Occurrence of apatite associated with magnetite in an ophiolite complex (Othrys), Greece

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ABSTRACT

Small irregular to lens-like occurrences (maximum 0.5 × 1 m) of apatite associated with magnetite and silicates are present in the Agoriani area of the Othrys ophiolite complex, central Greece. The Ano Agoriani area is dominated by peridotite (plagioclase lherzolite) of the mantle sequence, intruded by irregular bodies, dikes, and veins of gabbro, as well as by dikes of pyroxenite and pegmatitic gabbro.

Apatite occurs as large (up to 3 cm long) well-formed crystals associated with magnetite. The aggregates consist predominantly ofapatite, or massive magnetite with subordinate amounts ofapatite. Apatite may also be accompanied by silicate minerals, mainly chlorite and lesser amounts ofserpentinite, tremolite, and Ni-silicates (nepouite, pimelite), and by Ni-sulfides (pentlandite, violarite, heazlewoodite).

The apatite-magnetite association from the Agoriani area differs from nelsonite hosted by anorthosite suites with respect to: (1) the host rock type (ophiolites); (2) the highly variable proportion between apatite-magnetite; (3) the large size (up to 3 cm) of the apatite crystals; (4) the lack offluorine (<20 ppm F) in the apatite; (5) the presence of abundant liquid-rich, fluid inclusions inapatite, and (6) the lack of ilmenite.

The high V content (700–1000 ppm) of the magnetite from Agoriani differs from that of disseminated Fe-Ti mineralization (Ti-magnetite, ilmenite) in the magmatic sequence of ophiolite complexes (mainly hosted in gabbro-norrites), as well as the pure, massive magnetite associated with Fe-Ni-Cu-Co sulfides found in shear zones in ophiolite complexes. The composition of the apatite (chlor-hydroxyapatite), the presence of abundant primary two-phase aqueous fluid inclusions in theapatite, and the composition of the associated magnetite and sulfides, suggest that a hydrothermal system played an essential role in the formation of these deposits.

INTRODUCTION

Segregations of apatite in association with Fe-Ti oxides occur in a variety of geological settings. Nelsonites are rare igneous rocks composed largely ofapatite and Fe-Ti oxides (magnetite, ilmenite, or rutile) that occur in association with anorthosite suite rocks (Philpotts 1967, 1981; Watson and Green 1981; Kolker 1982; Herz and Force, 1987; Force 1991; Ashwal 1993; Owens and Dymek 1992; Darling and Florence 1995; Duchesne 1999). Nelsonite is thought by some to originate as an immiscible liquid separated from parent magmas of ferrodioritic composition (Philpotts 1967, 1981; Kolker 1982). Another kind of association of magnetite and apatite, without significant ilmenite or rutile, is found in alkaline or calc-alkaline igneous rocks (McKeown and Klemic 1956; Philpotts 1967; Darling and Florence 1995). The origin of apatite-magnetite associations in these types of igneous rocks is not clear. Both a magmatic (Park 1961; Henriquez and Martin 1978; Naslund et al. 1998) and hydrothermal origin (Barton and Johnson 1996; Murray and Oreskes 1997; Barton 1998) have been proposed for the El Laco deposit, Chile. The characteristics of the Kiruna deposit, in Northern Sweden, are not definitive regarding its origin. On the basis of field, textural, mineralogical, and geochemical data, an exhalative-sedimentary origin has been proposed by Park (1975) for the Kiruna deposits. Recently, the Kiruna deposit has been compared to the El Laco deposit in the Chilean Andes (Nystrom and Henriquez 1994).

Low-Ti, Fe-oxide (Cu-U-Au-Ag ± REE) deposits, like the giant Olympic Dam (Australia), Bayan Obo (China), and most of the New York-New Jersey deposits, are characterized by magnetite and/or hematite and most contain apatite with significant amounts ofREE. These deposits exhibit features consistent with a hydrothermal origin (Hitzman et al. 1992; Foos and McLelland 1995; Barton and Johnson 1996; Oreskes and Hitzman 1997).

Occurrences of apatite in ultramafic rocks are very rare (Mitchell et al. 1943; Southwick 1968; Honnorez and Kirst 1975; Nickel et al. 1979; Hopkinson and Roberts 1995; Gjata et al. 1995; Dick and Natland 1999). Recently, small concentrations of apatite associated with magnetite or silicates were discovered along a shear zone in the Othrys (Ano Agoriani area) ophiolite complex, Greece, at the tectonic contact between a gabbroic rock and serpentinitized lherzolite. This paper is probably the first report of an apatite-Fe oxide association in an ophiolite complex, and we provide a description of the apatite-magnetite occurrence, an account of its mineral chemistry, and a discussion of its genesis.

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CHARACTERISTIC FEATURES OF THE OTHRYS COMPLEX

The Mesozoic Othrys ophiolite complex consists of a stack of thrust sheets in which overlapping stratigraphic successions, consisting mainly of harzburgites, lherzolites, gabbros, mafic dikes, and pillow lavas, have been recognized (Hynes 1972; Nisbet 1974; Menzies 1974; Konstantopoulou and Rassios 1993). The presence of both lherzolite and harzburgite in the mantle sequence of the complex, and the variable geochemical affinities of the lavas, provide evidence for development of the complex during more than one oceanic stage, involving MORB and supra-subduction zone (SSZ) features that may be interpreted as related to a back-arc basin (Hynes 1972; Nisbet 1974; Smith et al. 1975; Sovatsoglou-Skounakis 1982; Paraskevopoulos and Economou 1986; Economou-Eliopoulos and Paraskevopoulos 1997).

Two tectonically separate chromite deposits, Eretria and Domokos, have been exploited for refractory-grade chromite resources (about 3 million tons). Small bodies of sulfide minerals (pyrrhotite, chalcopyrite, and minor pentlandite), are also found at the Eretria mine, whereas magnetite occurs at the periphery of a few podiform bodies (Economou and Naldrett 1984). Both high-temperature deformation (characterized by mylonite zones and mineral foliations) and low-temperature brittle deformation have been superimposed onto primary mantle fabrics, and onto magmatic textures of rocks and ores (Konstantopoulou and Rassios 1993).

DESCRIPTION OF THE APATITE-MAGNETITE OCCURRENCE

The Ano Agoriani area (8 km west of Domokos), in the western part of the Othrys complex, is dominated by plagioclase lherzolite (Fig. 1) consisting of forsterite, enstatite, diopside, and plagioclase, with minor spinel. Irregularly shaped bodies of gabbro and gabbroic dikes or veins intrude the plagioclase lherzolite of the mantle sequence. Pyroxenite and gabbro pegmatitic dikes containing 2–20 cm pyroxene crystals also cut lherzolite (Nisbet 1974; Menzies 1974). Apart from the gabbro units of the magmatic sequence, numerous small gabbroic bodies are found within the serpentinized lherzolite. An abundance of gabbroic pods and dikes within plagioclase lherzolite is considered to be characteristic of sections near the petrological Moho (Menzies 1973, 1974; Nicolas 1989). These gabbroic bodies are composed mainly of randomly oriented skeletal plagioclase in a matrix of clinopyroxene (diopside-augite). Small amounts of chlorite and spinel are also present. These gabbroic bodies appear undeformed in contrast to the ductile-brittle deformation along thrust surfaces at the tectonic contact between gabbroic rocks and serpentinized lherzolite.

Variable proportions of apatite in association with magnetite were discovered in the Ano Agoriani area along a shear zone, at the contact between lherzolite and a relatively large (50 × 250 m), fine-grained body of gabbro (Fig. 1).

METHODS OF INVESTIGATION

The apatite-magnetite association from the Ano Agoriani area was investigated as follows. X-ray powder diffraction patterns (XRD) of apatite were obtained with a Siemens D5005 X-ray diffractometer at the University of Athens. Major- and trace-element compositions, including rare earth elements (REE) were determined on bulk mineral separates by a combination of instrumental neutron activation analysis (INAA), and colorimetric methods at the XRAL Laboratories, Ontario, Canada. Thin sections were investigated by optical microscopy and scanning electron microscopy. Mineral compositions were determined by electron microprobe analysis at the University of Athens, Department of Geology, using a Cambridge Microscan-5 instrument and a JEOL JSM 5600 scanning electron microscope, both equipped with automated energy dispersive analysis system, LINK 2000 and ISIS 300 OXFORD, respectively. The H2O content of apatite was determined by the Penfield method (Mitchell et al. 1943). Thermogravimetric (TG) analysis of apatite was performed with a Perkin Elmer TGS-2 thermal analyzer using a 5.0 deg/m in heating and nitrogen atmosphere, in the temperature range 80–950 °C.

MINERALOGY

Small, irregular to lens-shaped (maximum 0.5 m × 1 m) apatite-magnetite occurrences are composed of large euhedral apatite crystals, ranging from a few millimeters to 3 cm in length, in a magnetite matrix (Fig. 2). The color of apatite is whitish, and it occurs mainly within massive magnetite or, where associated with silicates (∼magnetite), it occurs either as undeformed or fragmented to rounded crystals. Proportions of apatite to magnetite are highly variable (Fig. 2). Inclusions of magnetite within apatite, and Ni-sulfides (mainly pentlandite) dispersed throughout both apatite and magnetite are common, suggesting that all these minerals crystallized at the same time.

In some cases, apatite is accompanied only by silicate minerals, mainly chlorite that may be Ni-bearing, and lesser amounts of serpentine, tremolite, Ni-silicates (nepouite, pimelite), and Ni-sulfides (pentlandite, violarite, heazlewoodite). Moreover, chlorite is a common mineral along cracks and around the periphery of most apatite crystals, either associated with magnetite or silicates. Goethite is a common alteration product of magnetite.

Most apatite grains contain abundant fluid inclusions. They appear to be primary on a textural basis (Roedder 1984), and consist of very small, two-phase inclusions, containing aqueous liquid (L > 50%) and a vapor phase (Fig. 3).

The investigation of apatite with the scanning electron microscope and the microprobe revealed no zoning, very low REE contents (below the detection limit of the method), and inclusions of monazite crystals (Fig. 4).

MINERAL COMPOSITIONS

The large size of the apatite and magnetite crystals allowed for both bulk and electron microprobe analysis. The H2O content in apatite ranges from 1.1 to 1.9 wt% and Cl from 6300 to 7500 ppm, whereas F is less than 20 ppm (Table 1). The presence of many small fluid inclusions, containing aqueous fluids as the main phase, indicates that bulk H2O contents do not reflect only the (OH) anions in the apatite. Nevertheless, the predominant anions are (OH) and Cl, corresponding to chlor-hydroxylapatite, consistent with the XRD pattern.

The minor and trace element contents of apatite (Table 1)
are consistent with the presence of chlorite and Ni-silicates along cracks in the apatite, and with the presence of magnetite and Ni-sulfides (mainly pentlandite) inclusions. The rare-earth element (REE) content in the Agoriani apatite is relatively high (up to 1350 ppm REE). In addition, the apatite displays steeply fractionated chondrite-normalized patterns (Fig. 5) with very high La/Lu ratios (average 1570).

Magnetite is pure, with very little Al, Mg, Ni, and Ti. Bulk samples, however, have high Ni because of the presence of Ni-sulfide inclusions (Table 1). The REE content of the Ano Agoriani magnetite is below the detection limit of the INAA method (for example <1 ppm La); see Table 1.

**REVIEW OF OTHER Fe-Ti OXIDE–APATITE OCCURRENCES**

**Anorthosites**

Nelsonites (Fe-Ti oxide + apatite rock) and OAGNs (oxide-apatite gabbro-norites) are two varieties of apatite-rich rocks found in association with anorthosite suites. Nelsonites form small portions of massive Fe-Ti oxide ore deposits within anorthosite or they occur as dike-like bodies in country rocks. OAGNs contain ilmenite, magnetite, apatite, two pyroxenes, and plagioclase, and form sill-like layers within or near the margins of anorthosite suites (Owens and Dymek 1992). Apatite separates from both rock types within individual complexes, have higher REE contents relative to host rocks, but the chondrite-normalized patterns of apatite and whole rocks are parallel (Dymek and Owens 2001). Nelsonites have been interpreted by some as the product of liquid (rich in Ti, P, ± Zr) immiscibility from magmas of ferrodioritic composition (Philpotts 1967, 1981; Watson and Green 1981; Kolker 1982; Herz and Force 1987; Ashwal 1993; Darling and Florence 1995), or as cumulate zones within oxide ores (locally mobilized as dike like bodies), although their host Fe-Ti oxide ores may represent immiscible oxide liquids (Owens and Dymek 1992; Dymek and Owens 1996, 2001).
Alkaline or calc-alkaline rocks

The origin of apatite-magnetite associations in alkaline or calc-alkaline igneous rocks is not clear. For example, the El Laco deposit, Chile, situated on the flanks of an andesite-rhyodacite volcano, consists of five massive magnetite-hematite bodies surrounded by numerous dikes and veins of intergrown magmatic pyroxene and apatite. Some researchers favor a magmatic origin (Park 1961; Henriquez and Martin 1978; Hitzman et al. 1992; Naslund et al. 1998) and others a hydrothermal origin (Barton and Johnson 1996; Barton 1998). On the basis of field, textural, and mineralogical data, Parak (1975) proposed that the Kiruna deposits were exhalative-sedimentary in origin. It is remarkable that within banded ores, small monazite needles occur as inclusions in individual apatite crystals (Parak 1975).

Recently, the features of Kiruna have been compared with those of El Laco and it has been suggested that such magmatic ores, occurring in rocks ranging from Proterozoic to Cenozoic, are not unique (Nystrom and Henriquez 1994). For example, the deposits of the Cerro de Mercado, Durango, Mexico, are considered to have formed as a result of a variety of subaerial volcanic processes. During the later stages of the cooling process, a quartz latite dike intruded the deposit, while a volatile-rich, iron-oxide-rich phase is suggested to have evolved from...
tite-actinolite veins, breccias, and wall-rock replacement, and an outer zone of disseminated sulfides. It was concluded that high temperature, low initial water content, and shallow-level emplacement by intermediate plutons are necessary for the development of Kiruna-type deposits (Hildebrand 1986). Mafic-ultramafic rocks

Layered mafic intrusions. Apatite-enriched layers have been reported in the Upper Zone of the Bushveld complex. Textural and compositional relations suggest that the periodic development of an immiscible Fe-Ti-Ca-P liquid in the topmost 1000 m of the Upper Zone (Von Grunewaldt 1994). The development of the mineralized zones at the base of distinct geochemical cycles suggests the formation of the immiscible Fe-Ti oxide and apatite by magma mixing processes (Von Grunewaldt 1994). Also, in the Bushveld complex, with the exception of its abundant fluorite, the Vergenoeg deposit is related to granites containing fayalite, fluorite, apatite, ilmenite, and magnetite, and is similar to massive iron deposits as Kiruna and Cerro Mercado (Borrok et al. 1998). Furthermore, based on isotope and fluid inclusion data on fluorite from the Vergenoeg deposit which contain abundant aqueous inclusions, Borrok et al. (1998) concluded that this mineralization formed from hydrothermal fluids of magmatic origin.

Ultramafic chlorite rocks. Well-documented occurrences of fluor-hydroxyl-apatite have been found in Georgia and Maryland of the U.S.A., associated with chlorite-talc schists located in the peripheral parts of small ultramafic bodies (Mitchell et al. 1943; Southwick 1968; Herz and Valentine 1970). More specifically, a small body of ultramafic chlorite rock containing unusually large quantities of rutile, magnetite, apatite, and ilmenite is present in Harford County, Maryland. The central part of the ultramafic body is mostly massive to schistose soapstone and serpentinite, whereas its southwest margin contains lenses of strongly deformed uralitized gabbro and pyroxenite. Mitchell et al. (1943) and Southwick (1968) concluded that...
the hydroxyl-apatite in these rocks was initially normal fluorapatite, and that exchange of (OH) for F-anions took place during low-grade metamorphism and associated black-wall metasomatism in the presence of excess water.

Within serpentinized peridotite near Nullagine, Western Australia, Ni mineralization associated with lesser amounts of magnetite, apatite, and chlorite occurs along shear zones, and has been attributed to hydrothermal and/or metasomatic activity (Nickel et al. 1979).

**Ophiolite complexes.** Apatite has been reported in Fe-Ti oxide-rich gabbro localized along shear zones in the Lizard complex, U.K. (Hopkinson and Roberts 1995), and in core samples from hole 735b at the Atlantis II Fracture zone, Southwest Indian Ridge (Dick and Natland 1999). In layer 3, Fe-Ti oxide-rich gabbro of the Lizard ophiolite, ilmenite and magnetcite (in a ratio of 12:1) poikilitically enclose zircon and apatite. The origin of this association is attributed to the migration and impregnation of evolved Fe, Ti-rich melts in deformed areas (including shear zones) of gabbro (Hopkinson and Roberts 1995). Subordinate quantities of apatite are found in veins composed mainly of zoisite, actinolite, and euhedral chlorite, which are related to hydrothermal brecciation in and adjacent to shear zone.

In rocks collected from the Atlantis II Fracture zone, Southwest Indian Ridge, Dick and Natland (1999) described large euhedral crystals of apatite contained in ilmenite-magnetite patches. These Fe-Ti oxides (which locally include Fe-Cu-Ni sulfides) are abundant in the most-deformed (sheared and brecciated) gabbro and least-abundant in the least-deformed rocks. In most cases, the oxides occur as an undeformed coarse matrix in shear zones, postdating the major phase of deformation. However, in a few cases, the oxides predate the deformation. Small patches of late felsic material contain mainly amphibole, ilmenite, and magnetite, with minor amounts of sulfides, quartz, apatite, and zircon, suggesting that the Fe-Ti oxides precipitated from highly evolved melts and/or late-magmatic hydrous fluids.

In the Puka ophiolite massif, Albania, occurrences of disseminated apatite in Fe-Ti oxide rich gabbro also have been reported but no interpretation was offered (Gjata et al. 1995).

**Low-Ti oxide-apatite**

A distinct class of mineral deposit has been recognized recently that are characterized by low-Ti Fe ores containing variable amounts of Cu, U, Au, and REE, like the deposits of Missouri and Kiruna of Sweden, the giant Olympic Dam of Australia, the giant Bayan Obo of China, the Humboldt of Nevada, the New York and New Jersey (Oreskes and Einaudi 1990; Hitzman et al. 1992; Foose and McLelland 1995). All these deposits are characterized by magnetite and/or hematite ores with low Ti content (<2 wt%), and the majority contain Cu sulfide minerals. Apatite in several deposits is abundant and contains sufficient amounts of REE to be of economic interest (Klemic et al. 1959). The genesis of these types of deposits is ambiguous and a variety of origins have been proposed. Many deposits display evidence of a hydrothermal origin, as indicated by fluid inclusions, replacement textures, extensive zones of wall-rock Fe metasomatism, and geochemical characteristics (isotopic, major, and trace elements). It has been suggested that Na- and K-metasomatism associated with these Fe deposits involves CI-rich hydrothermal fluids, which may be efficacious agents for transporting Fe (Hitzman et al. 1992; Hemley et al. 1992; Foose and McLelland 1995). Hematite breccias, the host rocks to Cu-U-Au-Ag ore at the Olympic Dam deposit, occur within fractured granite. Oreskes and Einaudi (1990) have emphasized that these breccias are highly enriched in light and heavy REE and contain hydrothermal REE phases, including monazite. Based on the abundance of REE in hydrothermal phases, REE enrichment of altered relative to unaltered wall rock, concentration of REE in the center of the system, and variable slopes of REE-patterns, they concluded that the Olympic Dam deposit is a hydrothermal breccia complex formed by major upward flow of hydrothermal fluids.

**DISCUSSION**

Geological, textural, mineralogical, and geochemical data (Figs. 2–5; Tables 1 and 2) indicate that the apatite-magnetite association in the Ano Agoriani area differs from most nelsonites in terms of (1) its host rock (i.e., an ophiolite complex; (2) its restriction to highly deformed shear zones; (3) its highly variable proportions of apatite and magnetite; (4) the large grain size (up to 3 cm) and euhedral form of the apatite crystals; (5) the composition of the apatite (chlor-hydroxylapatite) and its lack of fluorine (<20 ppm); (6) the greater REE fractionation in the apatite, as exemplified by the La/Lu ratio (average 1570 vs. 160 in nelsonites); (7) the presence of monazite inclusions within apatite; and (8) the chemical composition of the associated magnetite (Ti-free vs. titanomagnetite) (Philpotts 1967, 1981; Watson and Green 1981; Kolker 1982; Herz and Force 1987; Owens and Dymek 1992; Ashwal 1993; Dymek and Owens 1996, 2001).

The apatite-magnetite association from the Ano Agoriani area also differs from those found within ferrogabbro of the cumulate sequence of the Puka (Kcira) ophiolite complex, Albania (Gjata et al. 1995; Tashko et al. 1998), those within amphibolite dikes cross-cutting the Zidani, Greece, serpentinized peridotite (Karkanas et al. 1996), and those within oxide-rich gabbro localized along shear zones in the Lizard ophiolite (Hopkinson and Roberts 1995) and at ODP site 735B, SW Indian Ridge (Dick and Natland 1999) because in all of these cases, only small apatite crystals are associated with Fe-Ti oxides. The lack of Ti-oxides (ilmenite, rutile) and the negligible F content of apatite from Agoriani are also major differences compared to those found with ultramafic rocks in Georgia and Harford County, Maryland (Mitchell et al. 1943; Southwick 1968), although the composition of the apatite (hydroxyl-apatite) is a common feature.

Thus, the occurrence of large chlor-hydroxyl-apatite crystals with massive-pure magnetite in the Agoriani area (Fig. 2), the REE-enrichment and fractionation for apatite (Table 1; Fig. 5), and the presence of monazite exsolutions and two-phase fluid inclusions (Figs. 3 and 4) may be characteristic features of a new type of apatite-magnetite association within shear zones cutting plagioclase peridotite in an ophiolite complex.

The presence of fluor-apatite, as an accessory phase in unaltered mafic ophiolitic rocks, and of corroded hydroxyl-apa-
tite crystals within pillow lavas, which have been strongly affected by hydrothermal alteration (Economou-Eliopoulos, unpub. data), may indicate that the apatite was initially F-rich and that a gradual exchange of (OH) for F has occurred. However, the large size (up to 3 cm) of the apatite crystals and their spatial association with shear zones seems to be consistent with its deposition into preexisting lithologies rather than being the product of a replacement process. The dominance of (OH) ions in the studied apatite, and the presence of abundant primary, liquid-rich, two-phase fluid inclusions (Fig. 3) suggests that apatite formed in the presence of an aqueous fluid phase.

Deposition of apatite and the associated minerals are related to the circulation of an oceanic hydrothermal system, probably a Cl-rich brine, as is exemplified by the presence of Cl-apatite. The presence of inclusions of magnetite within apatite and the association of sulfides with both apatite and magnetite suggest that these minerals share a common origin. As far as the origin of the association of massive magnetite with sulfides of both Cyprus and Fe-Cu-Ni-Co type in ophiolite complexes elsewhere, it has been suggested that they too have precipitated from circulating hydrothermal systems. Interaction of the hydrothermal system with the host rocks produces a reduced, slightly acidic, saline solution, which can be assumed to rise preferentially along a zone of high permeability. Physicochemical changes (temperature, redox, pH conditions) within the hydrothermal system at near-surface or at lower stratigraphic levels like that of the gabbros, cause precipitation of sulfide-oxide mineralization (Economou and Naldrett 1984; Foose et al. 1985; Scott et al. 1990; Eliopoulos et al. 1998).

Recently, on the basis of fluid inclusion data, replacement textures, extensive zones of wall-rock Fe metasomatism, geochemical data (isotopic, major- and trace-element compositions) and the presence of Cl-apatite, the hydrothermal origin has been suggested for another class of low-Ti iron-oxide deposits (Cu-U-Au-REE), like those deposits in Missouri, Kiruna in Sweden, Olympic Dam in Australia, the Bayan Obo in China, and Humboldt in Nevada (Oreskes and Einaudi 1990; Hitzman et al. 1992; Foose and McLelland 1995; Barton and Johnson 1996; Barton 1998). With respect to the source of the P for these low Ti iron-oxide deposits, Barton and Johnson (1996) proposed an evaporitic-source model.

The Agoriani apatite mineralization is similar to the latter class of deposits in terms of the association of apatite with low-Ti Fe-oxides (magnetite), the presence of REE-bearing minerals (monazite) that are considered to be of hydrothermal origin, and abundant aqueous fluid inclusions within apatite. Although the above distinct class of deposits and the Agoriani apatite-magnetite association both appear to be hydrothermal in origin, the source for the P is different in each. Apart from apatite that is a common accessory phase in all mafic ophiolitic rocks, high whole-rock concentrations of P2O5 and abundant apatite have been reported in some mafic ophiolitic rocks (Hynes 1972; Gjata et al. 1995; Tables 1 and 2). In addition, amphibolite dikes cross-cutting the Zidani, Greece, serpentinitized peridotite, are characterized by high contents of Ti (2.9 wt% TiO2) and P (up to 0.71 wt% P2O5) and contain ilmenite and apatite. A salient feature of the latter dikes is the highest P content in the less-altered samples (2 wt% H2O), whereas strongly deformed, altered, vermiculite-bearing samples (11.7 wt% H2O) exhibit low (0.1 wt%) P2O5 contents (Karkanas et al. 1996). Such a decrease in P content in the deformed, highly altered dikes from the Zidani area, combined with the presence of small crystals of apatite with replacement features, within strongly altered pillow lavas (Economou-Eliopoulos, unpub. data) suggests that P might be mobile and enriched in hydrothermal systems related to ophiolites.

Therefore, the composition of the apatite (chlor-hydroxyl-apatite) and the presence of abundant, primary, two-phase, aqueous fluid inclusions (Fig. 4), coupled with the composition of the associated magnetite and sulfides, may indicate formation of apatite under hydrothermal conditions.

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