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STRUCTURAL CRITERIA IN LOCATING CHROMITE ORES: EVIDENCE FROM THE RIZO DISTRICT, VOURINOS OPHIOLITE, GREECE

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ABSTRACT

The Rizo chrome ore district of North Vourinos contains fine-grained low-grade chromite ores of schlieren, disseminated, massive, and nodular types. The ore zone itself is poorly exposed and highly sheared; potential continuations of the surficial ore deposits cannot be predicted from standard host rock mapping.

A structural evaluation of the area suggests subsurface continuations of Rizo ore bodies to the west of the exposed ores based on the following observations: Fold axes of schlieren ore parallel mineral lineation of host rocks trendind around 270° and impart an appearance that down-dip ore continuations would lie west of the surface occurrence. The ores themselves coincide with the position of Z-fold hinges formed during dextral shear around the ore zone. This dextral shear resulted in deformation of host dunites to east-west trending tabular bodies.

The presence of ductile structures of low temperature (950-750°C) plastic deformation are inferred from rotations of high-temperature fabrics into lower-temperature ductile shear zones: The intense brittle shearing and faulting in these zones obscures observations of these ductile structures themselves.

All structures present formed within a single strain orientation, apparently during a continuous evolution of deformation from plastic through brittle conditions. All stages of deformation have strongly imprinted the chromite ore. A drilling program based on these structural criteria has subsequently confirmed the predicted subsurface continuations west of the exposed ore zone.

INTRODUCTION

The metalliferous zone of the Vourinos ophiolite is a tabular feature about 2 km thick that crosses the mantle section of the complex parallel and 5 km west of the basal thrust: The Rizo chrome ore district crops out at the southeastern extreme of this

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zone in the North Vourinos region (figure 1).

The major ore body of Rizo is exposed within the central part of the district, and contains reserves of 400,000 tons (Psihoyiopoulos et al., 1978). The ores are poor in quality, grading between 5 and 25% chromite, and very fine-grained. Exploration in the area is hampered by sedimentary cover and the highly fractured and faulted nature of the ore bearing rocks. More than 80% of the ore district is covered by an overlapping sheet of alluvia up to 5 meters thick: These sediments occlude host rocks to such an extent that structures can only be discerned in a few stream sections and trenches that penetrate the sediments.

This study aims at undestanding the tectonic history of the area and the effect of incremental deformation on the ores and host rocks, in order to structurally predict the continuation of the known ore zone of central Rizo.

LITHOLOGY

Mappable lithologic units of the studied area are as follows:

i) Restite hartzburgite is the dominant lithology of the district. Its characteristic texture is porphyroclastic granoblastic, and its phase chemistry is similar to other harzburgites of Vourinos (Frison, 1987). The harzburgites of Vourinos are interpreted to represent a residue remaining after a high-degree of partial melting of the upper mantle (Beccaluva and others, 1984; Pearce and others, 1984; Roberts, 1986; Paraskevopoulos and Economou, 1986; Konstantopoulou, 1990). Harzburgite at Rizo is nearly always pervasively sheared and fractured, and at only a few outcrops are large coherent blocks preserved (figure 2).

ii) The exclusive hosts to chrome ores at Rizo are dunite bodies included in dunite-harzburgite alternation zones. Each zone strikes east-west, and ranges from 50 to 150 meters thick in outcrop. Individual dunite layers in the alternation zones are typically one centimeter up to 20 meters thick. The largest dunite body of the Rizo district is 80 by 300 meters and crops out within the alternation zone of the central part of the district (east of the area mapped, figure 2). Alternation zones have been mapped as dunites, because hartzburgite layers in them are ussually less than 5 meters thick and the relative proportion of hartzburgite less than 35%. A second set of dunites are present within massive harzburgite adjacent to alternation zones: These are sheared lenses 10 to 50 cm thick with no chromite in them. What spinels are present are fine-grained with no preferred orientation.

iii) Coarse-grained pyroxenite dikes, ranging in thickness from several centimeters up to 10 meters, are abundant over the district constituting about 10% of the mantle section volume. The dikes crop out more commonly near and about parallel to contacts of dunite with harzburgite. Elsewhere, the dikes show no systematic orientation.

iv) All chromite ore textures are present in Rizo area. Individual occurences include schlieren, disseminated, massive and nodular ore types. The chief ore zone itself, contained within an alternation zone of the central area, consists of schlieren layers, with small pods of massive ore. Spinels in ore are fine- to medium-grained and irregular in shape. Chromite has been severely deformed during emplacement of the ophiolite.

The degree of serpentinization varies with distance from shear and fault zones: Massive sheared serpentinites coincide in position with fault zones, while at distances of 2-3 meters, host rocks contain as little as 5% serpentine.

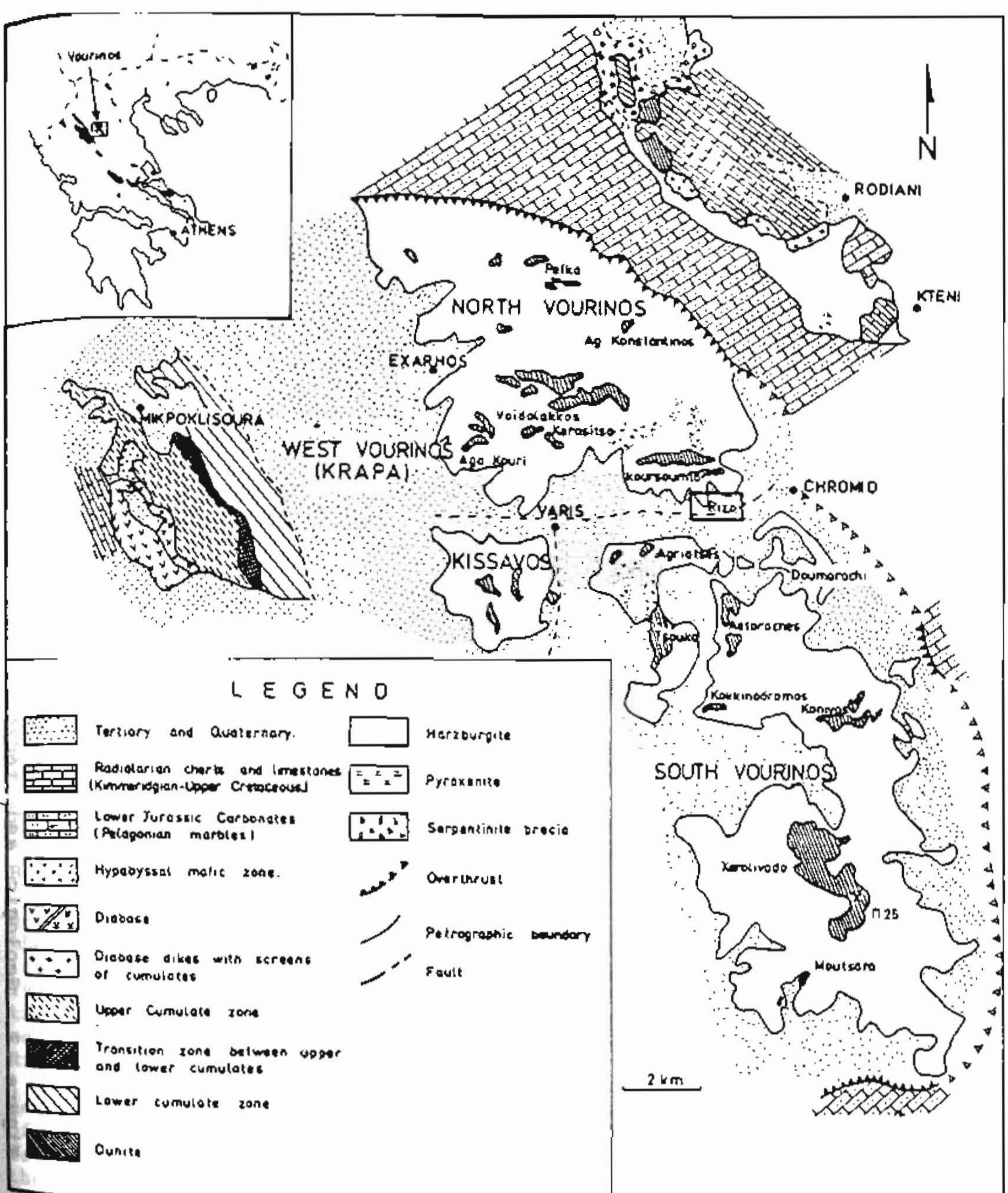

Figure 1. Simplified geological map of the Vourinos-Rodiani ophiolite complex, showing the distribution of lithologies and the position of Rizo area.

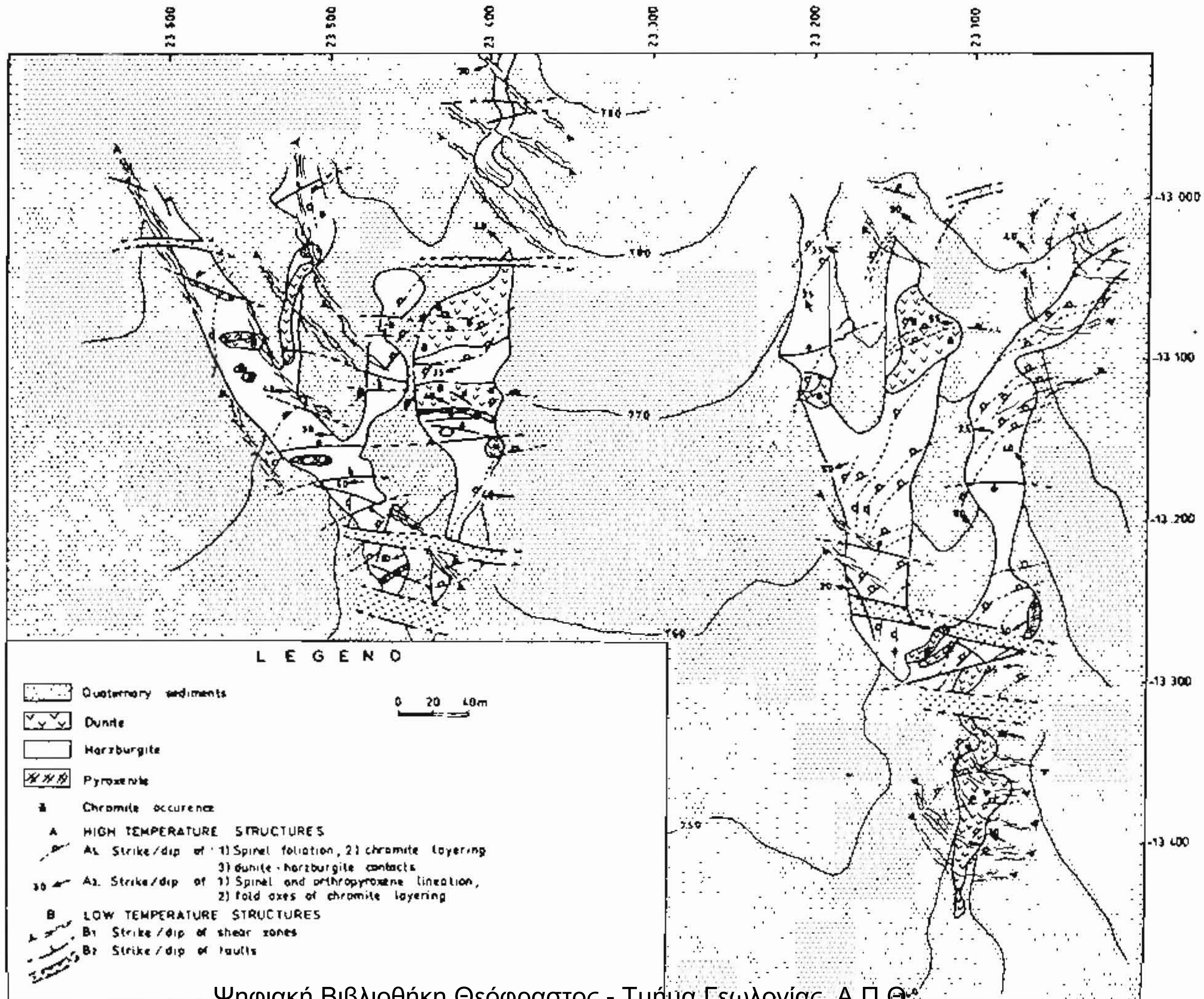

Figure 2. Geologic and tectonic map of the Rizo ore district
(modified from 1:1000 scale

STRUCTURES OF THE RIZO DISTRICT

Structures representative of high- and lower-temperature plastic deformation at Rizo are obscured by a strong overprint of brittle structures. The sequence of deformation is incremental representing a continuous evolution from plastic to brittle structures within a single strain orientation.

A. Structures Related to High-Temperature Plastic Deformation

Dunite-harzburgite contacts, chromite layering, mineral foliations and lineations and the folding of schlieren ore represent the highest temperature structures apparent in the area (1250-1200°C, Nicolas, 1989). Spinel fabrics show weak preferred orientations of flattened or elongate spinels. Orthopyroxene in harzburgite is blocky, and no consistent orientations are obtained.

Spinel foliation in host rocks (dunite and harzburgite) as well as in chromitite ores define antisymmetric folds with dominant limbs at 20-60/25-60 NW and shortened limbs at 80-100/25-50 N (figures 2, 3). Folds are best defined in the alternation zones and within chromite ores themselves.

Spinel lineations in the host rocks (alternation zone or surrouding massive hartzburgite) trend 250-320 with 30 degrees plunge to the west (figure 3). The axes of folded schlieren ore generally have similar trend to the spinel lineations. Dunite-harzburgite contacts within the alternation zones strike 20 to 60E with 40 to 60 degrees northwest dip. Figure 3 details the macrofabric relations of the Rizo district. Early structures such as spinel foliation and ore layering broadly parallel dunite-harzburgite contacts in the alternation zones (that is, strike northeast). Pyroxenite dikes are displaced by faults and shears locally, but in general are also parallel to the early structures.

B. Structures Related to Low Temperature Plastic Deformation

Typical low temperature (1000-800 °C, Nicolas, 1989) plastic deformation structures such as mylonite zones are not observed in the Rizo area. Mylonitic structures have been observed at Voidolakkos (Ross et al., 1980; Roberts et al., 1988; Grivas et al., 1990) and Koursoumia (Konstantopoulou, 1992) districts, in a distance of 10 and 3 km from Rizo respectively. However, ductile and semi-brittle (Ross and Lewis, 1989) structures can be inferred at Rizo.

The mapped fabric patterns (figure 2) indicate dextral shear accommodated by brittle deformation within the main dunite bodies of the area. Dextral shear also explains the geometry of Z-type folds within the ore bodies as well as mineral fabrics parallel to those fold planes. Thus, we deduce that shear initiated in low temperature plastic conditions, and persisted through decreasing temperatures into brittle conditions.

C. Brittle Deformation

Brittle shears and faults dominace the appearance of the Rizo area. Shears and faults geometrically belong to several systems.

C1. Shears

Two sets of shears are observed in Rizo area, both formed concurrent to late stages of emplacement of the ophiolite.

The first system strongly imprints thin serpentinized dunites in harzburgite. These dunites hosting parallel shear zones strike

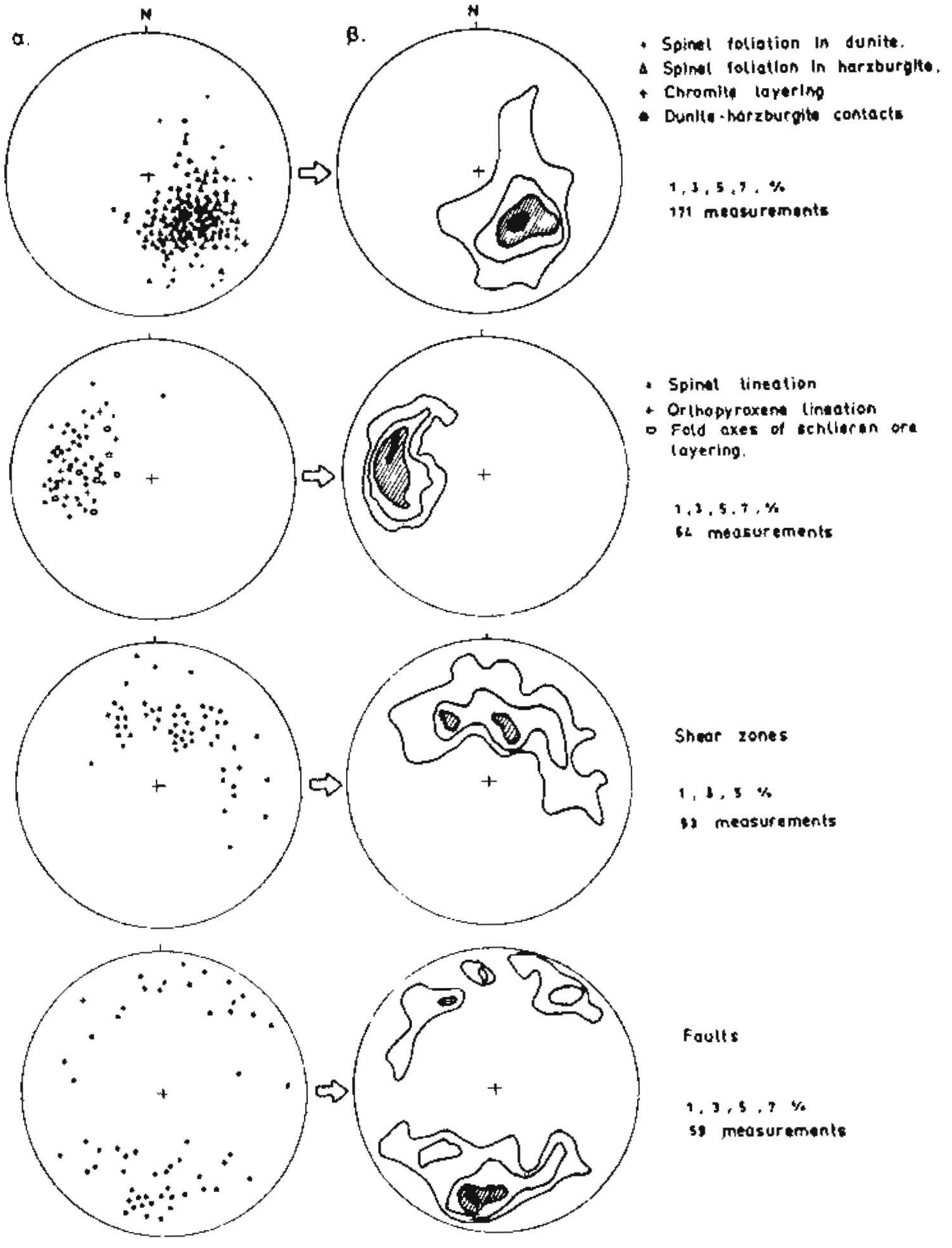

Figure 3. Stereonet data of the Rizo district fabric elements.

0-40E with 40 degrees northwest dip. Shearing does not penetrate the surrounding, more coherent blocks of harzburgite. Minor shear structures within these zones as well as the sense of displacement between the harzburgite units indicate over-riding movement to the northeast. The sheared dunites, thus, form the soles of harzburgite imbricates.

The second set of shears penetrates similarly both dunite and harzburgite, and is particularly intense over several outcrops. These shears imparts a "schistose" appearance to the rock: Locally the schistosity is constrained to serpentinized rocks, but elsewhere relatively fresh rocks demonstrate a "gneissic" compact planar fabric. These relations suggest that these shears initiated near the ductile-brittle boundary. These shears strike northwest to north-south (140-180 with 15-30W dip ,figures 2, 3). In the south Rizo area, these shears appear folded, rotating from their dominant orientation to 80-115/30S (figure 2).

C_2. Faults

Because of the extensive sedimentary cover the sense of movement and the displacements along major fault zones can not be measured. Several offsets can be estimated from displacement of pyroxenite dikes or schlieren ores. The orientation of fault planes exposed in limited outcrops define three main systems, as follow:

(i) A northeast striking system: 020-060/60-80N, with some reverse dips;

(ii) An east-west striking system: 080-120/70-85N, with some reverse dips;

(iii) A northwest to north-south striking system: 130-180/60-80E, with some reverse dips.

Faults of the first system appear to be reverse faults with less than one meter displacement. The second system dominates the area and comprises a sequence of stepped brecciated fault zones, each zone ranging in thickness from a few centimeters up to 10 meters. Small faults parallel to this system show minor left-lateral displacement. However, these may be parasitic faults, antithetic to major right-lateral fault zones. Fault zones of the third system are less wide than those of the second system. They are chiefly right-lateral strike-slip faults, with much greater displacement compared to the E-W trending faults.

DISCUSSION

Previous work has described the geometry of fabric elements in various mining districts of the Vourinos ophiolite. Regardless of petrogenesis, chrome ores tend to be trapped in emplacement structures such as: 1) thrust parallel mylonite zones (Grivas et al., 1990), 2) Z-folds produced by ductile shear (the structure described herein), 3) tear parallel faults produced by ductile constriction (Rassios et al., 1990). Structural studies detailing emplacement strain have located "blind" ore deposits, and are being used as on-site guides for drilling and location of high potential terrain in reconnaissance exploration.

Figure 4 reconstructs the successive stages of deformation of a chromitiferous dunite body (formation at stage I) in a Rizo-type structural environment. We consider deformation to the ore body incremental, such that stages overlap in time. Plastic structures relating to mantle flow that we indicate in stages II and III (figure 4), are not preserved in Rizo, but deduced from considerations

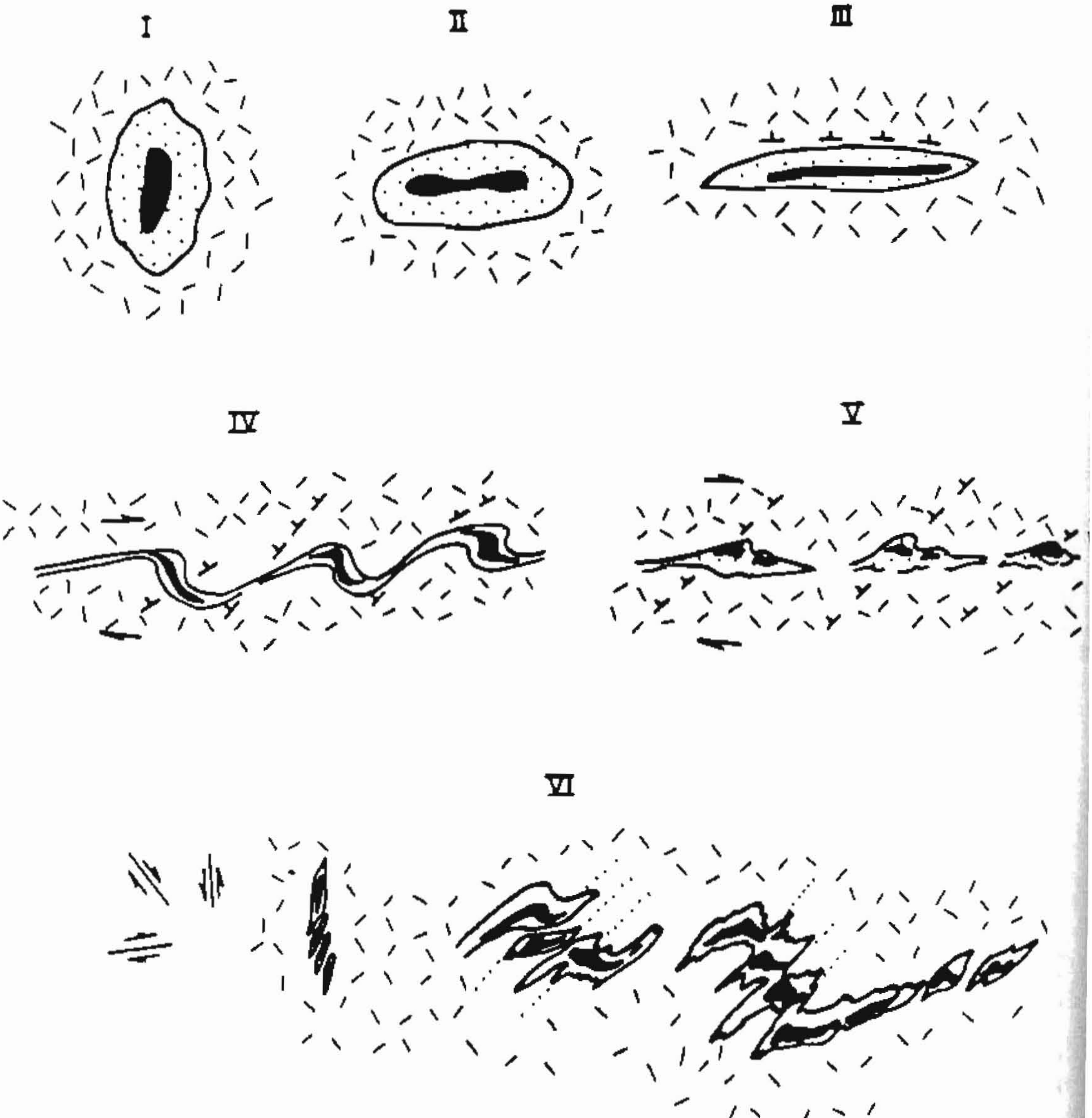

Figure 4. Structural evolution of the Rizo ore bodies:
I. Dunite and chromite formation within the upper mantle.
II, III. High-tepmerature plastic deformation resulting from mantle flow.
IV, V. Low-temperature plastic to semi-brittle deformation resulting in folding of dunite and chromite and re-orientation of spinel grains parallel to the fold axes.
VI. Brittle deformation (thrusts and faults) displaces the initia dunite and chromitite bodies.

of regional structures of Vourinos (Nicolas, 1990; Frizon, 1987; Ross and others, 1980). The major deformations affecting the present position of the ore bodies are the following:

Stage IV represents the initiation of ductile displacements along the deforming margins of a dunite body within massive harzburgite. Shear stress is preferentially resolved by plastic deformation along these margins and within the dunite because of the higher plasticity of dunite relative to harzburgite host (Carter 1976). The intensity of shear stress varies from place to place within the main shear zone. Thus the shear zones bordering the dunite bodies of Rizo generate formation of many subzones, each of which reconciles shear stress at variable rates. This shear deformation results in elongation and subsequent folding of the dunite body as well as concurrent re-orientation of spinel grains parallel to axial planes of Z-type folds. It seems likely that all the high-temperature structures that we observe in Rizo today date from this stage of deformation.

Within dunites, deformation consistently appears more intense compared to that shown in surrounding rocks. Mass movement (especially of olivine) in axial regions of folds in dunite bodies tend to "concentrate" chromite ores in the hinges of folds within dunite bodies (fig. 5b). Individual chromite layers within the ore zone are conformable to local foliation planes, but the main ore zone do not parallel component layers, but consist of Z-fold sets trending east-west within the parallel dunite host. Thus, ore zones of Rizo are east-west trending structures with strong northeast striking overprinted structures. Mineral lineations and fold axes of schlieren ore, plunge to the west, implying a continuation of the ore zone to the west.

Intrusion of pyroxenite dikes parallel to axial planes of this early fold system indicates the concurrence of magmatism to this deformation. Thus, pyroxenite dikes have escaped plastic and ductile deformation. They only have been displaced by shears and faults (stages V and VI, fig.4).

Near the ductile-brittle boundary, shear zones and faults develop in parallel and overprint earlier structures. The thin intensely sheared and fractured dunites within the harzburgite facilitate over-riding movement between hartzburgite blocks with continuing deformation. At about stage V of figure 4, dextral strike-slip faults develop, accommodating further the shear stress responsible for the east-west elongation of the dunite body. Individual faults in this system show either left- or right-lateral offsets relative to their position within dextral shear planes.

The set of northeast striking (020 to 060) are reverse faults with minimum offset, accommodating minor compression towards the core of the emplacement movements of the ophiolite towards the NE (050).

Northwest-striking (140/20SW) brittle shears also form as a direct result of emplacement of the obducted slab towards the northeast (stage V).

Combined strain elements result in the form of a dunite body as portrayed in figure 4, stage V. The ore-bearing alternation zones of Rizo consists of ductile-brittle imbricates of the dunite-harzburgite margin. The orientations of the imbricates parallel that of early folding within the dunite. The form and distribution of chrome ores are affected in all stages of deformation undergone by the host rocks of Rizo.

Figure 5a,b depicts a simplified model of the central Rizo mine which is applicable to the regional macrostructure of Vourinos as well. In this model, the long axes of ore bodies trend east-west.

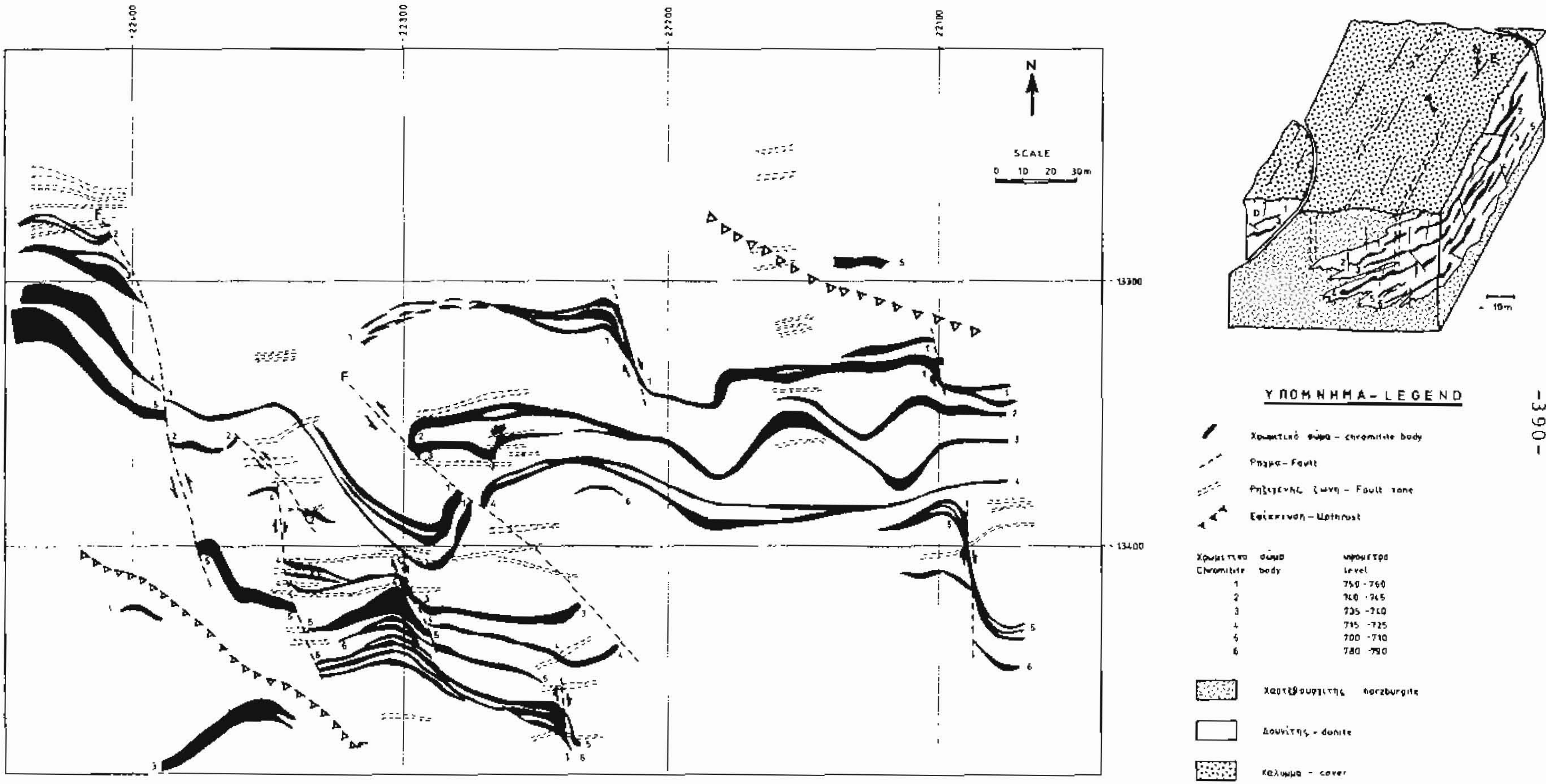

Figure 5. a) Distribution and form of the chromitite ore bodies of the central Rizo [illegible] development of the "alternation zone" of central Rizo and the relative position of the chromitite bodies of figure 5a (konstantopoulou, 1990b).

A significant displacement of 'ores is noted along 140 striking, thrust parallel, fault systems. Internal thrusts parallel to the basal thrust of the ophiolite imbricate. The multifolding and displacement of the ore bodies by minor faults is evident even in the scale of an outcrop.

Macrostuctures in the Rizo area suggest that the ore zone of the central Rizo should continue beneath sedimentary cover to the west. While similarly deformed, alternation zones of Rizo may represent bodies formed in independent magma chambers within the upper mantle. Petrologic evidence confirms the existence of multiple magma chambers within northern Vourinos (Konstantopoulou, 1990, Harkins and others, 1980.) Each ore-bearing dunite body in the deformational setting similar to that of Rizo (Z-fold system) ought to show similar structural exploration criteria.

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REFERENCES

BECCALUVA, L., OHNENSTETTER, D. and OHNENSTETTER, M. (1979). Geochemical discrimination between ocean floor and island arc tholeiites: application to some ophiolites Can. Journ. Earth Sci. 16, 1874-1882.

CARTER, N.L. (1976). Steady state flow of rocks. Rev. Geophys. Space Phys., 14, 301-360.

GRIVAS, E., RASSIOS, A., KONSTANTOPOULOU, G., VACONDIOS, I., and VRAHATIS, G. (1990). Case history: Drilling for "blind podiform chrome ore bodies at Voidolakkos, Vourinos ophiolite, Greece. in Tectonic Controls on Chrome Ore Localization in Ophiolites, Greece. IGME-EEC unpubl. report 1-18 (submitted to Econ. Geol.).

FRIZON, J.V. (1987). Les peridotites du Massif Ophiolitique du Vourinos (Grece). Etude petro-structural Mise en evidence d'un structure diapirique. These, Institut de Physique du Globe de Paris, Universite Paris, 250pp.

HARKINS, M.E., GREEN, H.W. and MOORES, E.M. (1980). Multiple intrusive events documented from the Vourinos ophiolite complex, northern Greece. Amer. J. Sci. 280-A, 283-295.

KONSTANTOPOULOU, G. (1990). Distribution of platinum-group elements and gold in chromite ores and host rocks of the Vourinos ophiolite complex. (unpubl. Ph. D. Thesis), University of Athens, 272pp.

KONSTANTOPOULOU, G. (1990b). Structural Geology of the Rizo chrome ore district, Vourinos ophiolite, Greece. in Tectonic Controls on Chrome Ore Localization in Ophiolites, Greece. EEC unpubl. rept, Part II, (Rassios, A., Konstantopoulou, G. and Vacondios, I. eds), 48-71.

KONSTANTOPOULOU, G. (1992). Tectonic analysis of Koursoumia area, Vourinos ophiolite. Unpubl. IGME rept., 14pp, 1map.

NICOLAS, A. (1990). Preliminary analysis of the structural data of Vourinos. In Tectonic Controls on Chrome Ore Localization in Ophiolites, Greece . IGME-EEC unpubl. rept., Part II, (Ras-

sios, A., Konstantopoulou G. and Vacondios, I., eds) 72-78.
NICOLAS, A. (1989). Structures of Ophiolites and Dynamics of Oceanic Lithosphere. Kluwer Academic Publishers, 367pp.
PARASKEVOPOULOS, G. and ECONOMOU, M. (1986). On the origin of chromite ores of the Vourinos ophiolite complex, Greece. Neues. Jahrburh Miner. Abh. 154, 2, 179-192.
PEARCE, J.A., LIPPARD, S.J. and ROBERTS, S. (1984) Characteristics and tectonic significance of supra-subduction zone ophiolites in Marginal Basin Geology, Kokelaar, B.P. and Howells, M.F., (eds), Blackwell Scientific Pubs., 77-94.
PSIHOYIOPOYLOS, G., SKAMNELOS, G. and ZAMPARAS, S. (1978). Exploration program for chromite ore localization in the Rizo district, Vourinos ophiolite complex. IGME, Int. Rept.
RASSIOS, A., KONSTANTOPOULOU, G., VACONDIOS, I. and GRIVAS, E. (1990). Tectonic controls on chrome ore localization in ophiolites, Greece. EEC unpubl. rept., Part I, Synthesis (Rassios, A., Konstantopoulou, G. and Vacondios, I. eds), 35pp.
ROBERTS, S., RASSIOS, A., WRIGHT, L., VACONDIOS, I., VRACHATIS G., GRIVAS, E., NESBITT, R., NEARY C., MOAT, T., and KONSTANTOPOULOU G. (1988). Structural controls on the location and form of the Vourinos chromite deposits. Mineral Deposits within the European Community (ed. by J. Boissonnas and P. Omenetto). Springer-Verlag Berlin Heideberg 1988, 249-266.
ROSS, J.R., MERCIER, J.C., AVE LALLEMENT, H.S. CARTER, N.L. and ZIMMERMAN, J. (1980). The Vourinos Ophiolite complex, Greece: the tectonite suite. Tectonophysics, 70, 63-81.
ROSS, J. and LEWIS, P. (1989). Brittle-ductile transition: semi-brittle behavior. Tectonoph., 167, 75-79.