GEOLOGICA CARPATHICA, 48, 1, BRATISLAVA, FEBRUARY 1997
11–18

REVIEW

VOURINOS COMPLEX (GREECE) — AN EXAMPLE OF EASTERN MEDITERRANEAN OPHIOLITE

SERAFIM SAVVIDIS[1] and DUŠAN HOVORKA[2]

[1]Technological Education Institute, 50100 Kila Kozani, Greece
[2]Department of Mineralogy and Petrology, Faculty of Sciences, Comenius University, Mlynská dolina, 842 15 Bratislava, Slovak Republic

(Manuscript received March 21, 1996; accepted in revised form June 20, 1996)

Abstract: The Vourinos Ophiolite Complex, (northern Greece) of Jurassic emplacement, is one of the most intensively studied Mediterranean ophiolites. A highly depleted upper mantle of harzburgite character (in the basal section represented by "basal serpentinites") was generated in a spreading environment. The harzburgite tectonites are overlain by crustal magmatites of cumulate type. In vertical section they gradually change from Ol-rich to Plg-dominated cumulates. Exploitable chromite concentrations together with newly described mineralization of Pt-group minerals underline its economical importance.

Key words: Hellenides, Mesozoic ophiolites, geodynamic evolution.

Introduction

Ophiolite complexes represent objects of continual interest to geologists due to the: a) significance of ophiolites in paleotectonic reconstructions, in addition to, b) their metallogenetic potentiality.

The well exposed Vourinos Complex (northern Greece) is one of numerous Mesozoic eastern Mediterranean ophiolites outcropping within the Balkan Peninsula (the Vardar Zone ophiolites, Pindos, Othris, Chalkidiki etc. — Fig. 1).

The Vourinos Complex represents an ultramafic and mafic rock sequence outcropping over an area of 200 km^2. It is named after the Vourinos mountain range (reaching 1800 m a. s. l.). It is one of the most intensivelly studied eastern Mediterranean Mesozoic ophiolites, and has in the past, served as an example to test different ideas dealing with ophiolites (Brunn 1956; Moores 1969; Moores & Vine 1971; Zimmerman 1972; Jackson et al. 1975; Rassios et al. 1983a, b etc.) and their metallogeny (Zachos 1954; Augé 1985; Augé & Johan 1988).

Geology

The Vourinos Complex is located on the western rim of the Pelagonian massif. The tectonic position of the Vourinos Complex on Early to Mid-Jurassic sediments, which form the Mesozoic cover of the Pelagonian Paleozoic metamorphites have been well described in the past (Brunn 1956). To the west, the Vourinos Complex is covered by Tertiary sediments of the Meso-Hellenic trench. Jurassic emplacement of the Vourinos Ophiolite Complex is supposed (170–180 Ma — Spray & Roddick 1980). Just below the lower tectonic contact blocks of metamorphites (mostly of the greenschist facies) are located. Within them even lenses of quartz garnet amphibolite bodies occur (Moores 1969). They have been dated as 179 ± 4 Ma (Spray & Rodick 1980). The stratigraphical top of the complex is represented by Upper Jurassic radiolarian cherts which overlie the pillow lavas of island arc affinity (Noiret et al. 1981; Beccaluva et al. 1984).

These are in turn transgressively overlain by pelagic Upper Jurassic limestones (Pichon 1976; Mavridis et al. 1979). Generally Jurassic sediments indicate a continental slope environment which is followed by the Upper Cretaceous transgression and molasse deposition (Pichon & Lys 1976).

On the present-day surface the Vourinos Complex is present in the following partial massifs: South Vourinos, North Vourinos, Kissavos and Krapa (or West Vourinos — Fig. 2). The northern and southern blocks are separated by W–E trending oblique slip fault which passes near Chromio (Moores 1969). Despite this segmentation of the complex several authors rank together ophiolites on the Vermion range on the eastern side of the Pelagonian massif, with those (Vourinos) of the western side. This suggests that the Pindos, Vourinos and Othris ophiolites once probably formed a single body more that 120 km in width (Smith 1983).

Past works (Jackson et al. 1975; Harkins et al. 1980; Ross et al. 1980) have split the Vourinos Complex into two generally different rock sequences: i) harzburgite tectonites having the main features of the depleted upper mantle lithologies, and ii) crustal magmatites placed stratigraphically over harzburgite tectonites (Fig. 3).

Main rock lithologies

Moores (1969) divided the Vourinos Complex into three zones: ultramafic, transitional and mafic. It was later reexamined by Jackson et al. (1975) who re-divided the complex into the following two parts:

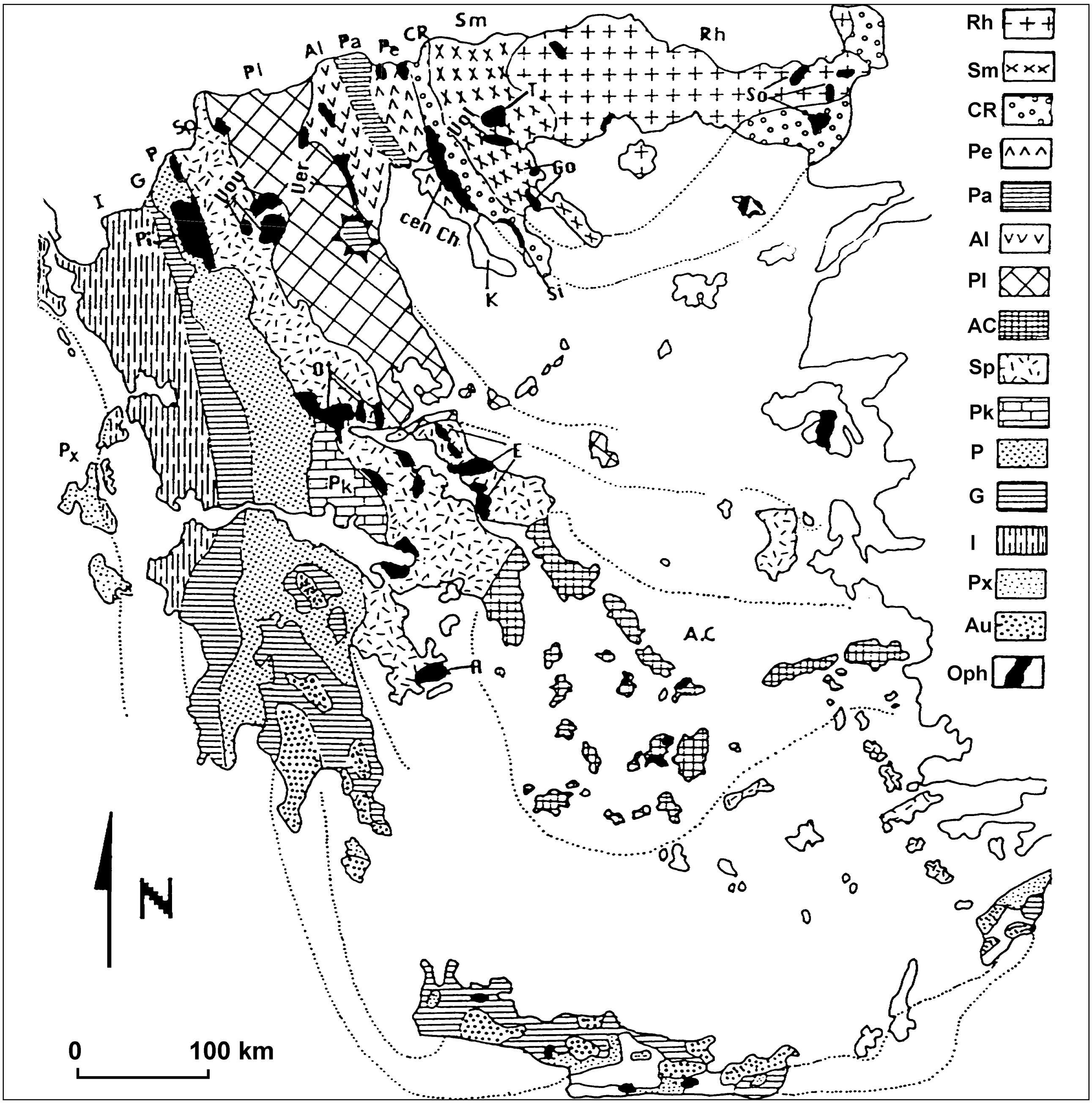


Fig. 1. Geotectonic zones with named Hellenic ophiolites in Greece. **Rh** — Rhodope Massif; **Sm** — Serbomacedonian Massif; **CR** — Circum Rhodope Zone; **Pe** — Peonian Zone; **Pa** — Paikos Zone; **Al** — Almopias Zone = Vardar Zone; **Pl** — Pelagonian Zone; **Sp** — Sub-Pelagonian Zone; **Pk** — Parnass-Giona Zone; **P** — Pindos Zone; **G** — Gavrovo-Tripolis Zone; **I** — Ionian Zone; **Px** — Paxos Zone; **Au** — Unit Talea Mountains; **Oph** — Ophiolites; **A** — Argolis; **E** — Euboea; **K** — Kassandra; **Pi** — Pindos; **T** — Therma; **Go** — Gomati; **Ot** — Othris; **Si** — Sithonia; **So** — Soufli; **Ver** — Vermion; **Vol** — Volvi; **Vou** — Vourinos; **cen Ch** — central Chalkidiki (Mountrakis et al. 1983).

a) stratiform peridotite-gabbro complex, and
b) highly deformed harzburgites and dunites (= harzburgite tectonites).

Within the Vourinos Complex the following main lithologies (Pl. I) can be distinguished:

— *Basal serpentinites* form the lowermost section of the Vourinos Complex. They are represented by a unit tens to several hundred meters thick (Moores 1969) which is traceable practically along the whole lower contact (eastern rim) of the complex. They pass gradually into the overlying harzburgite tectonites.

The basal serpentinites are characterized by two constituents: a) by serpentinized harzburgite and dunite blocks of different size and generally oval shape. On their surfaces a very thin ”skin” composed of relativelly light serpentine (of the lizardite-chrysotile polymorphs) is observed in places. Blocks ”float” in b) serpentinite tectonite which split into small fragments of sharp morphology. No veins/veinlets of chrysotile asbestos type are present in basal serpentinites.

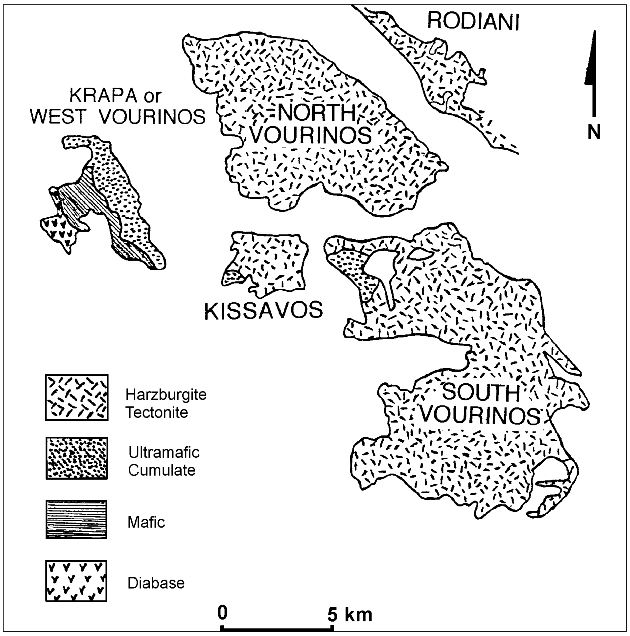


Fig. 2. The general geology of the Vourinos Massif, Greece (Rassios 1983).

For the discussed sequence blocks of limestones/dolostones which can be seen perfectly outcropping (spring 1996) in the new road-cut between Chromio and Museum completely enclosed in basal serpentinite are characteristic (Moores 1969).

— *Harzburgite tectonites*, total thickness up to 7 km (Jackson et al. 1975) bear all the main features of a strongly depleted upper mantle sequence which is probably the residuum left after partial melting of the upper mantle protolith. They form about 85 per cent of the Vourinos Complex. In the majority of cases they are well foliated. Foliation planes are defined by elongated and flattened (2 to 5 cm) clots of orthopyroxenes (Harkins et al. 1980). Among the prevailing deformities two penetrative deformation phases have been distinguished (Ayrton 1968). Within the harzburgites irregular dunite pods and lenses with economical chromite accumulations are characteristic. They are concentrated in the top kilometre of the mantle sequence (Augé & Johan 1988).

It is characteristic that the extent of the ore bodies bear no relation to the size and shape of the enclosing dunite bodies (l.c.). The contacts of the dunites and the surrounding harzburgite tectonites are sharp. It should be mentioned that their origin within the upper mantle harzburgites is still poorly understood. The composition of the harzburgite tectonites as well as dunites and chromitites should be considered as a record of a fast-spreading (= large magma chamber) environment (Nicolas 1989).

The degree of serpentinization of the mantle harzburgite tectonites is low (less than 15 per cent) except in the neighbouring fractures in the vicinities of W–E trending faults where the degree of serpentinization is higher. In general, serpentinization of the southern block is more intensive (Ross et al. 1980).

— The next genetical unit of the Vourinos ophiolites are *crustal magmatites* (= cumulate complex) which overlie the harzburgite tectonites (Harkins et al. 1980).

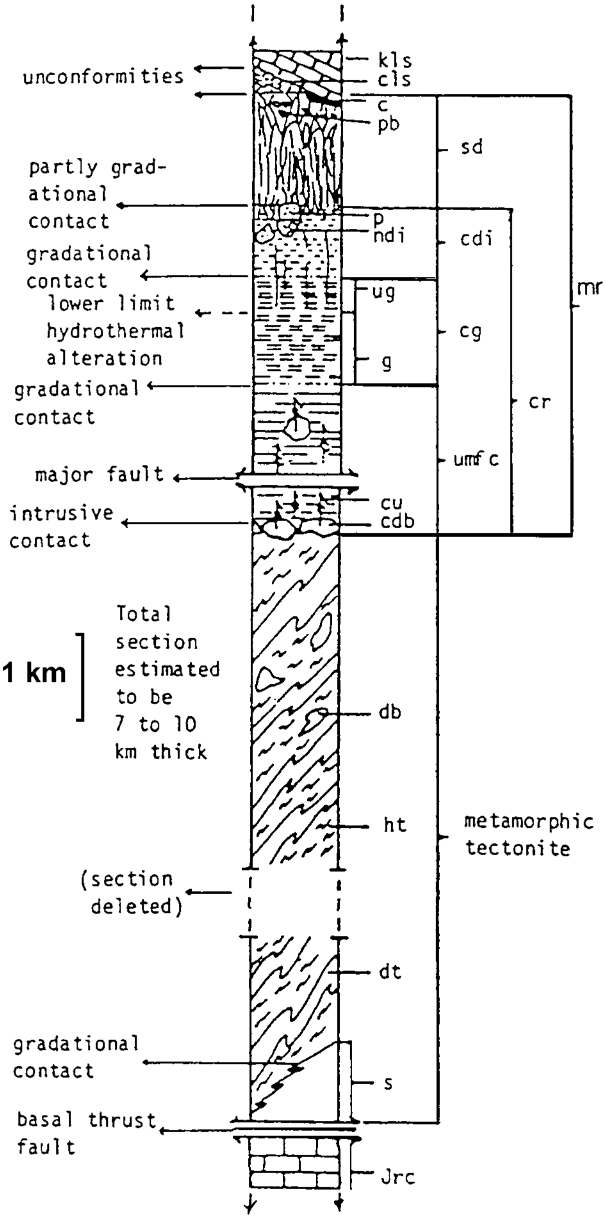


Fig. 3. Generalized stratigraphic column of the Vourinos Ophiolite Complex, Greece. **Kls** — Cenomanian limestone; **cls** — Calpionellid limestone; **c** — chert; **pb** — pillow basalt; **sd** — sheeted dikes; **p** — plagiogranite; **ndi** — non cumulate diorite; **cdi** — cumulate diorite; **ug** — uralitized gabbronorite; **cg** — cumulate gabbronorite; **g** — unaltered gabbronorite; **cr** — cumulate rocks; **umf c** — ultramafic cumulates; **cu** — cyclic unit; **cdb** — cumulate dunite body; **db** — dunite body; **dt** — dunite tectonite; **ht** — harzburgite tectonite; **s** — massive serpentinite; **Jrc** — Jurassic carbonates; **mr** — magmatic rocks (Rassios 1981).

The presence of such cumulates in numerous ophiolites have been summed up by Jackson (1971). This complex (thickness 1500 m) has been originally characterized by Jackson et al. (1975) as a cyclic unit with changeable composition in vertical section. It is rich in coarse-grained (up to 2 cm) olivine at the base and rich in feldspars at the top (Jackson et al. 1975). Magmatic cumulates, in contrast to the metamorphic section of the complex, preserve their initial mineralogical layering (24 cyclic units of the Stillwater or Bushveld type have been distinguished by Jackson et al. 1975). The cyclic units now stand nearly vertically. Structures typical for sedimentary sequences have been reported (Harkins et al. 1980). Later studies (Rassios et al. 1983b) brought evidence that some features of cyclic development of magmatites exist, but this feature is not universal for the whole complex.

Within the lowermost section of cumulates Jackson et al. (1975), described cyclic units of dunites (with various textural types of chromite mineralization, not of economical concentrations), wehrlites and clinopyroxenites. In a stratigraphically upward direction this portion changes to the upper cumulates which consist of Ol-gabbros, gabbros followed by notitic gabbros passing to leucodiorites (= small bodies of "plagiogranites").

The upper cumulate complex is locally intruded by dolerite sills and dykes. Dyke swarm occurs in diorites. On top of the magmatic sequence massive basaltic lava flows are known to occur, through only within a small area.

Metallogenic aspects

— Vourinos is well known for its chromite ores. Xerolivado and its neighbouring mines were the most productive on the European continent. Chromitites are known to occur in both main lithological units, though those of economic importance are found in dunites within harzburgite tectonites (Roberts et al. 1988; Rassios & Kostopoulos 1987).

Chromite ores are confined to tabular zones up to 2 km thick that occur subparallel to the basal plane of the complex. It could be supposed that the chromite-rich horizons represent the remnant of deformed dunite-chromite enriched zones of the mantle.

Taking into account chromite occurrences in both, the main lithological units, according to Zachos (1954) classification, the following textural types of chromite ores could be distinguished: a — disseminated, b — schlieren, c — massive, d — nodular (ooidal, leopard-type known from cumulates only), e — layered (Pl. II). In the majority of cases different types of ores coexist in one occurrence. Consequently it is classified according to the prevailing textural type of ore. On the basis of the nodular type occurring in the basal part of cumulates (for example at Tsouka) it seems that this is the prevailing type among cumulate dunites. On the other hand schlieren type ores form the bulk of the economic deposits of Vourinos. Modal chromite in this type varies between 15 to 44 per cent (Rassios 1986).

— Systematic studies performed during the last decade enable us to list Pt-group minerals (PGM) determined within the Vourinos Complex as follows (Augé & Johan 1988): laurite, alloys: iridosmine, rutheniridosmine, osmiridium and sulpharsenides: osarsite and irarsite. PGM were determined both in chromitites and in disseminated chromites. They are present as minute grains (1 to 10 μm) and are generaly euhedral.

— The asbestos mine at Zindani is located within the antigotite serpentinite body. It belongs most probably to the Pelagonian massif located east of Vourinos. Deposits of slip-fiber asbestos of complicated mineralogy (Hovorka et al. 1997), which locally reache quality of textile asbestos are exploited.

— A crust of lateritic weathering is preserved in only a few places on the Vourinos ophiolites (Microcastro-Siatista area). Taking into account the eroded section of the ophiolite, preservation of laterites (were elevated nickel concentrations can be expected) should occur in ancient topographical depresions.

Genetic aspects

The dunite bodies could have originated in one of the following ways: as depleted solid residues of a partial melting of a peridotitic precursor, or, as magmatic segregations. Following Harkins et al. (1980) the problematics of dunite bodies can be summed up as follows: 1 — they are produced by a process that forms consistently sharp contacts, 2 — they are formed both before and after deformation, 3 — the composition of chrome spinels included in them is the same in all bodies and the same as that of the lower cumulate chromites, 4 — morphologies of chrome spinels in all their occurrences are similar.

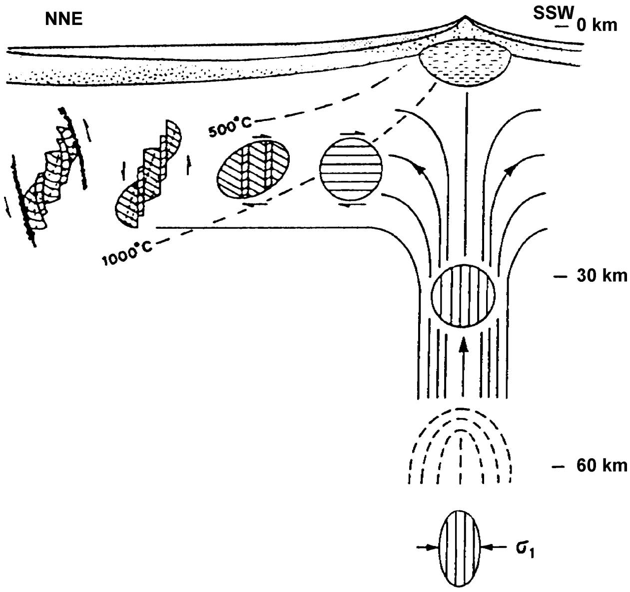
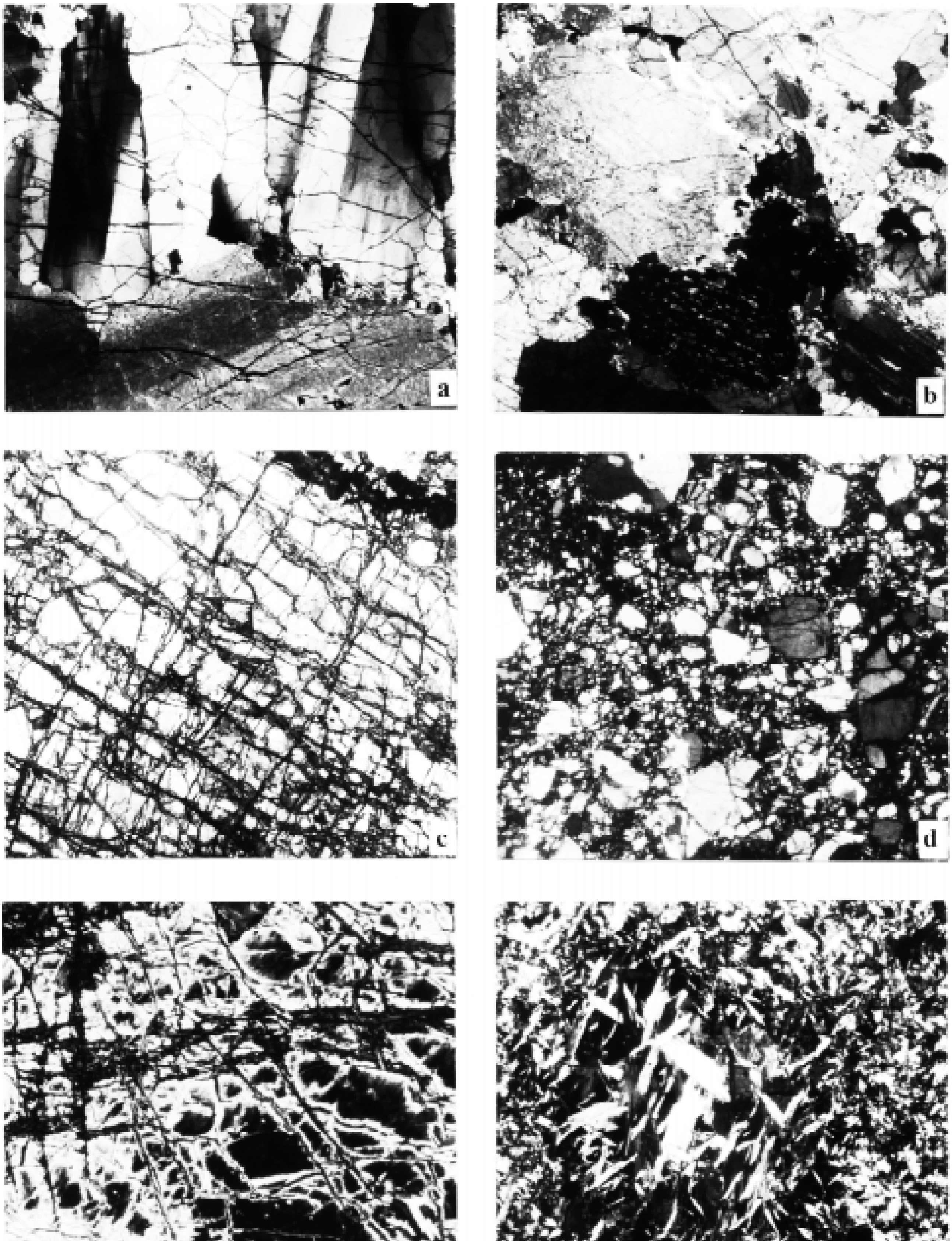
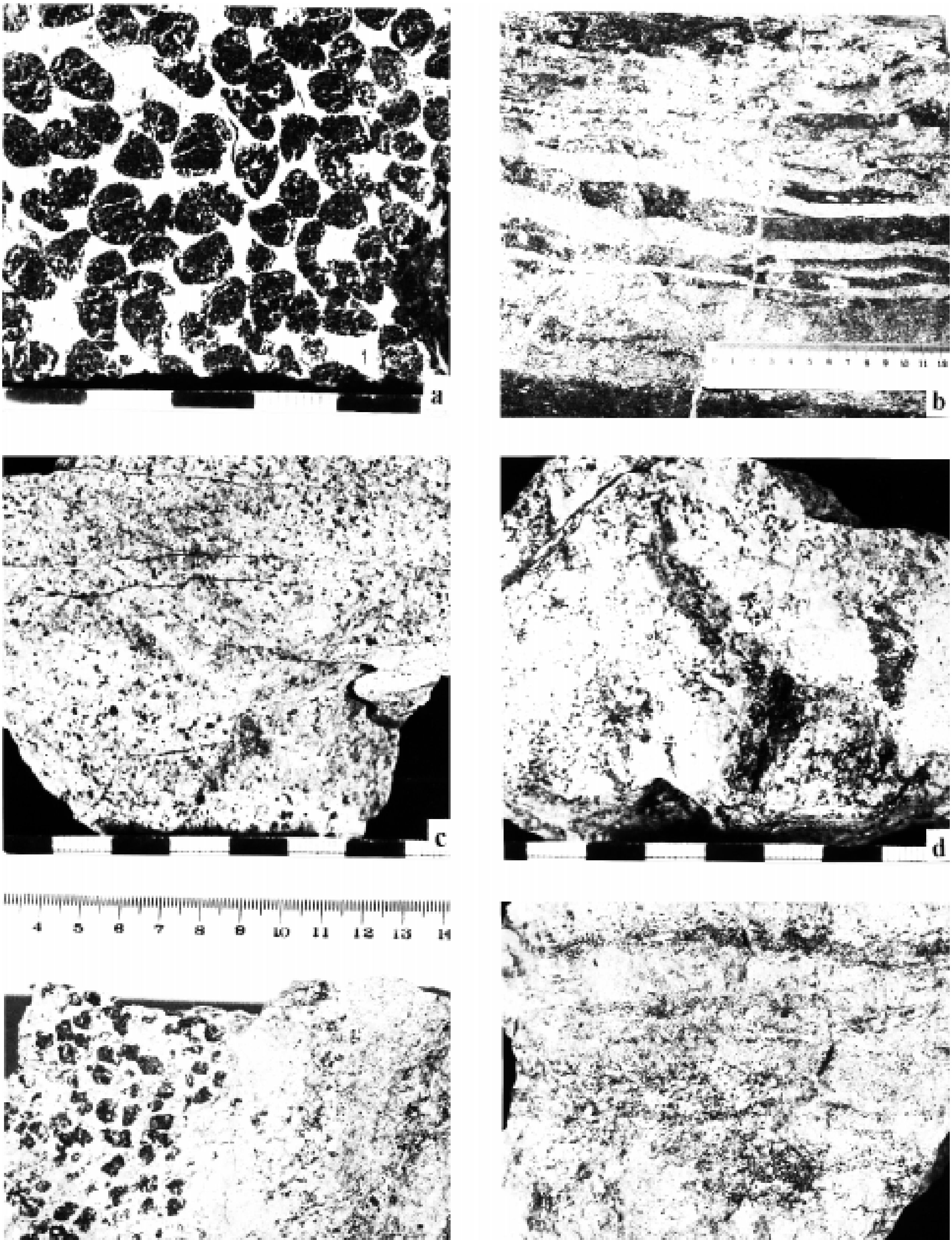


Fig. 4. Model for genesis of the Vourinos ophiolites. Hypothetical NNE–SSW cross-section through the ridge and lithosphere of which the Vourinos Complex is a fragment. Olivine crystals at a depth of about 60 km within the diapir are oriented with [100] axes vertical. At about 30 km flow lines rotate to the horizontal and kinking of olivine occurs; subsequently, mylonites develop. Stippled areas represent sediments; short random lines represent crystalline crust; horizontal lines represent a small magma chamber (Ross et al. 1980).

Plate I: a — Deformation bands in olivine of dunite (located within the upper mantle harzburgite tectonite). Enl. ×27, crossed nicols. **b** — Harzburgite tectonite with core-mantle structure of pyroxenes; exsolution of Cpx of Opx. Enl. ×27, crossed nicols. **c** — Intensively crushed olivine in harzburgite tectonite with slight serpentinization on cracks. Enl. ×45, crossed nicols. **d** — Harzburgite tectonite (cataclasite). Enl. ×45, crossed nicols. **e** — Total serpentinization of olivines in harzburgite tectonite — mesh texture. Enl. ×45, crossed nicols. **f** — Antigorite serpentinite (Kamvounia-Zindani) with random orientation of antigorite blades. Enl. ×43, crossed nicols.


a
b
c
d
e
f


a
b
c
d
4 5 6 7 8 9 10 11 12 13 14
e
f

Jackson et al. (1975) located the formation of the Vourinos stratiform (cumulate) complex near the actively spreading mid-oceanic ridge (Fig. 4). The composition of olivine and pyroxenes in the Vourinos indicate that they were produced from a mantle source with an 100×Mg/Mg + Fe of about 89. After melting of the protolith harzburgite residuum, Ol and Px in the range Mg91–93 would have originated. Cumulus olivines have more-or-less the same composition (Jackson et al. 1975).

Following the results of Jackson et al. (1975) the Vourinos ophiolites can be characterized by:
i) the presence of well developed cyclic magmatites (cumulates) in the upper part of the section,
ii) strong lineate lamination of its rocks,
iii) by sharp, undisturbed boundaries between magmatite cumulates and harzburgite tectonites.

Widespread postcumulus overgrowth within cyclic magmatic unit (cumulates) indicates that the Vourinos Complex was formed on a relatively slowly spreading ridge (Jackson et al. 1975). This general idea was later corrected with the view that the Vourinos Complex is a remnant of a mantle diapir with an overlying magma chamber (Ross et al. 1980).

The degree of serpentinization of the harzburgite tectonites as well as the lower part of the cumulates is generally low. It is more intensive in the cracks and shear zones (Ross et al. 1980). Intensive serpentinization is characteristic of the "basal serpentinites". Applying generally accepted ideas, the serpentinization of the Vourinos could be attributed to the low-temperature hydration processes which it underwent within the upper crust P-T regime during final emplacement of the complex.

Open problems

— Following the paper by Moores (1969), later authors have described the presence of metamorphic rocks on the south eastern rim of the complex.

These metasmorphic rocks can be seen outcropping on the slopes of the Aliakmon River in the vicinity of Zaborda monastery. Metamorphics of the amphibolite facies occur on the tectonic boundary of the Vourinos Complex and the rock sequences of the Pelagonian massif. The presence of garnet amphibolites (Moores 1969) — only a few metres thick — indicates processes of high-grade metamorphic recrystallization during the emplacement of the complex. Such metamorphic recrystallization should be characterized as "deep blastomylonites". The possibility of the retrogressive origin of garnet amphibolites (original eclogites) should be taken into consideration.

— Among the not yet definitely solved problems that should be mentioned here is that of the metamorphic gap between the amphibolite facies rocks on one side and the lizardite-chrysotile serpentinites (= basal serpentinites) on the other one. Metamorphically contrasted lithologies occur on both sides of the emplacement (tectonic) zone only few meters thick. This metamorphic gap should serve for future considerations and studies.

— Within the harzburgite tectonites and the ultramafic (lowermost) members of the crustal cumulates serpentinites of the Vourinos Complex a remarcable serpentinite horizon which is located just above the basal plane (= basal serpentinites) has been reported by Moores (1969), Coleman (1971) and Ross et al. (1980). Information on the presence of mostly lizardite-clinochrysotile in Vourinos has been reported by Coleman (1971). Missing chrysotile in the form of cross-fiber chrysotile (namely in tectonically undeformed ultramafic cumulates) limits the P-T conditions of serpentinization processes. No further information regarding other problems is available at present.

Plate II: Main textural types of chromite ores of the Vourinos Complex: **a** — nodular/ooidal, leopard-type; **b** — layered; **c** — disseminated; **d** — schlieren; **e** — nodular-disseminated; **f** — disseminated-schlieren.

References

Augé T., 1985: Platinum-group-mineral inclusions in ophiolitic chromitite from the Vourinos complex, Greece. *Canad. Mineralogist*, 23, 163–171.

Augé T. & Johan Z., 1988: Comparative study of chromite deposits from Trodos, Vourinos, North Oman and New Caledonia ophiolites. In: J. Boissonnas & P. Omenetto (Eds.): *Mineral Deposits within the European Community. Springer Verlag,* Berlin-Heidelberg, 267–288.

Ayrton S., 1968: Structures isoclinales dans les péridotites du Mont Vourinos (Macédoine grecque), un example de déformation des roches ultrabasiques. *Schweiz. Mineral. Petrogr. Mitt.*, 48, 733–746.

Beccaluva L., Ohnenstetter D., Ohnenstetter M. & Paupy A., 1984: Two magmatic series with island arc affinities within the Vourinos ophiolite. *Contr. Mineral. Petrology*, 85, 253–271.

Brunn J.H., 1956: Contribution a l'étude géologique du Pinde septentrional et d'une partie de la Macédoine occidental. *Ann. Géol. Pays Hellén.,* 7, 1–358.

Coleman R.G., 1971: Petrologic and geophysical nature of serpentinites. *Geol. Soc. Amer. Bull.*, 82, 897–918.

Harkins M.E., Green H.W. & Moores E.M., 1980: Multiple intrusive events documented from the Vourinos ophiolite complex, northern Greece. *Amer. J. Sci.,* 280-A, 284–295.

Hovorka D., Savvidis S., Stankovič J., Šamajová E. & Turanová L., 1997: Serpentines of the ophiolite complexes Vourinos and Kamvounia Mts. (Northern Greece). *Geol. Carpathica*, 48, 19–26.

Jackson E.D., 1971: Origin of ultramafic rocks by cumulus processes. *Fortschr. d. Mineral. (Stuttgart),* 48, 128–174.

Jackson, E.D., Green H.W. & Moores E.M., 1975: The Vourinos Ophiolite, Greece: Cyclic units of lineated cumulus overlying harzburgite tectonite. *Geol. Soc. Amer. Bull.,* 86, 390–398.

Mavridis A., Skourtsis-Coroneou V. & Tsaila-Monopolis St., 1979: Contribution to the geology of Subpelagonian Zone (Vourinos area, West Macedonia). In: *VI Coll. Geol. Aegean Region. Institute of Geological and Mining Resarch,* Athens, 175–195.

Moores E.M., 1969: Petrology and structure of the Vourinos ophiolitic complex of northern Greece. *Geol. Soc. Amer., Spec. Pap.*, 118, 1–74.

Moores E.M. & Vine F., 1971: The Troodos Massif, Cyprus and other ophiolites as oceanic crust: evaluation and implications. *Phil. Trans. Roy. Soc. Lond.,* A, 268, 443–466.

Mountrakis D., 1983: Geology of Greece. *Univ. Studia Press,* Thessaloniki, 1–207 (in Greek).

Nicolas A., 1989: Structures of ophiolites and dynamics of oceanic lithosphere. *Kluwer Acad. Publ.,* Dordrecht, 1–367.

Noiret et al., 1981: Is the Vourinos complex an island arc ophiolith? *Earth Planet. Sci. Lett.*, 56, 375–386.

Pichon S.F., 1976: Conditions de gisement des ophiolithes sur la bordure occidentalle du Vermion zone pelagoniane, Grece. These schéme cycle, *Univ. Paris Sud.*, 1–197.

Pichon S.F. & Lys M., 1976: Sur l' existence d'une série du Jurassic supérieur a Crétacé inférieur, surmontant des ophiolites dans les collines de Krapa (Massif du Vourinos, Grece). *C. R. Acad. Sci.,* Paris, 282, 523–526.

Rassios-Ewing A., 1981: Geology and evolution of the magmatic rocks of the Vourinos ophiolite, Northern Greece. *Unpubl. Ph. D. Theses. Univ. of California*, Davis, 1–594.

Rassios A., Beccaluva L., Bortolotti V., Mavrides A. & Moores E., l983a: Vourinos ophiolite complex. Field quidebook for workshop on Vourinos-Guergueli ophiolites. IGCP 197, *Ofioliti,* 8, 275–292.

Rassos A.E., Moores E.M. & Green H.W., l983b: Magmatic structure and stratigraphy of the Vourinos cumulate zone, Northern Greece. *Ofioliti*, 8, 377–410.

Rassios A. & Kostopoulos D., 1987: The geochemistry of dunite and its relation to the position of chromitites in the Vourinos Ophiolite Complex, Greece. Ophiolites: Oceanic crustal analogues. *Proc. of the Symp. Trodos*, Zipern 1987, 593–603.

Rassios A., Grives E., Vacandios I. & Konstantopoulou G., l995: Structural-geochemical-metallogenetic unification of the Pindos and Vourinos ophiolites. *Manuscript, I.G.M.E,* Athens.

Rassios A., l986: Chromite mineralization and mining at Vourinos. Tectonic controls on chrome ore localization in Vourinos Complex, Greece. *IGME Athens 1986, Appendix II*, 128–142.

Rassios A.E., Morres E.M. & Green H.W., 1988: Magmatic structure and stratigraphy of the Vourinos Ophiolite Complex, Northern Greece. *Ofioliti,* 8, 3, 377–410.

Roberts S., Rassios A., Wright L., Vacandios I., Vrachatis G., Grivas E., Nesbitt R.W., Neary C.R., Moat T. & Konstantopolou L., l988: Structural controls on the location and form of the Vourinos chromite deposits. In: Boissonnas J. & Omenetto P. (Eds.): *Mineral Deposits within the European Community. Springer Verlag,* 249–266.

Ross J.V., Mercier J.Cc., Ave Lallement. H.G., Carter N.L. & Zimmerman J., l980: The Vourinos ophiolite complex Greece: the tectonite suite. *Tectonophysics,* 70, 63–83.

Smith A.G., l979: Othris, Pindos and Vourinos ophiolites and the Pelagonian zone. In: *6th Colloquium on the Geology of the Aegean Region (Vol. 3). IGME,* Athens, Greece, 1369-1374.

Smith A.G. & Woodcock N.H., l976: Emplacement model for some "Tethyan" ophiolites. *Geology,* 4, 653–656.

Spray J.G. & Rodick J.C., l980: Petrology and Ar^{40}/Ar^{39} geochronology of some Hellenic sub-ophiolite metamorphic rocks. *Contr. Mineral. Petrology*, 72, 43–55.

Zachos K., l954: Chromite deposits of Vourinos (Kozani) area. *IGME,* Athens, Rep. No. 3, 1–82.

Zimmerman J., l972: Emplacement of the Vourinos ophiolitic complex, northern Greece. In: Shagam R. et al. (Eds.): *Studies in Earth and Space Sciences — Hess volume. Geol. Soc. Amer., Mem.*, 132, 225–239.