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# Alpine - Mineral
# Mineral - Megacrysts

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**Content**

| Documenta naturae | 151 | p. 1-21 | 3 figs. | 2 tabs. | 4 pls. | München | 2004 |
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# New Occurrences of Mineral Megacrysts in Tertiary Magmatic-hydrothermal and Epithermal Environments in Greece

**P. VOUDOURIS & A. KATERINOPOULOS**

**Summary**

Recent fieldwork in Greece resulted in new discoveries of mineral species most of which in very large and well formed crystals. Hostrocks are volcanics, intrusive bodies, contact metamorphic zones, and minor pegmatites of Tertiary age. Over twenty different species (among them quartz varieties, garnet, vesuvianite, diopside, epidote, alunite, fluorite, and the silica microcrystalline species) are presented and geologically determined. The volcanic-hosted, epithermal altered environments in Evros region, Limnos, Lesvos, Samos and Milos Islands are excellent places to collect gem-quality amethysts, beautiful crystals of alunite and fluorite, as well as chalcedony and opal. The intrusive bodies exposed at Samothraki, Maronia, Kimmeria and Limnos Island are crosscut by numerous quartz veins including K-feldspar, muscovite and magnetite in well-shaped crystals. Garnet, tourmaline, muscovite and epidote are some of the minerals related to pegmatite bodies outcropped in northern Greece. Very rich in megacryst mineral samples are the scarn environments in northern Greece (Maronia, Kimmeria) and Seriphos Island. The minerals quartz, garnet, epidote, vesuvianite and diopside from the above localities are world-class, some of them reaching gem qualities. All the mineral specimens discovered in the present work are related to the development of Tertiary magmatic centers: The mineral depositing processes can be regarded as integral parts of magmatic-hydrothermal and epithermal systems. Some of the minerals described above are unique in Europe and probably in the world. Areas like Seriphos, Kimmeria and Maronia should be protected from mineral exploitation, and characterized as European mineralogical geotopes.

**Keywords:** minerals, megacrysts, magmatic environments, geotopes

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**Content** **Page**



## 1. Introduction

The largest crystals of minerals, reaching dimensions of up to several meters, are exhibited in many museums and mineral collections (RICKWOOD 1981). Pegmatites, contact metamorphic zones and hydrothermal veins are among the most favourable mineral depositing environments.

Recent fieldwork in Greece resulted in the discovery of new mineral occurrences, developed within tertiary magmatic rocks, most of which in megacrysts of best quality. The term “mineral megacrysts” refers to mineral species of extraordinary aesthetic and scientific value, suitable for exhibition in museums and collections. Up to the present mineral megacrysts in Greece are related almost entirely to three localities: the Laurion mines in Attika, Seriphos Island in the Aegean and Chalkidiki mines in northern Greece. Minerals from Laurion such as smithsonite, serpierite, annabergite, and mixite (KATERINOPOULOS & ZISSIMOPOULOU 1994, LAPIS 1999, BAUMGARTL & BURROW 2002) are unique in respect to their color and crystal size. The Seriphos scarn is famous because of the green quartz variety (prase) in the best quality worldwide (GAUTHIER & ALBANDAKIS 1991). Prase crystals from Dalnegorsk in Siberia (GRANT & WILSON 2001) and in Elba Island (EXTRA LAPIS 2001) are subordinate compared with those from Seriphos. Another Seriphos mineral of world-class is ilvaite (crystals up to 50cm are not rare). Finally, in the Chalkidiki area in northern Greece, pyrite crystals up to 50cm size associated with quartz and Mn-rich calcite were discovered during the 70s. Some other minor localities with interesting mineral occurrences should be notified, such as the sapphire and beryl occurrence in Naxos Island (PAPASTAMATIOU 1951), spessartite in Paros Island (PARASKEVOPOULOS 1958) and rubies in Xanthi northern Greece (ANDRONOPOULOS & TSOUTRELIS 1964).

In this paper new occurrences of mineral megacrysts in tertiary magmatic environments of Greece are presented. Three distinct geological environments were studied: granitoid intrusions, scarns, and volcanic rocks. The mineral megacryst occurrences in Greece are presented in Figure 1 and listed in Table 1.

## 2. Geological setting

After the closure of Paleotethys in the Upper Triassic, the rifting of Pangea continent and the opening of Neotethys resulted in the contemporaneous westward overthrusting of Axios on to the Pelagonian massif (Middle-Upper Jurassic) and the eastwards subduction beneath the Rhodope massif. The continent-continent collision (middle Eocene) resulted in the formation of the Hellenides mountain chains.

The tertiary magmatic belt in Greece, extended from W. Thrace in the north to the recent active Aegean volcanic arc in the south, can be considered the product of subduction and collisional processes between the African plate and the Pelagonian and Rhodope massifs (SIDERIS 1975, PAPAVASSILIOU & SIDERIS 1984, FYTIKAS et al. 1984, BALTATZIS et al. 1992, PE-PIPER & PIPER 2002). The magmatic rocks were emplaced at relatively shallow depths, under an extensional tectonic regime, accompanied by the post-orogenic collapse of the Hellenides. Locally, volcanic effusions are intimately associated with subvolcanic and plutonic bodies.

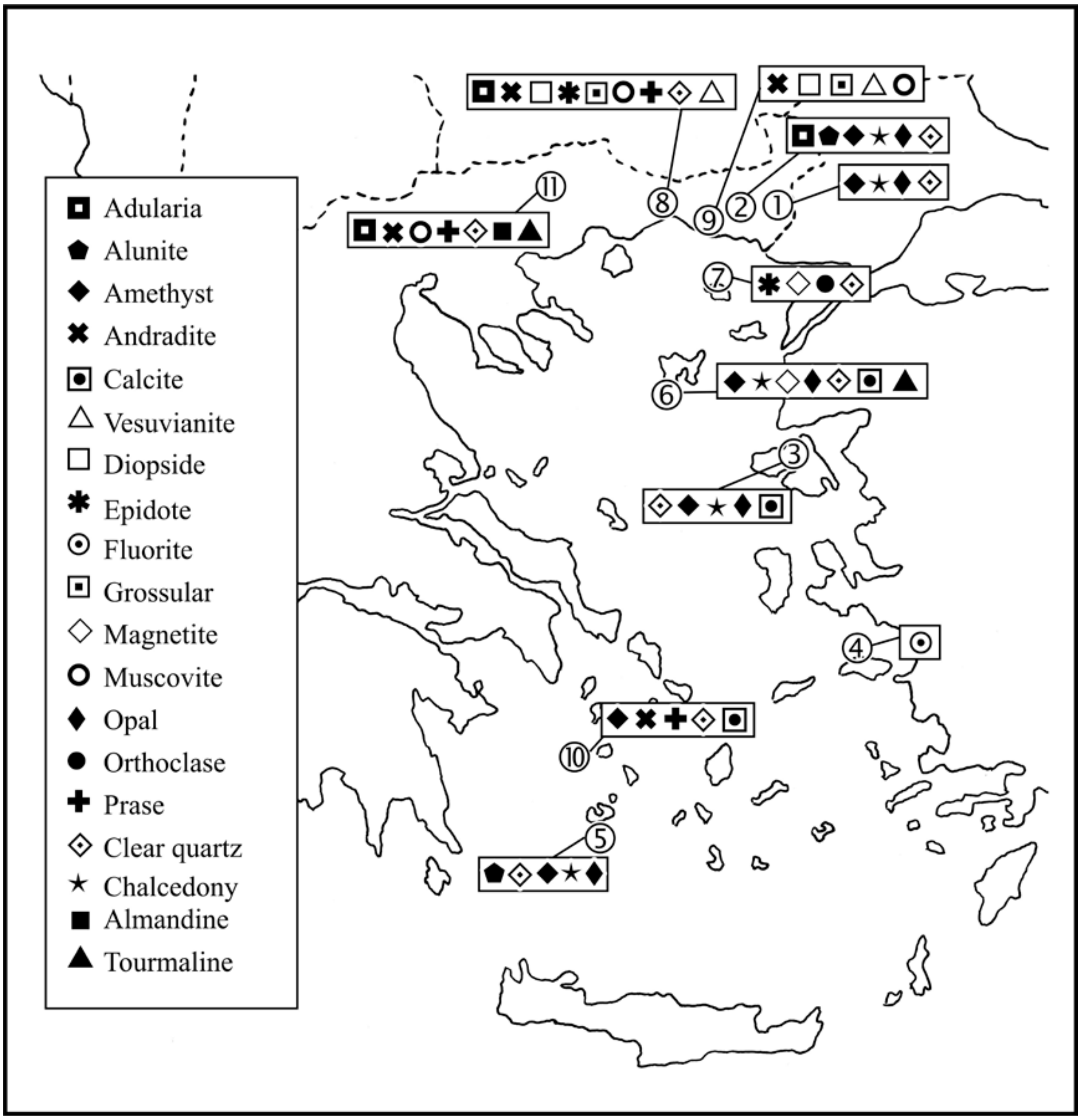


**Fig. 1**. New occurrences of mineral megacrysts in tertiary magmatic rocks and contact metamorphic halos in Greece: 1. Soufli (VR), 2. Sapes (VR), 3. Lesvos (VR), 4. Samos (VR), 5. Milos (VR), 6. Limnos (VR-GR), 7. Samothraki (GR), 8. Kimmeria (GR-SC), 9. Maronia (GR-SC), 10. Seriphos (SC), 11. Drama (SC-PE). Abbrev.: VR: volcanic rocks; GR: Granitoid; SC: contact metamorphism; PE: Pegmatites

## 3. Analytical methods

Analytical methods included optical microscopy, X-powder diffraction studies, and electron microprobe analyses, in the Section of Mineralogy-Petrology at University of Athens. X-powder diffraction measurements were obtained using a SIEMENS D-500 diffractometer with Cu tube and Co filter. For the mineral analyses a scanning electron microscope JEOL JSM-5600 combined with an energy dispersive X-ray microanalysis system Oxford Link Isis 300 system were used.

## 4. Mineral megacrysts in deep magmatic environments

In deep magmatic environments, the new megacryst mineral occurrences are spatially and genetically related to the emplacement and cooling of granitoid bodies. Three distinct sub-environments were distinguished: granitic intrusions, pegmatites and contact metamorphic zones.

### 4.1. Granitoid intrusions

Four new occurrences of mineral megacrysts in tertiary granitoids are presented: Samothraki and Limnos Islands in northern Aegean, and Kimmeria/Xanthi, Maronia/Rhodopi in the mainland in northern Greece (Fig. 1). The new megacryst mineral species include: quartz, K-feldspar, muscovite, magnetite and tourmaline.

Near Fegari Mt in Samothraki Island (photo 1), pink colored **orthoclase** crystals (sized 5 cm) are intergrown with quartz in the voids of veins that penetrate the granite (photo 2). Orthoclase and quartz are associated with minor scheelite, epidote and hematite. The new locality is totally different from the one already known, where the feldspars are incorporated into the granitic matrix (VLACHOU et al. 2001).

**Tab. 1**. Mineralogy of new mineral megacryst occurrences in tertiary magmatic rocks in Greece

| | VR<br>1 | VR<br>2 | VR<br>3 | VR<br>4 | VR<br>5 | VR-GR<br>6 | GR<br>7 | GR-SC<br>8 | GR-SC<br>9 | SC<br>10 | SC-PE<br>11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mineral** | Soufli | Sapes | Lesvos | Samos | Milos | Limnos | Samoth | Xanthi | Maronia | Seriphos | Drama |
| Adularia | | X | | | | | | X | | | X |
| Almandine | | | | | | | | | | | X |
| Alunite | | X | | | X | | | | | | |
| Amethyst | X | X | X | | X | X | | | | X | |
| Andradite | | | | | | | | X | X | X | X |
| Calcite | | | X | | | X | | | | X | |
| Grossular | | | | | | | | X | X | | |
| Diopside | | | | | | | | X | X | | |
| Epidote | | | | | | | X | X | | | |
| Fluorite | | | | X | | | | | | | |
| Magnetite | | | | | | X | X | | | | |
| Muscovite | | | | | X | | | X | X | | X |
| Opal | X | X | | | | X | | | | | |
| Orthoclase | | | | | | | X | | | | |
| Prase | | | | | | | | X | | X | X |
| Tourmaline | | | | | | X | | | | | X |
| Quartz | X | X | X | | X | X | X | X | | X | X |
| Chalcedony | X | X | X | | X | X | | | | | |

Abbrev.: VR: volcanic rocks; GR: granitoids; SC: contact metamorphic zones; PE: pegmatites; Samoth: Samothraki

**Magnetite** in well-shaped octahedral crystals, 1 cm long, represents a new found in Limnos Island (photos 3,4). Magnetite was formed during the potassic alteration of a monzonite porphyry stock, whereas the best crystals were found within fissures and quartz veins. It is associated with K-feldspar, hydothermal biotite, actinolite and chalcopyrite.

**Quartz** veins (up to 1m thick) crosscut altered granitoids (photo 5), and transparent quartz crystals with prismatic habit (up to 10 cm) usually accompany scheelite, hydrothermal muscovite and molybdenite (photo 6). Double terminated crystals were found in Maronia and Kimmeria granitoids.

Idiomorphic **muscovite** crystals and aggregates along with quartz were found in Maronia and Kimmeria. Hydrothermal muscovite intergrown with quartz in cavities of quartz veins is accompanied by molybdenite in Maronia (Melfos et al., 2002) and by pyrite and scheelite in Kimmeria (crystals up to 1cm in diameter).
Finally, **Tourmaline** (var. shorlite) in crystals up to 3cm length occurs in quartz veins and hydrothermal breccias, crosscuting the above mentioned potassically altered monzonitic body at Limnos Island. This is the first reported occurrence of porphyry-Cu related, magmatic-hydrothermal tourmaline in Greece.

### 4.2. Pegmatites

The Greek pegmatites are mostly poor in miarolitic cavities, and thus contain only incorporated mineral crystals. Some pegmatitic bodies in Drama and Evros regions (probable Paleocene age?) include large crystals of garnets, tourmaline, muscovite and epidote. Pegmatitic bodies in Paranesti-Drama area contain 24 sided trapezohedric, red colored **garnet** crystals, up to 3 cm associated with K-feldspar and muscovite. Prismatic **tourmaline** crystals (variety shorlite) sizing up to 10 cm, occur in pegmatites near Nevrokopi-Drama. The most important **muscovite** occurrence is the one in Evros area pegmatites, where well-shaped crystals up to 20 cm occur along with epidote and zoisite crystals. **Epidote** forms prismatic, green colored crystals up to 20cm incorporated in a feldspar- and/or quartz-rich matrix. Evros pegmatites are usually zoned, whereas the central quartz rich core hosts the best epidote crystals. The Naxos pegmatites host excellent sapphire and beryl crystals (3 and 10cm respectively) some of them exhibited in the Mineralogy Museum of Athens University (KATERINOPOULOS & VOUDOURIS 2002).

### 4.3. Contact metamorphic zones

The contact metamorphic zones (scarns) in Greece are very rich in megacryst mineral samples, some of them being unique worldwide. The most important areas are Seriphos, Xanthi, and Maronia and a subordinate one is Kresti near Vrontou Mt in Drama. The contact haloes were formed between granitoids and the surrounding marbles, amphibolites, gneisses and schists. Although minerals such as garnet, vesuvianite, epidote, and calcite are already described as petrogenetic constituents in the above localities (SAPOUNTZIS & CHRISTOFIDES 1982, LIATI 1986, MPOSKOS & DORYPHOROS 1993), for the first time large and splendid crystals and crystal-intergrowths were discovered at these localities and presented in this study.

**Quartz** is abundant in many varieties in Seriphos (GAUTHIER & ALBANDAKIS 1991, VOGT 1991), as well as in Kimmeria/Xanthi and Drama. Recently a new

locality was found in Seriphos, with quartz crystals, up to 20 cm, including unusual combinations of amethyst and prase forming scepter growths (amethyst deposited either on the top or in the basis of the crystals, photos 7, 8). In some cases platy calcite crystals are intercalated between amethyst scepters and the green quartz basis. A split growth is common in Seriphos material resulting in so called “Artischockenquarz”. These worldwide unique specimens were deposited a few meters from the granitic body within a hedenbergitic scarn. Andraditic garnets, hematite and pyrite belong to the mineral paragenesis.
Japan law twin quartz crystals, up to 3 cm long (photo 9), were observed for the first time in Greece at the Kimmeria/Xanthi area. The platy, transparent crystals overlay needle shaped quartz with Muzo habit. The crystals are developed within a wollastonite scarn (photo 10), and sometimes include actinolite needles, obtaining a pale green color. A similar occurrence was located in the Kresti scarn, near Vrontou Mt/Drama, where well-terminated green quartz crystals (due to actinolite inclusions) are intergrown with adularia.

**Calcite** in semi-transparent rounded crystals up to 35 cm (the biggest in Greece), in association with prase is also located in the Seriphos scarn. The intergrowth of platy calcite with prase indicates contemporaneous deposition.

**Garnet** is widespread in all the above mentioned contact metamorphic zones, in varieties reflecting the chemistry of the protoliths. Representative chemical analyses are given in Table 2. In the contact zone of Maronia area the garnets occur both in the exoscarn within the marbles (photo 11) as well as within the endoscarn, where they are associated to diopside, vesuvianite and calcite. The Maronia grossular-andradites (photo 12) reach spectacular sizes (up to 10cm) with color varying between pale green, brown to orange. Some transparent specimens with shiny dodecahedron faces and with striations are of gem quality. Unique for Greece are Ti-Cr-Zr-rich garnets representing solid solutions between andradite, schorlomite, uvarovite and kimzeyite (Tab. 2, Nr. 3). The later form black colored, rhombic dodecahedra up to 0.5cm. In Kimmeria area two new localities with splendid crystals of garnets, regarding their shapes and colors, were found. In western Kimmeria and at the contact of either marbles and/or amphibolites, deep green colored garnets (3 cm) are associated with wollastonite, sphene, adularia, epidote, and calcite; the endoscarns are best places for the collection of transparent grossulars and green diopside. In the eastern Kimmeria, within the gneisses, the garnets are zoned brown-colored andradites. Red-brown andradites also occur in the Kresti scarn at Vrontou Mt/Drama. Finally, in Seriphos scarns the already famous garnets are deep brown to orange colored usually with a zonal growth (VOGT 1991).

**Epidote** has already been described as a scarn constituent mainly at Seriphos, Lavrion and Western Kimmeria (BALTATZIS 1981, LIATI 1986). However, these localities are not comparable with the new occurrence of eastern Kimmeria. In this locality epidote and quartz rich pockets occur within granatitic hornfels as well as in endoscarns within the Kimmeria granodiorite (photo 13). Well-terminated, prismatic, deep green colored epidote crystals, up to 10 cm long, were found (photo 14). Many clusters show grooved slender crystals or acicular sprays, a common habit of Kimmeria epidotes.

The endoscarns in the granitoids from Kimmeria (photo 15) and Maronia are hosts of large **vesuvianite**, **diopside** and **adularia** crystals.

**Vesuvianite** crystals from Kimmeria, up to 10 cm long, are characterized by bipyramidal forms and by the absence of prismatic faces (photo 16). This is not only the best occurrence in Greece, but probably one of the best in the world. In the Maronia area the vesuvianites (up to 5 cm) display a large variety of crystal habits such as stubby bipyramidal, columnar prismatic and tabular. A pinacoid can truncate the pyramids. The tabular crystals are believed to represent preudomorphs after diopside. Pale green colored vesuvianite in both areas replace earlier deposited garnets and diopsides and reach gem qualities.

**Tab. 2.** Representative microprobe analyses of garnets from Greek scarns

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| $SiO_2$ | 38.22 | 39.03 | 27.68 | 31.61 | 35.01 | 35.40 |
| $Al_2O_3$ | 18.79 | 19.60 | 4.67 | 3.89 | 2.15 | 13.74 |
| $TiO_2$ | 1.10 | 0.13 | 8.68 | 7.04 | 0.08 | 0.00 |
| Fe2O3 | 6.25 | 4.89 | 13.17 | 24.18 | 29.12 | 15.24 |
| $Cr_2O_3$ | 0.00 | 0.09 | 7.42 | 0.00 | 0.34 | 0.05 |
| MnO | 0.2 | 0.07 | 0.07 | 0.29 | 0.02 | 3.56 |
| MgO | 0.64 | 0.39 | 0.74 | 0.41 | 0.09 | 0.00 |
| CaO | 34.92 | 35.4 | 32.74 | 32.11 | 34.98 | 34.08 |
| $ZrO_2$ | 0.00 | 0.00 | 4.14 | 0.42 | 0.00 | 0.00 |
| Total | 100.12 | 99.60 | 99.31 | 99.95 | 101.79 | 102.07 |
| Number of cations based on 12O | | | | | | |
| Si | 2.93 | 3.00 | 2.36 | 2.64 | 2.88 | 2.76 |
| Al | 1.69 | 1.76 | 0.47 | 0.38 | 0.20 | 1.26 |
| $Fe^{(3+)}$ | 0.32 | 0.21 | 0.85 | 1.52 | 1.80 | 0.89 |
| Ti | 0.06 | 0.01 | 0.56 | 0.44 | 0.01 | 0.00 |
| Cr | 0.00 | 0.01 | 0.50 | 0.00 | 0.02 | 0.01 |
| $Fe^{(2+)}$ | 0.04 | 0.07 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mg | 0.07 | 0.04 | 0.09 | 0.05 | 0.01 | 0.00 |
| Mn | 0.01 | 0.01 | 0.01 | 0.02 | 0.00 | 0.23 |
| Ca | 2.87 | 2.90 | 2.99 | 2.88 | 3.08 | 2.85 |
| Zr | 0.00 | 0.00 | 0.17 | 0.02 | 0.00 | 0.00 |
| Mol % end members | | | | | | |
| Almandine | 1.34 | 2.32 | 0.00 | 0.00 | 0.00 | 0.00 |
| Andradite | 19.00 | 11.05 | 35.60 | 77.00 | 94.76 | 46.35 |
| Grossular | 76.99 | 84.48 | 0.00 | 0.00 | 3.87 | 45.66 |
| Pyrope | 2.34 | 1.32 | 0.00 | 0.00 | 0.32 | 0.00 |
| Spessartite | 0.33 | 0.33 | 0.00 | 0.00 | 0.00 | 7.47 |
| Uvarovite | 0.00 | 0.50 | 26.18 | 0.00 | 1.05 | 0.52 |
| Schorlomite | 0.00 | 0.00 | 29.32 | 22.00 | 0.00 | 0.00 |
| Kimzeyite | 0.00 | 0.00 | 8.90 | 1.00 | 0.00 | 0.00 |

1. Brown grossular-andradite associated with diopside from Maronia; 2. green grossular-andradite associated with phlogopite from Maronia; 3. black Cr-Ti-Zr "andradite" from Maronia; 4. black Ti-Andradite from Maronia; 5. green andradite with titanite and wollastonite from Kimmeria; 4. Red andradite-grossular from Drama area.

**Adularia** in milky short prismatic to tabular crystals (up to 2cm) were found in association with andradite, epidote, calcite and pyrite in northern Kimmeria scarn (photo 17).

Green colored **Diopsides** from Maronia and Kimmeria are intergrown with grossular and andradite in small cavities (photo 18). They form prismatic and/or tabular crystals reaching sizes up to 5cm.

**5. Minerals in volcanic rocks**

New finds of amethyst, rose quartz, alunite, fluorite, chalcedony and opal, genetically related to tertiary volcanic rocks, were tracked down in still unknown localities. Clear quartz crystals in Greek volcanic environments is widespread, and thus not further described here. Although chalcedony and opal do not occur in crystalline forms, they will be presented because of their excellent quality.

**Amethyst**, already described in Soufli area (SAPOUTZIS & CHRISTOFIDES 1982), occurs also in Sapes-Rhodopi region and in Lesvos, Limnos and Milos Islands. In Sapes and Lesvos Island, amethyst occurs in the form of banded quartz-chalcedony veins hosted within adularized volcanics and is accompanied by gangue adularia (VOUDOURIS 1993, KELEPERTZIS 1998). Amethyst from these localities is deep purple color, usually massive, rarely crystals up to 2cm were observed in vugs. In Milos and Soufli/Evros, amethyst-chalcedony bearing veins crosscut propylitic altered and fresh subaqeous dacitic lavas (photo 19). In both areas amethyst occurs as late vein-filling, intergrown with barite and zeolites respectively. Well-developed stubby crystals with pyramid terminations (up to 2cm) occur as open space filling in the centre of the veins.
Recently a new occurrence of amethyst was localized in Lesvos Island, where well-shaped, transparent crystals occur in epithermal veins, hosted in propylitized lavas (photos 20, 21). Amethyst is accompanied by calcite and epidote. In contrast to the above mentioned occurrences, the Lesvos amethyst is prismatic, up to 10cm in length and displays sceptre and window growths, and double terminated forms, typical for the Mexican and Sardinian amethysts (LIEBER 1994). A new find of stubby rose quartz crystals from Lesvos Island is related to quartz-chalcedony veins penetrating subaqeous lavas and overlaying limestones of Miocene age.

**Chalcedony**, the microcrystalline variety of quartz, accompanying amethyst in Milos and Sapes is massive and usually restricted to vein walls. At Soufli, Lesvos and Limnos, chalcedony forms typical botryoidal and stalactitic aggregates. The Soufli chalcedony fills fissures in relatively fresh lavas, and is accompanied by clear quartz and/or amethyst. In cavities, purple to blue chalcedony stalactites (up to 5cm in length) were observed. In Lesvos Island, chalcedony rich veins crosscut volcanic rocks (KELEPERTZIS A. 2000, pers. comm.), representing the only locality in Greece with typical geodes. Voids in the lavas are filled with botryoidal chalcedony aggregates with dimension up to 10cm, varying in color from pale to deep blue (photo 22). Recrystallization of chalcedony resulted in the late development of small quartz crystals. Achate (banded chalcedony variety) was also found in Lesvos in close relation to the above mentioned rose quartz veins.

**Opal** occurs all around Greek volcanic fields, in several varieties and colors (deep red, yellow, black, orange and green) reflecting chemical impurities. In Lesvos Island opal is the main component of fossilized wood (KELEPERTZIS & VELITZELOS 1992, VELITZELOS & ZOUROS 1997). New localities with opal occurrence include Sapes area, Soufli, Limnos and Milos. Fault related opaline silica associated with alunite is widespread in the epithermal altered environments of Evros and Lemnos (VOUDOURIS & SKARPELIS 1998). Stratiform opalized zones are developed mainly within fresh volcanic rocks (Evros, Limnos, photo 23) or argilically altered ones (Milos). Representative X-powder diffraction diagrams from Greek opals are given in Figure 2, demonstrating the transformation of opal-CT to quartz in some samples.

**Alunite** was located in altered volcanics in Kassiteres/Sapes area (Evros) and Milos Island. Alunite forms tabular to flattened rhombohedral looking crystals. The pseudorhomboedric forms are a combination of two trigonal pyramids. In Kassiteres, coarse-grained alunite rich veins (up to 50 cm thick with crystals sizing up to 2 cm) crosscut silicified volcanics. Electron microprobe analyses indicated a composition close to end member alunite with $Na_2O$ up to 1.7 wt%, $K_2O$ up to 9.41 wt%, SrO up to 0.3 wt%, BaO up to 0.9 wt %, $Ce_2O_3$ up to 0.4 wt%, $SO_3$ up to 40.4 wt% and $P_2O_5$ up to 0.6 wt%. The Milos alunites are world-class with rhombohedral looking crystals reaching up to 5 cm size.

A new occurrence of **fluorite** megacrysts was found in volcanic rocks in Samos Island, where monomineralic fluorite veins, crosscut epithermally silicified zones. The veins are banded and the voids are filled with deep purple crystals up to 5 cm.

**Calcite** in platy crystals up to 5cm accompany the quartz varieties in Lesvos and Limnos Islands.

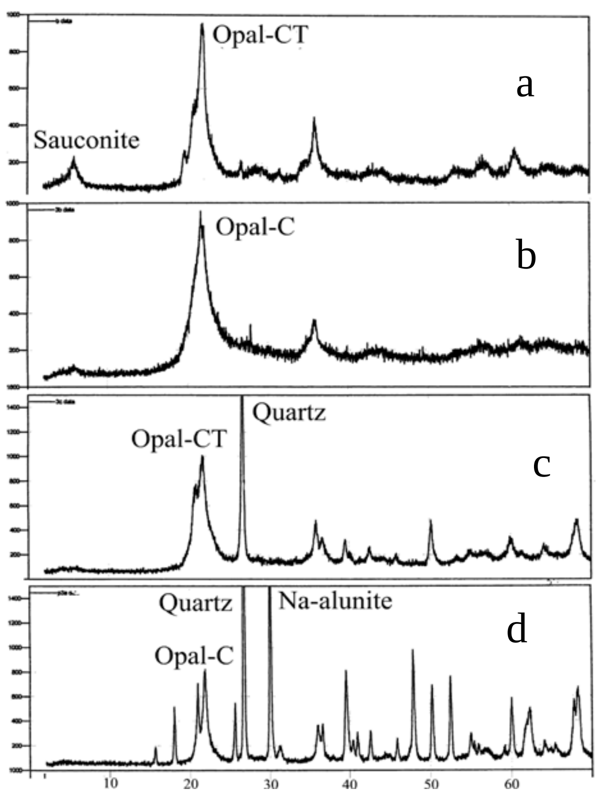


**Fig. 2.** X-ray powder diffraction diagrams of various Greek opals (a): green opal-CT (color due to sauconite admixtures) from Sapes; (b, c) white and brown opal-CT and quartz from Lykofi Evros; (d) opal-C, quartz and alunite from Limnos Island.

**6. Discussion**

All the new finds of mineral megacrysts described are genetically related to the tertiary magmatic activity in Greece and especially to the magmatic centres developed in Thrace (Kimmeria, Kassiteres-Sapes, Maronia-Perama, Soufli-Dadia-Levkimi, Drama, Samothraki), Limnos, Lesvos (Lepetymnos-Stipsi), Seriphos and Milos Islands. The minerals are deposited as a result of the development of magmatic-hydrothermal and geothermal (epithermal) systems, during the waning stages of magmatic activity in the studied areas.

Figure 3 represents a hypothetical schematic model, where the mineral megacryst occurrences in Greece are related to the various geological environments (plutonic-subvolcanic intrusions, zones of contact metamorphism and peripheral volcanic rocks), taking into consideration that the mineral depositing mechanisms within a single magmatic center, represent a continuous process in time and space. The hypothetical depths are speculated on the basis of geological criteria.

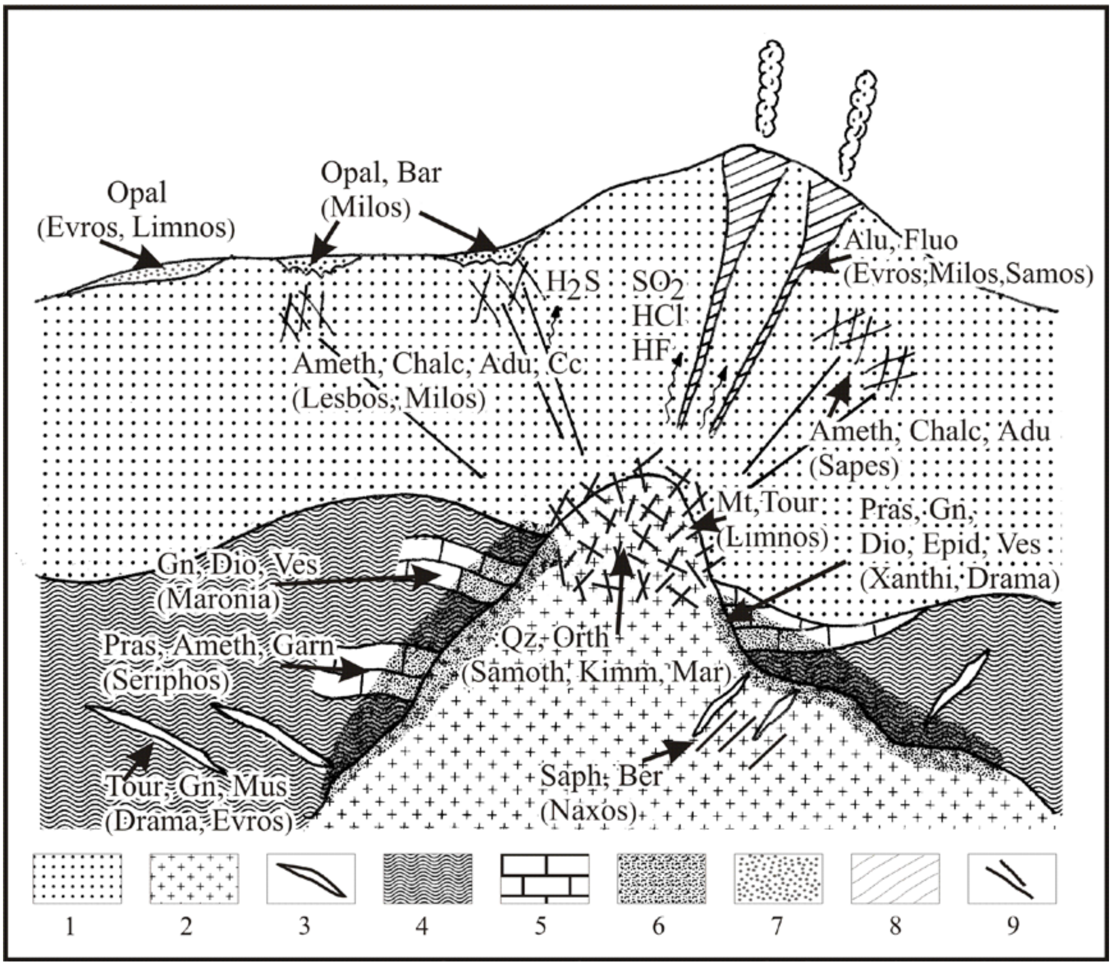


**Fig. 3**. Hypothetical model presents the various mineralization environments related to magmatic-hydrothermal and epithermal processes of tertiary age. 1. Volcanic rocks, 2. Granitoid intrusions, 3. Pegmatites, 4. Metamorphic basement (gneisses, schists, etc), 5. Metamorphic basement (marbles), 6. Scarn, 7. Silica sinters, 8. Residual silicification, 9. Quartz veins, Abbreviations: Adu: adularia, Alu: alunite, Ameth: amethyst, Bar: barite, Ber: beryl, Cc: calcite, Chalc: chalcedony, Dio: diopside, Epid: epidote, Fluo: Fluorite, Gn: garnet, Mus: muscovite; Mt: magnetite, Orth: orthoclase, Pras: prase; Saph: sapphire, Tour: tourmaline, Ves: vesuvianite.

The mineralization in the scarns started with the deposition of anhydrous minerals such as garnets and pyroxenes and ended in the deposition of quartz, actinolite, epidote, and vesuvianite in a retrograde stage and under temperature decrease and meteoric water incursion (according to MEINERT 2000). Contemporaneously, magmatic-hydrothermal fluids circulating within the granitoids were responsible for the deposition of quartz veins with feldspars, magnetite, muscovite, molybdenite and scheelite. Approximately during the same stage, gases rich in $SO_2$, HCl and HF released from the granitoids, as they ascended towards the surface, reacted with the deep-circulating groundwaters and led to the formation of acid sulfate-chloride fluids in a subvolcanic-volcanic environment. The hypogene (according to the criteria of RYE et al. 1992), vein-type alunites and the fluorite described from Thrace, Milos and Samos as well as some of the silicified zones in Thrace and Limnos are ascribed to this environment.
Later, the systems shifted from a magmatic-hydrothermal dominated stage to a geothermal one, due to the increasing incursion of meteoric waters. Changes of the physico-chemical conditions of the ascending geothermal fluids were the major factors controlling the mineral deposition in this geothermal-epithermal environment. The crystallization of the silica varieties (quartz, amethyst, chalcedony and opal), calcite and adularia is attributed to these changes. Opalized horizons in Thrace and Limnos could represent silica sinter deposition from alkali or neutral geothermal fluids (HENLEY & ELLIS 1985). Rapid cooling, probably due to mixing and/or boiling processes, resulted in deposition of microcrystalline silica varieties whereas slow crystallization resulted in coarse-grained and well developed crystals. Boiling processes are responsible for the crystallization of adularia and platy calcite (SIMMONS & BROWNE 2001). The transition from chalcedony to quartz crystals in the geodes of Lesvos, indicate recrystallization of a probably amorphous silica gel during cooling (FOURNIER 1985). The recrystalization from an amorphous material to opal-CT and finally to quartz, was verified by the XRD studies. Amethyst, indicative of oxidizing conditions (FOURNIER 1985), was probably deposited as a result of mixing of the ascending hydrothermal fluids with meteoric and/or seawater.

The Seriphos, Maronia and Kimmeria contact metamorphic zones, the granitoids of Samothraki and Kimmeria, as well as many mineralized volcanic environments e.g. Sapes, Milos, Lesvos and Limnos can be considered as mineralogical treasures, unique in Europe, and some of them, all round the world. They belong to the Greek mineralogical and geological heritage (VELITZELOS et al. 2002), and should be characterized as European mineralogical geotopes.

**Acknowledgements**
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## Photo Catalogue

**Plate 1**

**Photo 1:** Panoramic view of Samothraki granite- Mt Fengari.

**Photo 2**: Quartz-orthoclase veins crosscutting the Samothraki granite

**Photo 3:** The monzonite porphyry of Fakos/Limnos.

**Photo 4:** Octahedral magnetite crystals (up to 0.5cm) on fissure of a monzonitic specimen from Limnos.

**Photo 5**: Quartz boulders from the quartz veins crossucuting the Kimmeria granodiorite.

**Photo 6:** Quartz crystals in cavity from the veins crosscutting the Kimmeria granodiorite (crystals up to 2cm).


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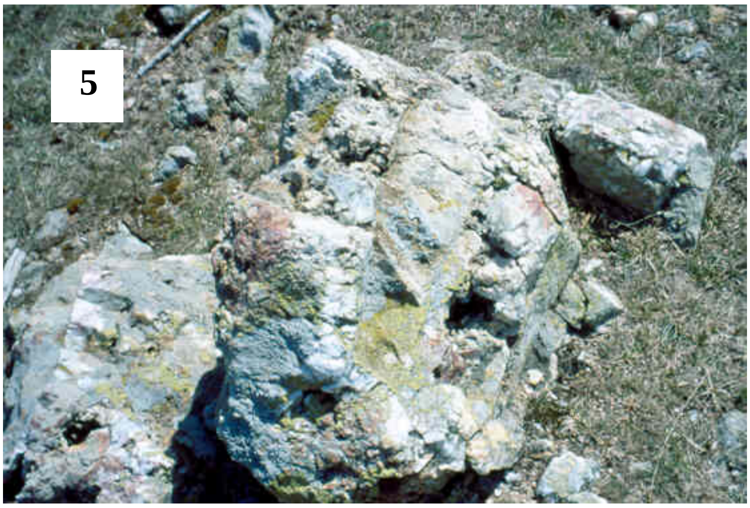
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**Plate 2**

**Photo 7:** Bi-colored quartz crystal from Seriphos: prase (lower part), amethyst in the upper part (length 15cm).

**Photo 8:** "Artischockenquarz" with lower amethystine part and upper green quartz ceptre.

**Photo 9**: Cavity within the wollastonitic scarn of Kimmeria filled with quartz crystals twinned after the Japan twin law.

**Photo 10:** Quartz crystals with Japanese twinning from Kimmeria (single crystals up to 4cm length).

**Photo 11**: Panoramic view of the Maronia scarn: on the left, the marbles on the right the scarns.

**Photo 12:** Pale green rhombic dodecahedra grossular crystals from the Maronia endoscarn (crystal size 3cm).


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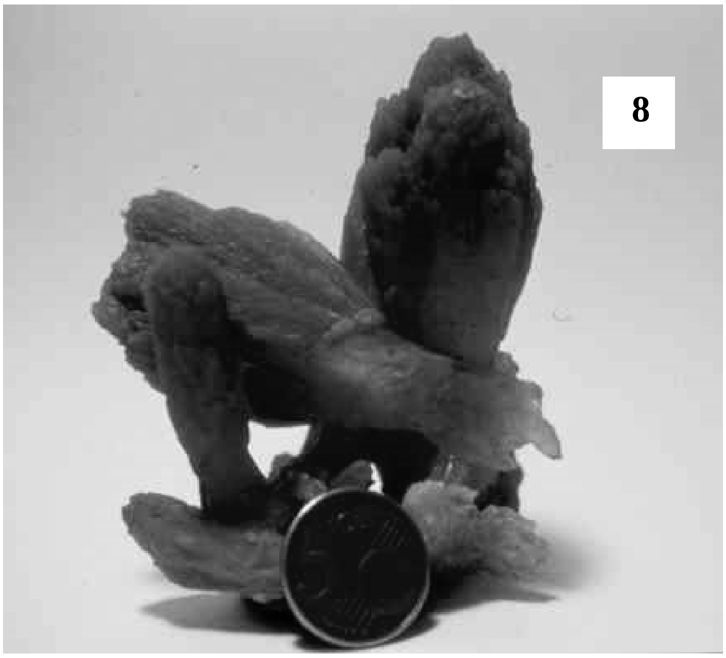
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**Plate 3**

**Photo 13**: Panoramic view towards the epidote bearing scarn in eastern Kimmeria: on the left the granodioritic body, on the right contact metamorphic rocks.

**Photo 14**: Quartz and epidote from Kimmeria (specimen size 20cm).

**Photo 15:** Vesuvianite cavity within endoscarn in Kimmeria

**Photo 16**: Bi-pyramidal crystals of vesuvianite from Kimmeria (specimen size 11cm)

**Photo 17**: Adularia crystals up to 1cm with epidote and pyrite from Kimmeria scarn,

**Photo 18**: Brown grossular and diopside from Maronia (specimen size 12cm)

**13**

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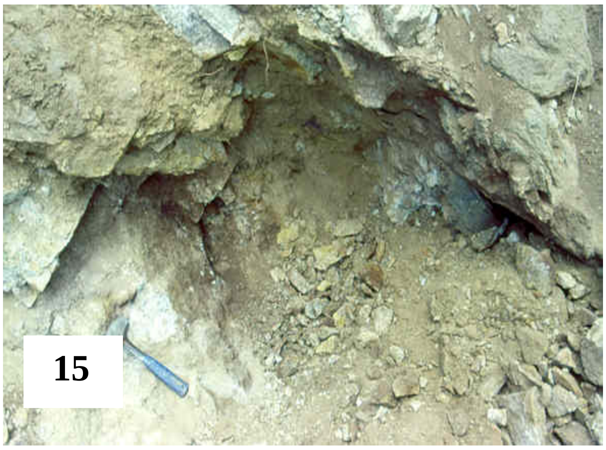

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**18**

**Plate 4**

**Photo 19:** Subaqeous dacitic lavas, crosscut by amethyst bearing veins, Milos island

**Photo 20:** Double-terminated amethyst crystal from Lesvos Island (length 5cm)

**Photo 21**: Amethyst crystals and calcite from Lesvos Island

**Photo 22**: Bortyoidal blue chalcedony from Lesvos (specimen size 20cm)

**Photo 23**: Achate and quartz in limestone from Lesvos (specimen size 15cm)

**Photo 24**: Red opal-horizon within pyroclastics south of Sapes/Thrace.


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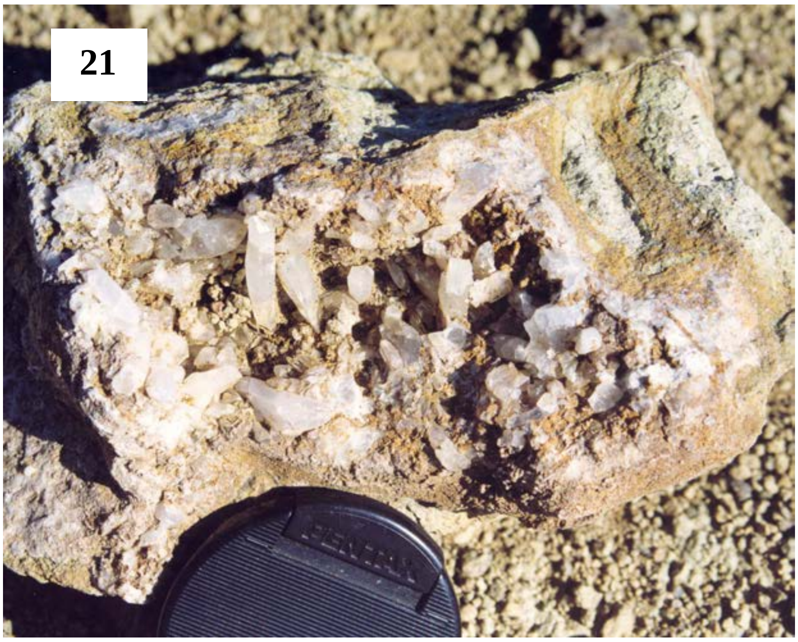
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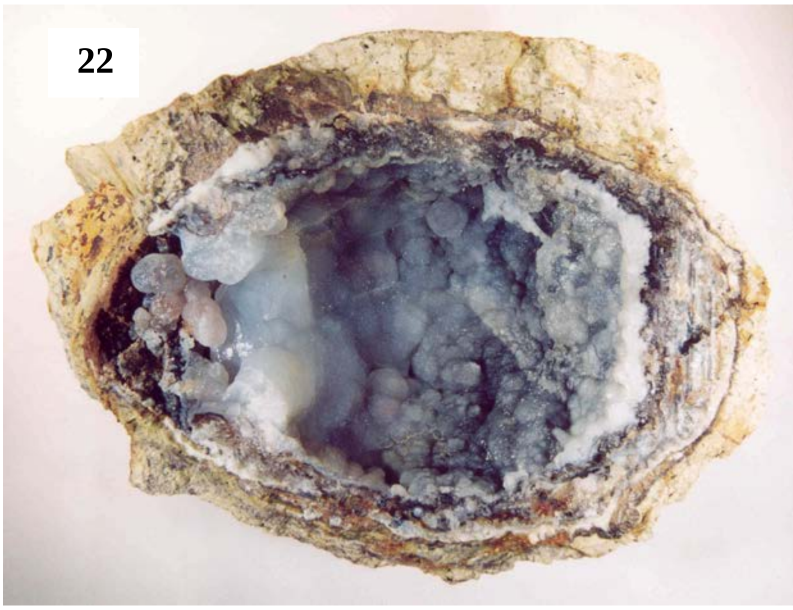
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# Alpine-type Fissure Minerals in Greece

**P. VOUDOURIS[1], A. KATERINOPOULOS[2], V. MELFOS[3]**

**Summary**

A systematic mineralogical research of the metamorphic complexes in Greece led to the localization of large crystals (megacrysts), mainly quartz, and other minerals such as adularia, albite, chlorite, byssolith, hematite, muscovite, rutile and epidote within alpine-type fissures. As a result, Greece can be regarded as an alpine-type mineralogical province. Alpine-type fissure minerals in Greece are identified in a wide range of rock lithologies (gneisses, amphibolites, quartzites, metapegmatites, schists, etc) mainly within three tectono-metamorphic provinces: the Rhodope Massif, the Attico-Cycladic Massif, and the metamorphic complex of Crete Island. Quartz crystals were found in an enormous variety of colors and forms with excellent material coming from Attica, Evia, Ios, Thassos and Drama areas. Gem-quality smoky- and rocky crystal quartz varieties, green-colored quartz and amethyst were found in several localities reaching sizes up to 40cm. Different crystal habits, as prismatic quartz, Tessin-habit quartz, fiber quartz, gwindle, sceptre- and window-shaped forms are of world-class quality. In addition adularia crystals (up to 3cm in size), albite (up to 6cm), hematite in iron roses (up to 5cm), chlorite (idiomorphic crystals up to 2cm in diameter), byssolith, calcite, epidote (up to 5cm in size), pyrite, white mica (flakes up to 3cm in diameter), rutile (needles up to 3cm) are localized for the first time in Greece.

Based on the existing data, it can be proposed that the formation of alpine-type fissures in Greece and their mineralogy are closely related to the extensional tectonics accompanying the exhumation of the metamorphic core complexes. Initial formation probably took place close to the brittle-ductile transition but most of the veins are clearly late-stage, filling subvertical fractures. Preexisting pegmatites and quartz veins in the Variscan and Mesozoic granitoids and associated rocks were probably involved in recrystallization processes and redistribution of chemical components in the fissures during the Miocene stage of extension in Greece.

Alpine-type fissure minerals are not only of great scientific interest, they can also be considered as mineralogical treasures, unique in Greece and in Europe. Areas like Evia, Thassos, Drama, Attika and Andros Island should be characterized as European mineralogical geotopes.

**Keywords:** alpine-type fissure minerals, megacrysts, post-metamorphic veins, exhumation, mineralogical geotopes

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**Content** **Page**



## 1. Introduction

The Austrian, Swiss and Italian Alps are famous for their large euhedral minerals (crystals reaching sizes up to 1.5m) contained in fissure veins, called Alpine fissure minerals (STALDER 1964, STALDER & TOURAY 1970, MULLIS 1975, 1988, 1996). Formation of the fissure veins began after the peak metamorphic conditions and continued during the retrograde paths of orogenic evolution under transpressional, transtensional and finally post-kinematic extensional conditions. Alpine fissure vein mineralizations represent important indicators of fluid activities during the last stages of continental collisional regimes (MULLIS et al. 1994).

Alpine-type fissure minerals also occur in other regions in the world with alpine-type collisional tectonics, such as Himalaya, the polar Urals, Norway, USA, and Brazil (NIEDERMAYER 1993). In Rheinisches Schiefergebirge/Germany, WAGNER & COOK (2000) demonstrated that formation of the Alpine-type quartz veins can be related to the late (retrograde) stage of the Variscan orogenic evolution.

The presence of large, euhedral crystals of alpine-type fissure minerals is scarcely known in Greece. There are only few reports, coming from German collectors, referring to quartz crystals in Crete Island and Attica (NIEDERMAYER 1993, WENDEL & KAPELAS 1996).

A systematic mineralogical research of the metamorphic core complexes in Greece, led to the localization of megacrystals, mainly quartz up to 40 cm in size, and of other minerals such as adularia, albite, chlorite, byssolith, hematite, muscovite, rutile and epidote. In the present study alpine-type fissures in Greece are described, as well as the paragenesis of associated crystals. The relative localities were completely unknown up to today. The new occurrences are presented in Figure 1 and listed in Table 1.

## 2. Geological setting

The Hellenides (the Greek mountain chains) belong to the Alpine-Himalayan orogenic zone that was formed through the Cenozoic collision between the Eurasia and the African, Apulian, Arabian and Indian plates, consuming the Tethyan ocean. In Greece three major tectono-metamorphic provinces have been distinguished: the Rhodope Massif, the Attico-Cycladic Massif with its northern extension the Pelagonian Zone and the metamorphic complex of Crete Island and south Pelopones. Besides relics of Hercynian (or even older) basement, the metamorphic complexes in Greece are mainly composed of tectonic units, which have been stacked during the Alpine orogeny.

The Rhodope Massif consists of a series of distinct tectonic units with different metamorphic evolution in time. Paleozoic and Mesozoic sedimentary and magmatic protoliths constitute a major part of the Massif (LIATI & GEBAUER 1999, MPOSKOS & KOSTOPOULOS 2001, MPOSKOS & KROHE 2001, LIATI et al. 2002). According to LIATI et al. (2004) there is a series of microcontinents separated by oceanic basins

that successively collided after subduction episodes at ca. 150 Ma, ca. 73 Ma and ca. 42 Ma.
In the Attico-Cycladic Massif the allochtonous Cycladic Blueschist Unit (CBU) consists of marbles with mica-schist intercalations and is grading upwards to a more than 1km thick quartzite-rich series containing basic and acid volcaniclastic materials with ophiolitic fragments (PAPANIKOLAOU 1978, OKRUSCH & BRÖCKER 1990).
The CBU covers the autochtonous Basal Unit consisting of Mesozoic platform carbonates.
The Phyllite-Quartzite Unit (PQU) in Crete Island and in south Pelopones consists of phyllites and quartzites with metavolcanic rocks, metaconglomerates and marble intercalations of Permian to Late Triassic age with relicts of a Hercynian basement (SEIDEL et al. 1982, ZULAUF et al. 2002).

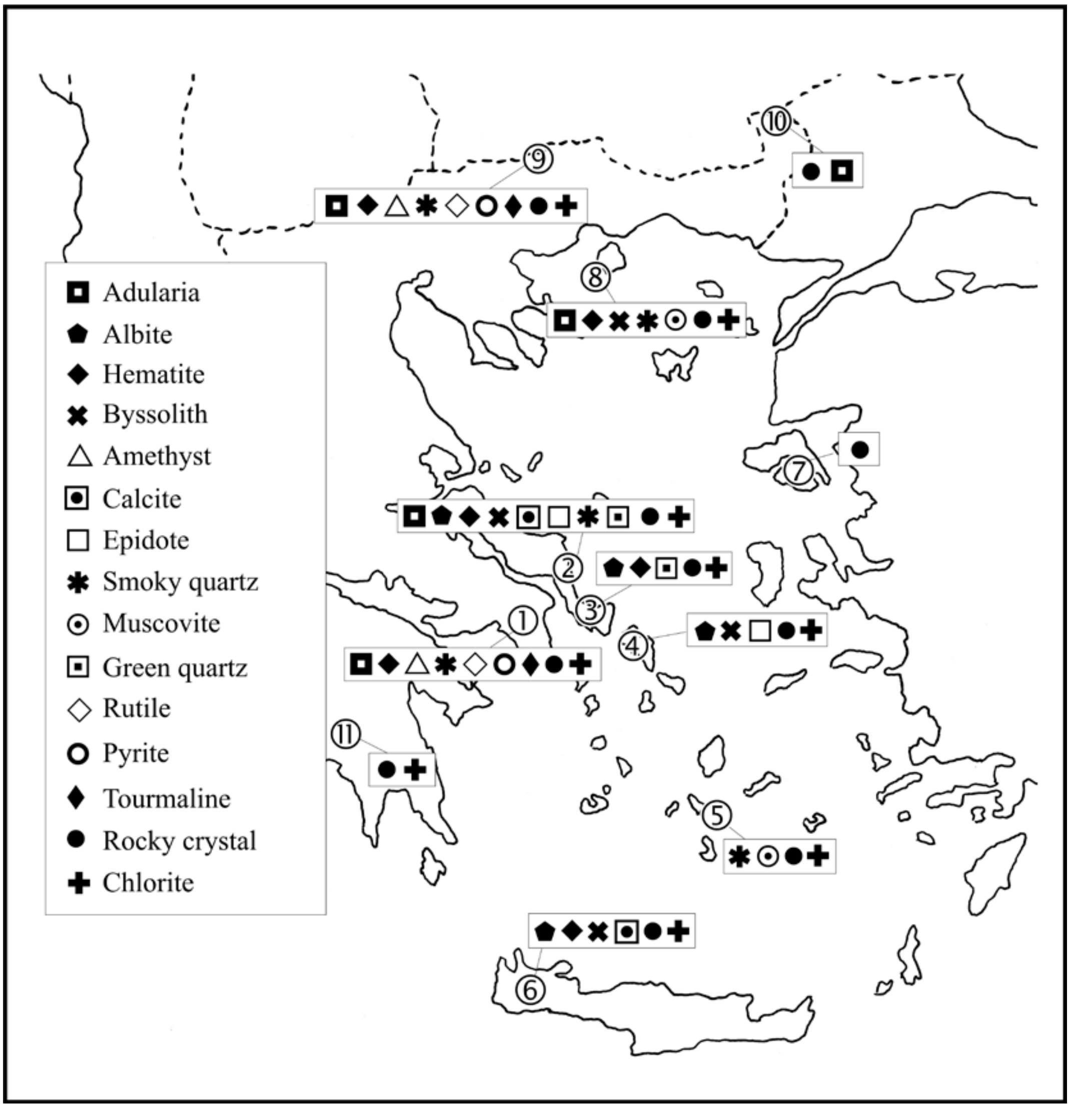


**Fig. 1.** New occurrences of Alpine fissure minerals in Greece: 1. Attika, 2. Central Evia, 3. South Evia, 4. Andros Island, 5. Ios Island, 6. Crete Island, 7. Lesvos Island, 8. Thassos Island, 9. Drama, 10. Evros, 11. South Pelopones.

Following an initial compressional phase of the Alpine orogeny related to HP/LT regional metamorphism of the rocks at 42-40 Ma in the Rhodope (LIATI & GEBAUER

1999), at 45Ma in the Cyclades (BRÖCKER & ENDERS 1999) and at 24-19Ma at Crete island (SEIDEL et al. 1982), subsequent exhumation of high-P rocks was accompanied by a regional Barrovian-type metamorphism that locally reached partial melting conditions (BALTATZIS 1996, KEAY et al. 2001). The onset of extensional deformation in the different tectonometamorphic terranes occurred at >20Ma for Rhodope Massif (DINTER & RHOYDEN 1993, GAUTIER et al 1999), 23-21Ma for the Cyclades (OKRUSCH & BRÖCKER 1990, GAUTIER & BRUN 1994, BRÖCKER & FRANZ 1998) and >19Ma for Crete island (THOMSON et al. 1998).

Alpine fissure minerals in Greece are hosted in a wide range of rock lithologies (gneisses, amphibolites, quartzites, metapegmatites, schists, etc). Analytically, in the Rhodope massif are examined: the Hercynian (KOSTOPOULOS D., personal comm.) orthogneiss of Dassoto/Drama belonging to the Sidironero unit (MPOSKOS & KROHE 2001), and the Hercynian ortho- and paragneisses of Thassos Island belonging to the lower- and intermediate units which constitute the metamorphic core of the Rhodope Massif (WAWRZENITZ & KROHE 1998). In the Attico-Cycladic Massif are examined: the Middle-Upper Permian orthogneisses in Pentelikon Mt (LOZIOS 1993, KOSTOPOULOS & REISCHMANN, personal comm.), the Permian – Middle Triassic meta-rhyolites of the Ochi-Unit (blueschist unit) in Evia (KATSIKATSOS 1991, SHAKED et al. 2000, PE-PIPER & PIPER 2002), and the Pre-Hercynian Ios orthogneiss (HENJES-KUNST & KREUZER 1982, VANDENBERG & LISTER 1996). In Crete Island alpine-type fissure minerals were mainly found in quartzites of the Phyllite-Quartzite unit (SEIDEL et al. 1982). Alpine-type fissure minerals were also located in metabasic rocks such as amphibolites in Evros area (Kymi complex after MPOSKOS & KROHE 2001), chloritic schists and amphibolites in Thassos Island and Evia as well as in Andros Island. Finally Carboniferous to Triassic phyllites of the Lesvos Island Autochton also host alpine fissure minerals.

### 3. Analytical methods

Analytical methods included optical microscopy, X-powder diffraction studies and electron microprobe analyses, in the Section of Mineralogy-Petrology at University of Athens, the Department of Mineralogy-Petrology-Economic Geology, University of Thessaloniki and the Department of Mineralogy and Petrology, University of Hamburg. X-powder diffraction measurements were obtained using a SIEMENS D-500 diffractometer with Cu tube and Co filter. For the mineral analyses a) a scanning electron microscope JEOL JSM-840 combined with an energy dispersive X-ray microanalysis Oxford Link Isis system and b) a Cameca-SX 100 wavelength-dispersive electron microprobe were used.

### 4. Occurrence of alpine-type fissures

Two types of Alpine fissures can be distinguished (MULLIS et al. 1994): tension gashes and interboudin gaps. According to MULLIS et al. (1994) the tension gashes usually develop parallel to the maximum stress at an angle of about 45º to the shearing surface. They are mostly arranged in en echelon fashion. Interboudin gaps generally develop parallel to the direction of maximum extension in rocks of different competence.

Both types of fissures, mainly occurring as individual veins, are sampled during the present study (photos 1, 2, 3, 4). Most fissure veins are elongate or sigmoidal, usually correspond to systems of en echelon tensional cracks, and are developed as lens-like bodies perpendicular to rock structure. The fissure veins display characteristic extensional features crosscuting the major structural elements of the Alpine compressive deformation.

Their thickness varies between a few cm and about 2m (in extreme cases up to 10m). Their length ranges between 1 and 50m. Usually there is an alteration zoning concentric to the fissure vein, with an innermost zone of a quartz layer (surrounding the cavity), grading outwards to a leached rock and then to the unaltered, fresh rock. In other cases the leached zone and the quartz layer are absent or very thin and the crystals are grown in direct contact to the almost fresh host rocks. In addition a complex network of veins and veinlets of different dimensions and orientations was prospective for euhedral crystal and also studied (photo 5). In this case the veins exhibit no consistent preferred orientation, nor are their orientations related to structures in the host rocks.
A feature of the fissure vein evolution is the early deposition of massive, blocky quartz, and late growth of idiomorphic quartz crystals in open spaces, indicating that the vein remained open for a significant period of time, enough for the crystals to grow into the cavity (OLIVER & BONS 2001). Brecciation during vein formation and deformation fabrics as the presence of S-shaped quartz crystals and brecciation of even idiomorphic quartz crystals are common and indicate ductile to brittle tectonic events during some stages of fissure vein formation.

**5. Mineralogy of alpine-type fissures**
As a general rule the mineralogy of alpine fissures is closely related to the chemistry of the host rocks: Chemical components released from the hostrocks are transferred to the interior of the fissures and gave genesis to Alpine minerals (according to NIEDERMAYER 1993). The alpine-type fissures in Greece are characterized mainly by the presence of quartz crystals (that have grown in from the walls at a high angle), and subordinate by adularia, albite, chlorite, epidote, byssolith, calcite, hematite, muscovite, rutile, pyrite and tourmaline.

**Quartz** was found in an enormous variety of forms (RYKART 1995), with excellent material coming from fissure veins hosted mainly within orthogneisses and pegmatoids from Attica, Evia, Ios, Thassos and Drama areas. Idiomorphic crystals reach sizes up to 40 cm. Both transparent smoky- and rocky crystal quartz varieties were found. Almost black colored quartz (variety morion) occurs in Drama area. Green-colored quartz was found in Attica, Evia, Andros and Thassos, the degree of coloring depending on abundance of chlorite or byssolith inclusions. Deep violet amethyst (in worldclass quality) is already known from Drama area (SAPOYTZIS & CHRISTOFIDES 1982).
Different crystal forms similarly to the Alps (MULLIS et al 1994) have been observed: prismatic quartz, Tessin-habit quartz, fiber quartz, and skeletal quartz, the later including sceptre- and window-shaped forms. Prismatic quartz crystals (as a result of the combination of a first class prism and two rhombohedral faces) are ubiquitous (photo 6, 7, 8, 9) and the Tessin-habit quartz occurs only in Thassos (photo 10), Drama and Evros areas. Tessin-habit quartz has apparent steep rhombohedral faces, which often result from an alternation of prisms and rhombohedra of different slopes.
Very rare crystal forms, as “gwindel” (twisted quartz, close and opened shapes) occur in Attika and Evia (photo 12, 13, 14), sceptres in Attika (photo 11) and Drama, and “Faden” (fiber quartz) in Evia (photos 13, 14, 15) and in Crete Island. Amethyst sceptre- and window-shaped crystals from Drama area overgrow Tessin-habit smoky quartz crystals in assemblages of worldclass quality.
The presence of combined “Faden-Gwindel” smoky quartz from Evia is probably worldwide unique (photo 13, 14). Double-ended “floaters” (photos 7, 8, 12, 13, 14) which have been detached from the vein walls and were subsequently rehealed during continuation of crystallization are also found.

"Phantoms" (ghosts) due to green-colored chlorite- or sericite coatings on crystal faces, or to different degree of coloring within smoky quartz crystals were sampled in Attika, Ios, Thassos and Evia (photo 9) respectively. Although prismatic quartz crystals are the most common habit from Attika, rarely tabular crystals are also present. Dauphinee and Brazil twinning are common, whereas Japan law twinning is absent.
Many quartz crystals usually have a macromosaic structure as a result of sub-parallel growth of multiple crystals. In some cases the crystals are faulted and rehealed and exhibit recrystallization.

**Tab. 1**: Mineralogy of the alpine-type fissures in Greece

| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|---|---|---|---|
| Mineral | **Attika** | **Central Evia** | **South Evia** | **Andros Island** | **Ios Island** | **Crete Island** | **Lesvos Island** | **Thassos Island** | **Drama** | **Evros** |
| Adularia | X | X | X | | | | | X | X | X |
| Albite | X | X | X | X | | X | | | | |
| Hematite | X | X | X | | | X | | X | X | |
| Byssolith | X | X | X | X | | X | X | X | X | |
| Amethyst | X | | | | | | | X | X | |
| Calcite | | X | X | X | | | | | | |
| Epidote | X | X | | X | | X | | | | |
| Smoky qtz | X | X | | | X | | | X | X | |
| White mica | X | | | | X | | | X | | |
| Green qtz | | X | | | | | | X | | |
| Rutile | X | | | | X | | | | X | |
| Tourmaline | X | | | | | | | | X | |
| Pyrite | X | X | | | | | | | X | |
| Rocky cryst. | X | X | X | X | X | X | X | X | X | X |
| Chlorite | X | X | X | X | X | X | X | X | X | |

**Adularia** as an alpine-type fissure mineral from Ouranoupolis/Chalkidiki in Greece, was firstly described and optically-structurally analyzed by DIMITRIADIS & SOLDATOS (1978). However crystals from the above locality are short prismatic and less than 1mm in length. Recent studies identified adularia as a widespread mineral in alpine fissures mainly from Evia, Thassos, Evros and Drama areas. The adularia crystals are milky to light pink colored, is some cases light green due to chlorite impregnation. Adularia constitutes well developed crystals up to 3cm in size, which occupy along with quartz (photo 17) the cavities of the fissures. Other minerals, besides quartz, that accompany adularia are hematite, chlorite, white mica in Thassos Island (photo 16), hematite, albite, chlorite and epidote in Evia. The most common habit is that of the so-called Felsöbanya type (SMITH 1974b) in rhombohedric crystals. Microprobe analyses indicated an ideal end-member composition (Tab. 2). Representative partial X-ray diffraction patterns of Thassos and Evia adularia are presented in Fig. 2. All the diffraction patterns have (201) reflections at $2\theta = 21^{o}$ suggesting the presence of pure, low-Na, K-feldspar (BOWEN & TUTTLE 1950). The (131) diffraction peaks at approximately $2\theta = 29.5^{o}$ are single and do not split into two diffractions, thus indicating mainly monoclinic symmetry (SMITH 1974a). However in the two samples from central Evia (Fig. 2b, c) the (131) reflection is flanked by low-intensity shoulders indicative of subordinate triclinic material (CERNY & CHAPMAN 1986). These data indicate that Thassos and central Evia K-feldspars are probably monoclinic adularia or monoclinic orthoclase.

**Albite** crystals are abundant in metabasites from Crete Island and in quartz-albite veins and in pegmatoids from Central and South Evia. Albite is usually associated with adularia and quartz in metarhyolites and with chlorite, epidote and calcite in basic rock lithologies. The best quality specimens were found in central Evia, where albite is present as idiomorphic transparent crystals, up to 6 cm in size, grown onto clear quartz crystals (photo 18, 21). The studied albite crystals are twinned according to the albite- or the Manebacher lows. Albite has an almost ideal end-member composition (Tab. 2). A representative partial X-ray diffraction pattern of a pegmatoid-hosted albite crystal (central Evia) is presented in Figure 2.

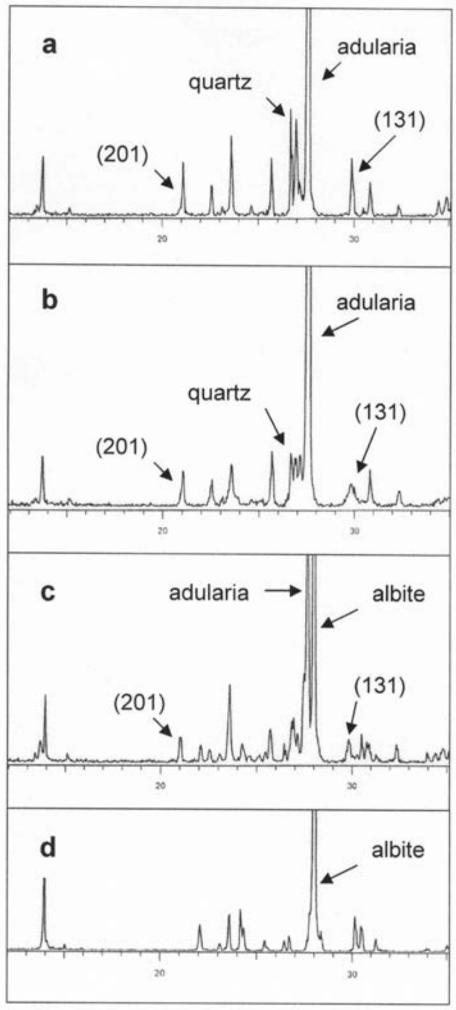


**Fig. 2.** X-ray powder diffraction diagramms of various Greek adularia and albite. a) adularia from a paragneiss-hosted fissure (Thassos Island); b) adularia with green-colored quartz containing byssolith inclusions from orthogneiss-hosted fissure (central Evia); Adularia and albite from orthogneiss-hosted fissure (central Evia) d) transparent albite from a pegmatoid (central Evia)

**Hematite** in hexagonal plates arranged in rosette form (iron roses), a form typical for this mineral from the Alps, was also found in Thassos and Evia Islands. The biggest iron roses come from Thassos (up to 5cm in size), intergrown with milky quartz, whereas in central Evia the hematite iron roses (up to 3cm in size) are intergrown with smoky and chloritized quartz (photo 20) and with adularia.

**Chlorite** as a widespread fissure mineral occuring in almost all rock lithologies is frequent in Attica, Thassos, Ios, Andros, Evia and Crete Islands. It was precipitated as an early phase in amphibolite-hosted fissures in Thassos (forming idiomorphic crystals up to 2cm) and in several later stages resulting in chlorite worm-similar inclusions in clear quartz (also in adularia and albite). In a still later stage chlorite deposition resulted to coatings on the quartz crystals. Late chlorite-depositing solutions were also responsible for corrosion and etching phenomena of quartz crystals. Microprobe analyses from chlorites (Tab. 2) indicate Fe/Fe+Mg ratios ranging between 0.32 and 0.36. They are classified as rhipidolite and clinochlore (after HEY 1954). Application of the chlorite geothermometry (after CATHELINEAU 1988, ZANG & FYFE 1995, XIE et al. 1997) resulted in formation temperatures ranging between 270 and 330 ºC.

**Byssolith (hornblende-asbest)** occurs in the form of the so-called horsetail inclusion in quartz and albite from Evia (photo 17) and Thassos Island sharing them a green, to blue-green color. Byssolith in deep green-colored needles was also found as early deposited open space filling meterial in albite rich fissures from south Evia.

**Calcite** is a common mineral in ampibolite-hosted fissures from Thassos, Evia and Andros Islands, and is associated with quartz, epidote and chlorite. One microprobe analysis (central Evia) indicated small amounts of FeO (0.43 wt %), MnO (1.20 wt %) and MgO (0.32 wt %). Calcite was deposited following formation of quartz, chlorite and epidote. Calcite has grown rhombohedrally in subrounded crystals up to 3cm in size.

**Epidote** was located in orthogneiss- and amphibolite-hosted fissures from central and south Evia and in Thassos Island. The best specimens were localized in central Evia were up to 5cm sized prismatic crystals are intergrown with calcite (metabasic host rocks). Smaller epidote crystals were deposited as early formed minerals in orthogneiss-hosted fissures from central Evia. Epidote crystals occur either as needle- like inlusions in clear prismatic quartz or immediately covering the fissure walls in association with adularia. Alpine-type fissure epidotes from Thassos are hosted in amphibolites and closely related to chlorite deposition. A microprobe analysis (Tab. 2) from central Evia epidote-clinozoisite indicated 24% of pistazite mole fraction ($Ps_{24}$).

**Pyrite** occurs as idiomorphic crystals up to 4 cm in size associated with quartz in Drama area. Clear prismatic quartz crystals from Pentelikon Mt in Attika include up to 0.5 cm pyrite hexaheder, sometimes eroded away leaving a negative crystal form.

**White mica** was found in three localities (Thassos and Ios Islands and Pentelikon Mt/Attika). The most spectacular samples come from Thassos where K-white mica (KWM) accompanies Tessin-habit smoky and clear quartz in ortho- and paragneiss-hosted fissure veins. KWM from that locality forms pseudohexagonal flakes up to 3cm in diameter. The Ios Island KWM occurs as solid inclusions along growth planes of euhedral prismatic quartz crystals, resulting in “phantom” figures. Pentelikon Mt prismatic quartz contains also white mica in association with pyrite and tourmaline. Small amounts of KWM were also detected from south Evia samples (together with chlorite) and analyzed with the microprobe. The analyzed KWM (Tab. 2) have interlayer contents between 0.93 and 0.98, $X_{Mg}$ between 0.15 and 0.30, Si-content between 3.15 and 3.51 and trioctahedral occupancy between 1.99 and 2.08 (based on 11O). Thassos KWM are mainly muscovites while Attika and Evia white micas represent mixtures between muscovite and seladonite. The pyrophyllite content is in all studied micas absent.

**Tab. 2.** Representative microprobe analyses of various alpine-type fissure minerals from Greece

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 8 |
|---|---|---|---|---|---|---|---|---|---|

| Mineral wt% | KWM | KWM | CHL | CHL | EP | TIT | ALB | ALB | ADU |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 47.56 | 50.66 | 28.43 | 27.93 | 38.73 | 30.01 | 68.00 | 67.66 | 64.61 |
| $TiO_2$ | 0.62 | - | - | - | 0.03 | 37.90 | - | - | - |
| $Al_2O_3$ | 32.10 | 24.,27 | 19.91 | 21.81 | 24.58 | 1.08 | 20.21 | 19.78 | 18.90 |
| FeO | 3.12 | 5.63 | 18.34 | 19.34 | 10.92 | 1.34 | - | - | - |
| MnO | - | 0.60 | 0.38 | 0.22 | - | 0.00 | - | - | - |
| MgO | 2.25 | 1.76 | 21.47 | 19.40 | 0.26 | 0.00 | - | - | - |
| CaO | - | - | - | - | 22.06 | 27.34 | - | - | - |
| Na2O | 0.49 | 0.30 | 0.11 | 0.28 | 0.37 | 0.00 | 12.01 | 11.73 | - |
| K2O | 10.92 | 10.09 | | - | 0.05 | 0.00 | - | - | 16.92 |
| Total | 97.06 | 93.31 | 88.64 | 88.98 | 97.00 | 97.67 | 100.22 | 99.17 | 100.43 |
| | 22 O | 22 O | 28 O | 28O | 25 O | 20 O | 8 O | 8 O | 8 O |
| Cations | | | | | | | | | |
| Si | 6.295 | 7,019 | 5.693 | 5.587 | 6.267 | 4.019 | 2.967 | 2.980 | 2.980 |
| $Al^{IV}$ | 1.705 | 0.981 | 2.307 | 2.413 | - | - | - | - | - |
| $Al^{VI}$ | 3.303 | 2.982 | 2.392 | 2.729 | 4.687 | - | - | - | - |
| $Al^{tot}$ | - | - | - | - | - | 0.170 | 1.039 | 1.027 | 1.028 |
| Ti | 0.062 | 0.000 | 0.000 | 0.000 | 0.004 | 3.817 | - | - | - |
| $Fe^{2+}$ | 0.345 | 0.652 | 3.071 | 3.235 | 1.478* | 0.150 | - | - | - |
| Mn | 0.000 | 0.070 | 0.064 | 0.037 | 0.000 | 0.000 | - | - | - |
| Mg | 0.444 | 0.364 | 6.409 | 5.785 | 0.063 | 0.000 | - | - | - |
| Ca | 0.000 | 0.000 | 0.000 | 0.000 | 3.824 | 3.923 | - | - | - |
| Na | 0.126 | 0.081 | 0.043 | 0.109 | 0.116 | 0.000 | 1.016 | 1.002 | - |
| K | 1.844 | 1.783 | 0.000 | 0.000 | 0.010 | 0.000 | - | - | 0.996 |

1. K-white mica associated with smoky quartz from Thassos Island, 2. K-white mica associated with chloritized quartz and albite from central Evia Island, 3. chlorite included in smoky quartz from Ios Island, 4. Chlorite associated with albite and epidote from an amphibolite-hosted fissure in Andros Island 5. Epidote intergrown with calcite from an amphibolite-hosted fissure in central Evia Island, 6. Titanite intergrown with quartz and albite from an orthogneiss-hosted fissure, south Evia Island, 7. albite intergrown with calcite and epidote from an amphibolite-hosted fissure in central Evia Island, 8. Albite associated with quartz from an orthogneiss-hosted fissure central Evia Island, 9. Adularia associated with green quartz from central Evia Island. (* Iron as $Fe^{3+}$).

**Tourmaline** in the form of black-colored needles (up to 3cm in size) occur as inclusions in quartz crystals from Drama and Pentelikon Mt/Attika (photo 19). Together with quartz it also fills open spaces in orthogneiss-hosted fissures at Thassos Island (photo 22).

**Rutile** needdles (up to 3cm in size) are common as inclusions in quartz crystals from central Evia and Drama. Occasionaly tetragonal bi-pyramidal crystals (3mm in size) are overgrown on Pentelikon Mt quartz. An assemblage of quartz + hematite + adularia + rutile was identified in an orthogneiss-hosted fissure from central Evia Island. Chloritized quartz crystals from south Evia include small (not macroscopically visible) rutile grains associated with titanite (microprobe analysis, Tab 2) and zirkon. One rutile microprobe analysis indicated small contents in $Al_2O_3$ (0.12 wt %), $Fe_2O_3$ (0.36 wt %) and MnO (0.19 wt %). In Thassos island rutile needles (up to 3mm in size) accompany chlorite and quartz in amphibolite-hosted fissures.

## 6. Discussion – Conclusions

Alpine fissures are hydrothermal systems that document the evolution of deformation, fluid composition, temperature and pressure during uplift of the surrounding rocks.

During the last 30 years several studies on alpine fissure minerals mainly from the Central Alps (MULLIS 1975, 1988, 1996) established a two stage process for fluid evolution and mineral precipitation: Although early Alpine fissures were opened by compressional tectonics close to peak of the neo-alpine metamorphic event, new fissures and veins containing the typical alpine fissure minerals were formed during exhumation and extension at retrograde conditions by $CO_2$- and meteoric water-enriched fluids which infiltrated to depths exceeding 10km. That meteoric fluids may penetrate to considerable depths within orogenic belts is well established (MORRISON 1994, MILLER & CARTWRIGHT 1997, BARKER et al. 2000, MULLIS et al. 2001).
In Greece there are very few data about the fluids involved in the formation of late-stage, post-metamorphic veins: GANOR et al. (1994) studied late calcite veins that penetrated the rock sequences of Sifnos, Tinos and Kythnos Islands and argued that they were deposited from surficial fluids at some stage following the regional greenschist-facies metamorphism and where tectonic conditions had evolved from ductile to brittle.
Preliminary fluid inclusion data of alpine-type fissure quartz from Pentelikon Mt/Attika (KILIAS et al. 2004) revealed homogenization temperatures in the order between 175 and 240 °C, and salinities mainly clustering between 4-5 wt % NaCl equiv. Calculated fluid pressures were below 1.5 kbar. These results are in accordance to the above mentioned arguments and strongly support an involvement of meteoric fluid in alpine-type fissure mineral deposition in Attika and a correlation to the $H_2O$-enriched zone as described by MULLLIS (1994) from the Swiss Alps.

Based on the existing data, it can be proposed that the formation of the studied alpine-type fissures in Greece and their mineralogy are closely related to the extensional tectonics accompanying the exhumation of the metamorphic rocks. Initial formation probably took place close to the brittle-ductile transition but most of the veins are clearly late-stage, post peak-metamorphic filling subvertical fractures.

Petrographic evidence such as the presence of various quartz forms (“sceptres”, “windows”, “faden” and “gwindel”) even within a single fissure studied, indicates several opening and mineralization stages and fluctuating hydrothermal conditions during mineral deposition. Each opening may correspond to a renewed fluid infux, leading to mineral growth or dissolution, “phantoms” or “faden” structures (as proposed by TOURET 2001). The gwindel forms exhibit helicoidal growth, while the sceptres indicate recrystallisation at the top of pre-existing crystals or deposition from new solutions. Multiple hydrothermal stages are also indicated by the “ghosts”, “window” forms, etc. Perfect double-terminated crystals were developed in the interior of the fissures after rehealing of crystal faces by the hydrothermal solutions. Precipitation of quartz and other mineral constituents in the studied fissures due to oversaturation of $SiO_2$ rich hydrothermal fluids is attributed to pressure and temperature decrease around the fissures during exhumation processes (as proposed by CARTWRIGHT & BUICK 2000). Leaching of chemical components from the host rocks after their interaction with the hydrothermal solutions could also explain fluid enrichment and deposition of alpine-type minerals in the fissures studied. However it is still unclear why in some mineralized fissure veins alteration halos are absent.

The study of the alpine-type fissure minerals in Greece can lead to certain conclusions regarding the cross-correlation of the various tectonic units. The identical mineralogical assemblages in Attico-Cycladic Massif (Attica, Evia and Ios Island) likely indicate similar petrological types and tectonometamorphic evolution. The presence of Tessin-habit quartz crystals in Thassos, Drama and Evros areas in northern Greece indicates similar conditions of crystallization and a distinct evolution during formation of alpine-type fissures in the Rhodope Massif in respect to the Attico-Cycladic Massif. Alternatively the distinct crystal habit between Rhodope and Attico-Cycladic Massif could correspond to distinct fluids involved in quartz deposition. As suggested by STALDER & TOURAY (1970), MULLIS (1975), MULLIS et al. (1994, 2001) the habit change may be related to an actual phase change ($CO_2$-dominated vs meteoric waters-dominated fluids) in the vugs where the crystals grew.

Field evidence in Greece indicates that the formation of quartz megacrysts in alpine-type fissures is best favoured in places where protoliths were previously enriched in silica, as a result of the development of magmatic-hydrothermal systems associated to pre-Hercynian, Hercynian and Mesozoic magmatism: this can be best demonstrated in Dassoto/Drama, Thassos and Ios Islands where initial deposition of pegmatites and quartz veins within the granitoids and the surrounding rocks is attributed to Pre-Variscan and Variscan magmatic-hydrothermal events following the solidification of the granitoid bodies. Similarly the later development of Mesozoic magmatism in Greece (PE-PIPER & PIPER 2002) and the associated volcanosedimentary hydrothermal activity in Attico-Cycladic Massif (Evia, Attika, Andros, Kythnos, etc) resulted in enormous deposition of quartz either in the form of veins, pegmatoids, or as manganiferous horizons (REINECKE et al 1985, REINECKE 1986, CHRYSANTHAKI & BALTATZIS 2003).
Both the (pre)-Hercynian as well as the Mesozoic quartz-vein material was probably involved in recrystallization processes, redistribution of chemical components, and redeposition in the form of enormous crystals within the Alpine-type fissure veins.
Unfortunately on the absence of any chronological data from the studied material it is a matter of speculation whether all mineralization in alpine-type fissures were formed during the Miocene phase of extensional tectonics in Greece, or if some of them are related to earlier Mesozoic or even (pre)-Variscan events.
The Alpine-type fissure minerals described above are not only of great scientific interest, as they give us information about the conditions and timing of final exhumation paths of the metamorphic core complexes in Greece, furthermore they can be considered as mineralogical treasures, unique in Greece and also in Europe. Areas like Evia, Thassos, Drama, Attika and Andros Island belong to the Greek mineralogical and geological monuments (VELITZELOS et al. 2002) and should be characterized as European mineralogical geotopes in order to be protected from commercial mineral exploitation, and also to be developed for educational and social purposes.

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## Photo Catalogue

### Plate 1

**Photo 1:** Alpine-type fissures as interboudin gaps from Andros Island

**Photo 2**: A quartz-rich alpine-type fissure in amphibolitic host rock (Thassos Island)

**Photo 3:** Amphibolite-hosted tension gash fissures, containing adularia + hematite (Thassos Island)

**Photo 4:** En echelon sigmoidal tension gashes within an orthogneiss from central Evia. The fissures are filled with quartz + adularia.

**Photo 5**: Quartz veins penetrating quartzitic rocks in Crete Island

**Photo 6:** Augengneiss-hosted quartz crystals (Ios Island)


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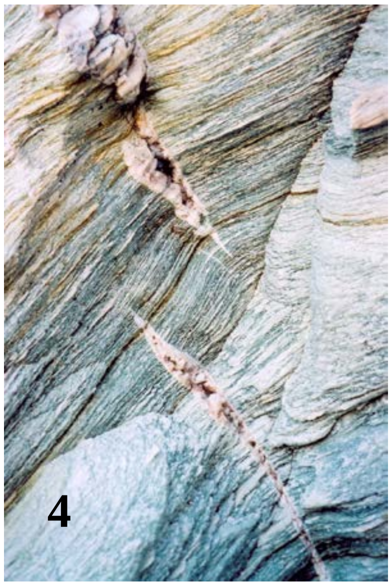
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**Plate 2**

**Photo 7:** Double-terminated prismatic smoky quartz crystal from Pentelikon Mt/Attika.

**Photo 8:** Double-terminated prismatic smoky quartz crystals from Pentelikon Mt/Attika.

**Photo 9**: Prismatic smoky quartz “phantom” with an inner black zone, covered by a pale brown rim (central Evia Island).

**Photo 10:** Smoky quartz with “Tessin” habit from Thassos Island (10cm in length).

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**Plate 3**

**Photo 11**: Smoky quartz sceptre from Pentelikon Mt/Attika (5cm).

**Photo 12**: Double-terminated twisted (“gwindel”) smoky quartz crystals (from Evia Island orthogneisses).

**Photo 13:** Double-terminated twisted (“gwindel”) smoky quartz crystals with “Faden” from central Evia Island.

**Photo 14**: Double-terminated twisted (“gwindel”) pale brown “Faden” quartz from central Evia Island (3cm in size).

**Photo 15**: Parallel plate growth of clear “Faden” quartz from south Evia Island (3cm in size).


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**Plate 4**

**Photo 16:** Fissure-type adularia crystals and chlorite on Augengneiss from Thassos Island (specimen size 25cm).

**Photo 17:** Adularia intergrown with smoky quartz containing byssolith inclusions (length of the quartz crystal 4cm).

**Photo 18**: Quartz associated with albite crystals (up to 3cm) from a meta-pegmatite in central Evia Island.

**Photo 19**: Quartz with inclusions of tourmaline from Pentelikon Mt/Attika (2cm in size).

**Photo 20**: Quartz with hematite iron roses from central Evia Island (quartz crystal 5cm in size).

**Photo 21**: Smoky quartz with albite from central Evia Island.

**Photo 22**: Sigmoidal tension gashes within an orthogneiss from Thassos Island. The fissures are filled with quartz + tourmaline.


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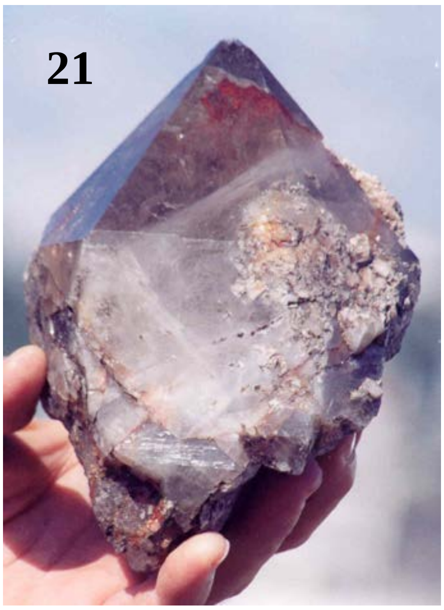
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