodated significant ductile deformation preceeding intrusion of the gabbros; the latter share in the brittle phase deformation along the thrust contact. Ore pods trend 040 (parallel to the emplacement direction) within an ore zone that strikes at 080, and trails into an 025 striking right-lateral tear system.

Several occurrences of massive magnetite crop out within the massif (previously mapped as chrome deposits, (Marinos and others, 1962); these share similarities in tectonic position to the Ayios Stefanos ores in that they are associated with gabbroic intrusions near the contact with the lherzolite nappe, and crop out near major tear systems.

SIGNIFICANCE

Our structural study explains the anomalous presence of important chrome resources within a terrain dominated by fertile upper mantle rocks in the following ways:

Ore deposition can be attributed to generation of magma that resulted in depleted harzburgites following the concensus model (Pearce and others, 1984, Nicolas, 1989): These harzburgites are poorly represented in Othris, being occluded by the over-riding lherzolite nappe. Where in outcrop, dunite bodies and chromite shows are pervasive, and similar in appearance to the more chromite-poor areas of Vourinos.

The petrologic moho of the Othris ophiolite itself accomodated ductile to brittle dismemberment of the oceanic slab. Remnants of "near moho" harzburgite and impregnated lherzolite sections crop out near their contact.

Massive ore pods were apparently entrapped along the detachment surface at the moho: thus, the mechanically competent ores suffered the brunt of deformation ranging from ductile to brittle field. Form line maps (figures 3, 4, and 5) trace the history of this deformation from high- (mineral foliation, mantle layering, figure 3) through intermediate- (mylonitic cataclasis, figure 4), and low-temperatures (brittle shears and faults, figure 5). In all phases of deformation, form lines parallel the emplacement front and tear systems. Ore localities coincide to positions where southwest-dipping form lines turn into northeast striking tear systems. Of the three maps, cataclastic structures correspond most precisely to the position of ore bodies.

CONCLUSION

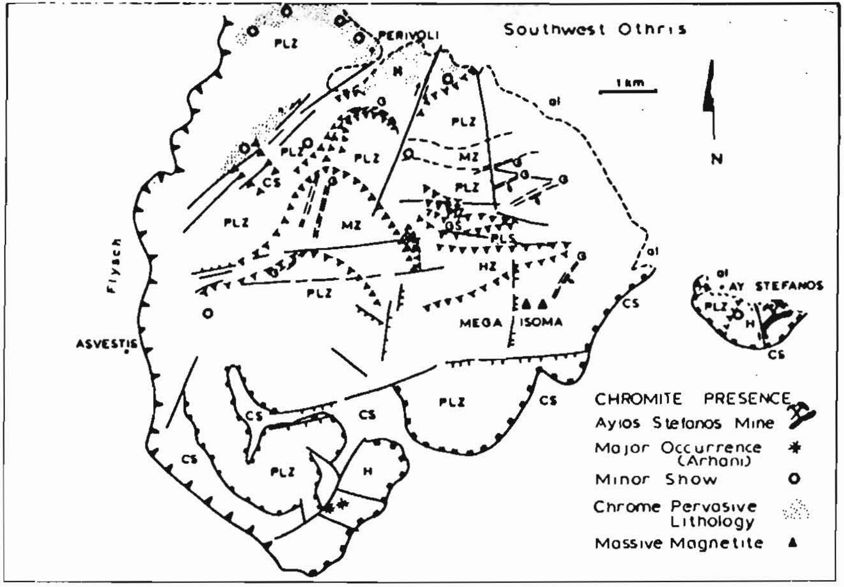

FIGURE 8. Chromite and magnetite localities of Mega Isoma.

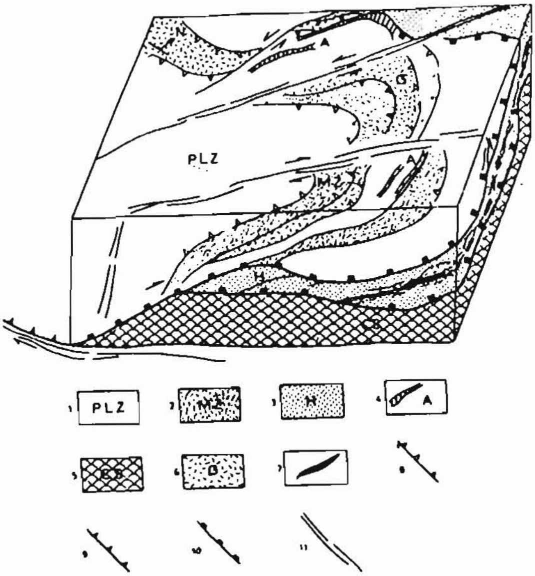

FIGURE 9. Block diagram illustrating structural history and position of ore traps of the Mega Isoma Massif.

Legend: 1 = Plagioclase lherzolite; 2 = Mixed zone; 3 = Harzburgite; 4 = Amphibolite zones; 5 = Undifferentiated ophiolitic crustal section rocks; 6 = Gabbro cumulates; 7 = Chrome ore bodies; 8 = Internal thrusts; 9 = Basal thrust to ophiolitic nappes (onto flysch); 10 = Tear fault systems.

Chrome ores of Mega Isoma (figure 9) are found in structural "traps" relating most closely to cataclastic detachment tectonics. When these "traps" are preserved along the tectonically destroyed petrologic moho, they may be ore bearing; elsewhere, they are sterile.

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