Gold deposits in Greece: mineralogy and genetic considerations

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The Hellenides constitute part of the Alpine-Himalayan orogen and formed when Apulia collided with Europe in Late Cretaceous to Tertiary times. After the closure of the Vardar Ocean, shortening and syn-orogenic exhumation of HP-LT rocks occurred during the late Cretaceous-Eocene, before an acceleration of slab retreat changed the subduction regime and caused the collapse of the Hellenic mountain belt and the thinning of the Aegean Sea from the middle Eocene/late Oligocene to the present (Jolivet et al. 2004a, b). During this post-orogenic episode large scale detachments formed which exhumed metamorphic core complexes, in a back-arc setting (Lister et al. 1984; Gautier and Brun 1994a, b). Tertiary to Quaternary magmatism in the Aegean region occurred mostly in a post-collisional setting behind the active Hellenic subduction zone.
Geodynamic framework of the Mediterranean region

Agostini et al. (2009)
Tertiary volcanism in Greece

Map showing the distribution, age data and petrogenetic affinity for the subduction-related rocks in Aegean–Western Anatolian region. C-A, calc-alkaline; Sho, shoshonitic; U-K, ultra potassic; SAAVA, South Aegean Active Volcanic Arc.

Agostini et al. (2009)
Fig. 6 Latitude versus age diagram of magmatic events in the Aegean region. Data are taken from Fig. 5 and the time range is taken in the grid shown on Fig. 5. The age and position of the main tectono-metamorphic events are also shown (see text for references).
Gold mineralization types

Porphyry-epithermal Cu-Mo-Au-Te
Intrusion-related Mo-W-Au-Ag-Te
Shear zone-related Au-Bi-Te
Simplified geologic map of the Hellenides (I.G.M.E. 1983) and location of the gold-bearing mineralization
Porphyry-Epithermal systems
(Oligocene-Miocene)
Oligocene-Miocene magmatic rocks in Southern Balkan peninsula

**RM**: Rhodope Massif  
**SMM**: Serbomacedonian Massif  
**CRB**: Circum Rhodope Belt  
**AZ**: Axios Zone

Melfos et al. (2002)
Distribution of the Tertiary ore districts and deposits within the Rhodope and the Serbomacedonian metallogenic provinces in the southern Balkan peninsula.

RM=Rhodope Massif
SMM=Serbomacedonian Massif
CRB=Circum Rhodope Belt
AZ=Axios Zone
SG=Srednogorie Zone

1. Esymi
2. Kirki--Sapes
3. Kavala
4. Thasos
5. Thermes--Madan--Luky
6. Spahievo,
7. Lozen
8. Madjarovo
9. Zvezdel
10. Chalkidiki
11. Kilkis (Doirani--Gerakario--Vathi--Pontokerasia)
12. Buchim--Damjan
13. Kratovo--Zletovo
14. Osogovo--Sasa--Toranica
15. Borov Dol, 16. Aridea--Kozuf
17. Balikesir

from Melfos et al. (2002)
The host magmatic rocks were emplaced under subvolcanic conditions in an extensional regime, related to the post-collisional collapse of the Rhodope province. De Boorder et al. (1998) suggested that the late Cenozoic hydrothermal mineral deposits of the European Alpine belt are related to the emplacement of hot asthenosphere into shallow crustal levels above a detached lithosphere plate. Such a process may have led to formation of the porphyry Cu-Mo and epithermal Au-Ag systems in western Thrace.
Skouries/Chalkidiki porphyry Cu-Au

Skouries deposit

Melfos et al. (2002)
Skouries/Chalkidiki
(porphyry Cu-Au deposit: native gold, hessite, sylvanite, merenskyite in chalcopyrite and bornite)

Tarkian et al. 1991
Porphry-epithermal systems in western Thrace

Sapes-Kassiteres, Pagoni Rachi-Kirki, Melitena/Komotini, Myli/Esymi, Ktisamta/Maronia, Perama Hill, Mavrokoryfi, Pefka

Moritz et al. 2010
Moritz et al. 2010
Northeastern Greece: Calc-alkaline to shoshonitic magmatism

Voudouris (2006)
Porphyry Cu-Mo±Au Mineralization

• Three events of porphyry mineralisation
  – The first two ones (32-31 Ma) are related to intermediate magmatism (diorite to quartz monzodiorite and dacite porphyry stocks)
    • Kassiteres/Sappes, Pagoni Rachi/Kirki, Myli/Esymi,
  – The late one (29-? Ma) is related to the acid magmatism (porphyry microgranite, rhyolite porphyry)
    • Ktismata/Maronia
## Porphyry Cu-Mo±Au Mineralisations

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Host intrusion</th>
<th>Alteration</th>
<th>Stockwork, veins</th>
<th>Advanced argillic lithocap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pagoni Rachi/Kirki</td>
<td>Dacite porphyry</td>
<td>Qtz-bi-alb/kfd, overprinted by qtz-ser-chl-cc</td>
<td>Qtz-py-cpy-mt-ht-mol, Gal-sph-cpy-tn-tellurides</td>
<td>Present alongside</td>
</tr>
<tr>
<td>Myli/Esymi</td>
<td>Dacite porphyry</td>
<td>Qtz-bi-alb/kfd overprinted by qtz-ser-chl-cc</td>
<td>Qtz-py-cpy, Gal-sph-cpy-tn-chl-cc</td>
<td>None known</td>
</tr>
<tr>
<td>Ktismata Hill/Maronia</td>
<td>Microgranite porphyry</td>
<td>Qtz-ser-chl overprinted by qtz-ser-chl-pyr</td>
<td>Qtz-py-mol-cpy-mol, td/tn-ch-fa</td>
<td>Present qtz-pyr (qtz-alu alongside, barren Odontoto)</td>
</tr>
<tr>
<td>Melitena</td>
<td>Dacite porphyry</td>
<td>Qtz-ser-py-dia</td>
<td>Qtz-mol-py-cpy</td>
<td>Present above (qtz-dia-alu) Barren</td>
</tr>
</tbody>
</table>
Epithermal Au-Ag-Cu Mineralizations in western Thrace

- Volcanic-hosted (also within sandstones, basement)
- Postdate the emplacement of rhyolitic dikes
- Three stages of evolution
  - Initial stage of acid leaching
  - Deposition of HS enargitic ore
  - Deposition of IS ore with chalcopyrite-tetrahedrite ss
  - Gold as native element and tellurides with both ore assemblages

*Sappes (Viper, St Demetrios, Kassiteres)*
*Perama (Perama Hill- Mavrokoryfi)*
*St Philippos/Kirki*
*Pefka*
## Epithermal Au-Ag Mineralisations

<table>
<thead>
<tr>
<th>Location</th>
<th>Deposit Type</th>
<th>Metals</th>
<th>Host rocks</th>
<th>Relation to porphyry systems</th>
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</thead>
<tbody>
<tr>
<td>Viper</td>
<td>HS-IS veins, breccias</td>
<td>Cu, As, Au, Ag, Te, Bi</td>
<td>Ash tuff, lavas</td>
<td>Alongside Kassiteres</td>
</tr>
<tr>
<td>St Demetrios</td>
<td>IS-HS stockworks, breccias</td>
<td>Cu, As, Au, Ag, Te, Bi</td>
<td>Lavas, rhyodacitic Pyroclastics</td>
<td>Alongside Kassiteres, mineralization at depth ?</td>
</tr>
<tr>
<td>Kassiteres</td>
<td>IS veins, breccias Also HS veins</td>
<td>Cu, As, Au, Ag, Te</td>
<td>Volcanics, Monzodiorite, Rhyolite</td>
<td>Alongside Kassiteres</td>
</tr>
<tr>
<td>Perama Hill</td>
<td>HS disseminations, Veins, breccias</td>
<td>Au, Ag, Cu, As, Sn, Te</td>
<td>Sandstones, Volcanics</td>
<td>Alongside Maronia</td>
</tr>
<tr>
<td>Mavrokoryfi</td>
<td>HS breccias</td>
<td>Cu, As, Au, Ag, Te</td>
<td>Andesitic breccias</td>
<td>Alongside Maronia</td>
</tr>
<tr>
<td>St. Philipp</td>
<td>HS breccias</td>
<td>Pb, Zn, Ag, Cu, As, Bi, Sn</td>
<td>Sediments, Rhyolite porphyry</td>
<td>Alongside Pagoni Rachi</td>
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<tr>
<td>Pefka</td>
<td>IS-HS veins</td>
<td>Cu, As, Au, Te, Bi, Sn</td>
<td>Volcanics</td>
<td>None known</td>
</tr>
</tbody>
</table>
Melitena
Porphyry Mo-Cu
HS Epithermal Au
The porphyry Cu-Mo mineralization in Melitena is associated with a Tertiary subvolcanic dacite.

**Alteration zone:** Sericite, argillic, silicified. A later epithermal event overprints the porphyry type mineralisation

Cu up to 400 ppm, Zn up to 500 ppm, Mo up to 6000 ppm, Au up to 0.3 ppm

The ore mineralization consists of pyrite and molybdenite.

**Microthermometric results:** homogenisation temperatures from 295° to 363°C and salinities from 2.7 to 3.4 %wt equiv. NaCl.
Melitena: porphyry Mo prospect

Quartz stockworks associated with sericitic and advanced argillic (pyrophyllite, diaspore, APS minerals) alteration of dacite. Silicic alteration on top includes alunite-diaspore.
Element scanning within an APS crystal at Melitena

Core: Ba-rich hinsdalite-woodhouseite-swanbergite → Rim: Ba-rich woodhouseite
<table>
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<tr>
<th></th>
<th>Wt%</th>
<th>n=49</th>
<th>sd</th>
<th>aver</th>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Re</td>
<td>0.21-1.74</td>
<td>(0.39)</td>
<td></td>
<td>0.79</td>
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<tr>
<td>Mo</td>
<td>57.99-60.20</td>
<td>(0.54)</td>
<td></td>
<td>59.36</td>
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<td>Fe</td>
<td>0.00-0.02</td>
<td>(0.01)</td>
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<td>S</td>
<td>38.42-41.85</td>
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<td>39.53</td>
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<td>Aton</td>
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</tr>
<tr>
<td>Re</td>
<td>0.00-0.02</td>
<td>(0.00)</td>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td>Mo</td>
<td>0.95-1.02</td>
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<td>Fe</td>
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<td>(0.00)</td>
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<tr>
<td>S</td>
<td>1.98-2.04</td>
<td>(0.01)</td>
<td></td>
<td>1.99</td>
</tr>
</tbody>
</table>

Melfos et al. (2001)
Sapes-Kassiteres
porphyry Mo-Re-Sn-Cu-Au
HS epithermal Au-Ag-Cu-Te
Sapes/Kassiteres

Voudouris et al. 2006

PI, PII: porphyry Cu-Mo mineralization

Lithology

Oligocene-Miocene
- Rhyolite porphyry
- Dacite porphyry
- Pyroxene-biotite microdiorite
- Quartz monzodiorite
- Pyroxene-hornblende andesite
- Two-pyroxene andesite
- Pyroclastic rocks and lavas

Middle-Upper Eocene
- Marls, sandstones
- Basal conglomerates

Mesozoic
- Circum Rhodope Belt

Hydrothermal alteration
- Surface outcrop of K-Na-silicate alteration
- Surface outcrop of diaspore-rich lithocap
- Surface outcrop of alunite-rich lithocap
Lithological map of the Sapes-Kassiteres district

Proportion: UTM 90S, zone 35 North Hemisphere

Fruits:
- "Dacitic andesite perlphyry" (reclassified as Granodiorite-Tonalite, Voukouras 2009)
- Dorite
- Monzodiorite
- Volcanics
- Alteration cap (rhyolite, alunite alteration...)
- Basal conglomerates
- Makri-Serie
- Dacitic rhyolite
- Rhyolite

M. Ortelli
K. Michael (1993)
F. Voukouras (1993)

Ortelli et al. 2009
Ortelli et al. 2009
Fig. 3.2: The Konos/St-Demetrios mineralization systems (see text for discussion).

Konos Hill/Sapes (porphyry-epithermal prospect)
Fig. 3.1: Landscape with the Konos Hill southern slope. The yellowish shaded area is representing the high-sulfidation system with widespread quartz-alunite alteration with minor vuggy silica restricted along N-S and W-E oriented faults. The blue shade area is representing the main quartz-stockwork vein area, where the best outcrops show molybdenite-pyrite and quartz veins suitable for fluid inclusions analyses (see chapter Fluid inclusions analyses). Curved arrows indicate the northern slope.

Fig. 3.3:  
a) Oxydized quartz-vein stockwork outcropping along the road (Fig. 3.1).  
b) Gypsum vein with sulfides in the sericitic altered granodiorite-tonalite.  
c) Cubic pyrite crystals in the gypsum veins with chalcopyrite and sphalerite.  
d) Molybenite-quartz-pyrite veins with dark gray quartz “B”-veins.  
Sapes porphyry-Mo prospect: Re-rich molybdenite, rheniite, native Sn

Voudouris et al. (2010a)
Fig. 3.2: The Konos/St-Demetrios mineralization systems (see text for discussion).
Koryphes porphyry-Cu prospect

K-silicate alteration (a) overprinted by IS polymetallic veins (b) with sericitic alteration. Late-stage veins postdate intrusion of rhyolite dikes (c). Barren lithocap (d) present

(d) quartz-diaspore-corundum-topaz
St Demetrios deposit – Sapanas prospect
From IS towards HS mineralisation?. Introduction of precious metals (Gold and Au-Ag-tellurides) with both assemblages

Enargitic ore

Native gold

Alunitic alteration and alunite veining accompanies enargitic ore

St Demetrios
St Demetrios: hessite, stützite, goldfieldite, tetradymite, native gold, aikinite

Voudouris et al. (2006)
Sapes/Kassiteres

Voudouris et al. 2006

PI, PII: porphyry Cu-Mo mineralization

Lithology
- Oligocene-Miocene
  - Rhyolite porphyry
  - Dacite porphyry
  - Pyroxene-biotite microdiorite
  - Quartz monzodiorite
  - Pyroxene-hornblende andesite
  - Two-pyroxene andesite
  - Pyroclastic rocks and lavas
- Middle-Upper Eocene
  - Marls, sandstones
  - Basal conglomerates
- Mesozoic
  - Circum Rhodope Belt

Hydrothermal alteration
- Surface outcrop of K-Na-silicate alteration
- Surface outcrop of diaspore-rich lithocap
- Surface outcrop of alunite-rich lithocap
- Faults and mineralized veins
- IGME drillholes
Kassiteres – St Barbara prospect

Precious metal veins developed below silicic and advanced argillic alteration: Early IS quartz-carbonate veins with Au-Ag tellurides are overprinted by late IS quartz veins with base metals.
St Barbara: hessite, petzite, sylvanite, electrum, native Te

Voudouris et al. (2006)
Kassiteres-St Demetrios/Sappes

\[
\begin{align*}
\text{clv} & \quad \text{calaverite } \text{AuTe}_2 \\
\text{sylv} & \quad \text{sylvanite } (\text{Au,Ag})_2\text{Te}_4 \\
\text{pz} & \quad \text{petzite } \text{Ag}_3\text{AuTe}_2 \\
\text{hs} & \quad \text{hessite } \text{Ag}_2\text{Te} \\
\text{stü} & \quad \text{stützite } \text{Ag}_{5-x}\text{Te}_3 \\
\text{emp} & \quad \text{empressite } \text{AgTe} \\
\text{te} & \quad \text{native tellurium } \text{Te} \\
\text{gld} & \quad \text{native gold } \text{Au}
\end{align*}
\]

Voudouris et al. (2006)
Pagoni Rachi
porphyry Mo-Re-Sn-Au-Te

St Philippos
HS epithermal Cu-Pb-Ag-Sn
High-sulfidation lithocaps distal to Na-K-Ca-silicate alteration and quartz stockwork (1 x 1 km²)
Early quartz veins related to Na-K-Ca-silicate alteration. Late carbonate-quartz-sericite veins.
Early veins (A- and M-types) related to Na-Ca-K-silicate alteration and mt+py+cpy+bn+Au mineralization

Quartz ± feldspar ± chlorite ± sericite ± calcite veinlets with pyrite-molybdenite ± chalcopyrite
Voudouris et al. (2009a)
Vein mineralogy

Fluorite (Fl) in the Quartz-Molybdenite-Rheniiite veins

Voudouris et al. (2010b)
Ore mineralogy

Voudouris et al. (2009a)
High Re-content in molybdenite Rheniite

Voudouris et al. (2009a)
Fluid inclusion results

Voudouris et al. (2009a)
Voudouris et al. (2009a)
Late carbonate-quartz Au-Ag-Te rich veins

Oligocene-Miocene
- Rhyolite - Rhyodacite
- Dacitic andesite porphyry
- Quartz monzodiorite - Monzonite
- Calc-alkaline volcanics

Middle-Upper Eocene
- Marls - Sandstones
- Basal conglomerates
- Surface outcrop of K-Na-silicate alteration
- Faults and mineralized veins
- Porphyry/epithermal mineralization
Early veins are overprinted by carbonate-quartz-sericite polymetallic veins with sericite-carbonate alteration. $\text{py} \rightarrow \text{sl} \rightarrow \text{gn} + \text{cpy} + \text{tn/td} + \text{hs} + \text{pz} + \text{Au} + \text{Bi}$-sulfosalts
Carbonate-quartz-sericite veins: Deposition of Bi-sulfosalts and Ag-Au-tellurides at 265° to 290 °C, with salinities of ~ 3.0 wt % NaCl equiv.
Carbonate-quartz-sericite veins: Intermediate sulfidation ore assemblage

Bi-sulfosalts and tellurides associated with sphalerite, chalcopyrite, galena and tennantite/tetrahedrite
Pagoni Rachi: wittichenite, a berryite-similar sulfosalt, hessite, bornite and galena in carbonate-quartz-sericite veins
Bismuth sulfosalts

Hessite
Ag-Au tellurides (Pagoni Rachi)

Voudouris et al. (2010b)
Bi-sulfosalts and Bi-tellurides (Pagoni Rachi)

Voudouris et al. (2010b)
St Philippos deposit: Regional Geology

Oligocene-Miocene
- Rhyolite - Rhyodacite
- Dacitic andesite porphyry
- Quartz monzodiorite - Monzonite
- Calc-alkaline volcanics

Middle-Upper Eocene
- Marls - Sandstones
- Basal conglomerates
- Surface outcrop of K-Na-silicate alteration
- Faults and mineralized veins
- Porphyry/epithermal mineralization

Map showing the distribution of geological features in the St Philippos deposit area.
St. Philippos polymetallic HS-IS deposit alongside the Pagoni Rachi porphyry Cu-Mo prospect. Massive sulfide vein ore assemblage.

Open pit

Michael et al. (1989a)
St. Philippos deposit

Rhyolite porphyry

HS

CV

gal

IS
St Philippos deposit

Ag-sulfosalts in IS ore assemblage (tennantite+galena).
Maronia
Porphyry Cu-Mo-Au

Perama Hill-Mavrokyoryfi
HS epithermal Au-Ag-Cu-Te
Geological sketch map showing the geology of the Maronia porphyry Cu-Mo mineralisation related to the Maronia pluton. Co-Ni-Pt mineralization is associated with the Maronia pluton. Melfos et al. (2002)
Maronia area

Ktismata Hill Cu-Mo-Au deposit related to a porphyry microgranite penetrating the Maronia pluton

The microgranite represents subvolcanic equivalent to the rhyolitic dikes

Melfos et al. (2002)
Maronia Pluton

Ktismata Hill

Porphyry microgranite
Sketch map of hydrothermal alteration zoning of the Maronia porphyry type deposit. Phyllic, silicified, argillic and propylitic zones are illustrated (Melfos et al. 2002)
Ktismata Hill Cu-Mo-Au deposit

K-silicate alteration absent. Cu-Mo ore related to sericitic (±pyrophyllite) alteration and intense silicification. Several stages of quartz veining: Early porphyry-style veins with Cu-Mo-Au mineralisation succeeded by HS ore assemblages.
Ore minerals of the Maronia porphyry Cu-Mo deposit:

- pyrite, chalcopyrite, pyrrhotite, molybdenite and magnetite
- minor Cu-Pb-(Sb+As) sulphosalts: tennantite, tetrahedrite, zinkenite, chalcostibite, famatinite, bournonite, boulangerite and meneghinite
- trace amounts of cubanite, pentlandite, sphalerite, galena and bismuthinite

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**Molybdenite**

- X-ray diffraction analyses: mixed 2H<sub>1</sub> and 3R polytypes
- microprobe analyses: 0.12 to 2.88 wt% Re
- average chemical formula Re<sub>0.01</sub>Mo<sub>0.99</sub>S<sub>2.00</sub>

Melfos et al. (2002)
Ore mineral associations from the Maronia Cu-Mo porphyry-type mineralisation

Melfos et al. (2002)
Distribution of copper (Cu) and molybdenum (Mo) within the Maronia porphyry type deposit. The element distribution corresponds to the zones enriched in chalcopyrite and molybdenite, respectively.

Surface samples of altered rock contain as much as 7,600 ppm Mo, 5,460 ppm Cu and 1 ppm Au.

Melfos et al. (2002)
FLUID INCLUSIONS

• Four types of fluid inclusions in ore-related quartz
• Salinities from 5 to 55 wt% NaCl equiv
• Homogenisation temperatures varying mainly from 280 to 460 °C
• Trapping temperatures in quartz-pyrite-chalcopyrite veins from the phyllic alteration zones range from 360 to 420 °C and record the main temperature range of copper deposition.
• Trapping pressures of the ore-forming fluids from 150 to 510 bar
• Boiling is considered to be the main process of ore formation

Melfos et al. (2002)
SULPHUR ISOTOPES

S-isotope compositions for the pyrite and molybdenite suggest an igneous derivation of sulphur.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\delta^{34}$S</th>
<th>py</th>
<th>mol</th>
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<tr>
<td>M 80/3</td>
<td>3.79</td>
<td>3.76</td>
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<tr>
<td>M 80/6</td>
<td>3.99</td>
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<tr>
<td>Average</td>
<td>4.14</td>
<td>3.73</td>
<td></td>
</tr>
</tbody>
</table>

CHLORRITE THERMOMETER

The application of the modified geothermometer to the chlorites from the propylitic alteration at the Maronia deposit yielded temperatures between 308 and 331 °C (320 °C on average)

Melfos et al. (2002)
• The Maronia porphyry Cu-Mo deposit was formed in a subvolcanic environment during Tertiary

• Boiling is considered to be a potential cause for ore formation

• The main temperature range of Cu-Mo deposition was 360 to 420 °C

Melfos et al. (2002)
Perama Hill
HS-IS epithermal Au-Ag-Te deposit
Geology of Petrota Graben

The Geology of the Graben of Petrota/Maronia

Legend

Quaternary
- Alluvium

Tertiary
- Upper Eocene to Oligocene
  - Upper Limestone
- Andesitic Succession
  - Shoshonitic Pyroxene-Biotite Andesite (Banhakite)
  - Two-Pyroxene Andesite
- Dacitic to Rhyodacitic Succession
  - Rhyodacitic Breccia Tuff
  - Biotite-Augite Dacite (Lava Sheets)
  - “Layered” Ignimbritic Tuff
  - Altered and Weathered Tuffs (undivided)
  - Rhyodacitic Ignimbrite (light-colored Basal Tuff)

Mesozoic
- Sediments of Drymos-Mellos-Unit
  - Diabase
- Gabbro
  - Gabbro, Main Facies
  - Cumulatic Suite

Alterations
- Silification Zone

Parts of the map are adopted by PAPADOPOULOS (1982)

Tertiary
- Monzonite of Maronia
- Nesozoic
  - Macr Unit

Arikas & Voudouris (1998)
**Perama Hill**: Upper parts oxidized ore within silicified sandstone. Lower parts andesite breccia with primary HS ore
Perama Hill (upper parts): Native gold in oxidized Perama sandstone and in low-sulfidation banded quartz-barite veins
Perama Hill (lower parts):
massive pyrite-enargite ore → base metals – tellurides
barite veins
Framboidal pyrite: lower parts of Perama Hill
Microchimney-similar structures: lower parts of Perama Hill
High-sulfidation enargitic ore at the lower parts of Perama Hill
Bismuthinite, Enargite, Pyrite at the lower parts of Perama Hill
High-sulfidation enargitic ore at the lower parts of Perama Hill with tetradyrmite, kawazulite and native gold

Voudouris et al. (2009b)
Tennantite postdates Enargite, Covellite at the lower parts of Perama Hill
Au-Ag tellurides associated with galena and tennantite (lower parts of Perama Hill)

Sylvanite-petzite intergrowths are very common and probably the result of decomposition of γ-phase. The Au content in sylvanite ranges between 26.9 and 30.0 wt% and Ag between 8.6 and 12.5 wt%.
Au-Ag tellurides associated with galena and tennantite (lower parts of Perama Hill)
Electrum associated with Au-Ag tellurides (lower parts of Perama Hill)

Voudouris et al. (2009b)
Au-Ag tellurides (lower parts of Perama Hill)
Fluid inclusion results (lower parts of Perama Hill)
Evolution of ore fluids during mineralization at Perama Hill

Voudouris et al. (2007)
Mavrokoryfyi
End-member HS epithermal Ag-Cu-Te mineralization
**Perama Hill**: Upper parts oxidized ore within silicified sandstone. Lower parts andesite breccia with primary HS ore. **Mavrokoryfi**: HS ore hosted in opalized andesites
Mavrokoryfi: High-sulfidation mineralization within andesitic hyaloclastites
Mavrokoryfi: Famatinite and Goldfieldite
Pefka mine
HS-IS epithermal Au-Ag-Te deposit
Voudouris (2006), modified after Michael et al. (1989b)
Pefka mine: Carbonate-quartz veins with Au-Ag tellurides postdate HS quartz veins with enargite)
Pefka/W. Thrace
(luzonite, hessite, altaite, coloradoite, hammarite)

Voudouris (2006)
Maronia porphyry: Mineralised HS overprint. Perama Hill and Mavrokorphi HS alongside
Kassiteres porphyry: Barren HS overprint Viper, St. Demetrios, Kassiteres HS & IS alongside
Pagoni Rachi porphyry: St. Philippos HS alongside
Melitena porphyry: Barren HS overprint
Myli porphyry: None known
North Aegean porphyry-epithermal systems
Limnos & Lesvos islands
(Lower Miocene)
Limnos island
Porphyry-epithermal Cu-Mo-Au-Ag-Te prospect (Fakos)
Voudouris (2006)

Oligocene-Miocene
- Rhyolite - Rhyodacite
- Dacite porphyry
- Dacitic andesite porphyry
- Quartz monzodiorite - Monzonite
- Shoshonitic volcanic rocks
- Calc-alkaline volcanic rocks

Middle-Upper Eocene
- Marls - Sandstones
- Basal conglomerates

Mesozoic
- Circum Rhodope Belt

Hydrothermal alteration
- Surface outcrop of K-Na-silicate alteration and quartz stockworks
- Surface outcrop of high-sulfidation lithocap
- Faults and mineralized veins
- Porphyry/epithermal mineralization

Voudouris (2006)
Limnos island
(Fakos porphyry-epithermal Cu-Mo-Au-Ag-Te prospect)
Fakos monzonite-late lamprophyre dikes
Early potassic alteration porphyry Cu mineralization
Sericite alteration
porphyry Mo mineralization
Sericite-tourmaline alteration
Arsenopyrite-Au mineralization
Magmatic-hydrothermal advanced argillic alteration
Intrusion- and sediment-hosted late-stage quartz-carbonate Au-Ag veins
Limnos: hessite, petzite, electrum, Ag-sulfotelluride

Voudouris (2006)
Peripheral Au-As-rich silica sinter
Lesvos island
Porphyry-epithermal Mo-Bi-Pb-Au-Te Stypsi prospect
Lesvos island: (porphyry-epithermal prospect)
Molybdenite and bismuthinite in quartz stockworks (Voudouris & Alfieris 2005)
Epithermal systems
(Pliocene-Pleistocene)
Milos island

Shallow submarine epithermal Au-Ag-Pb deposits
South Aegean Volcanic Arc

Friedrich (2000)
General Geology

Phase I (3.5-3.1 Ma)
felsic cryptodome-pumice cone volcanoes

Phase I-II (3.0-2.7 Ma)
volcanosedimentary series

Phase II (2.7-1.4 Ma)
dacitic/andesitic lavas, pyroclastic flows and breccias on submarine and partially on subaerial environment.

Phase III (1.4-0.5 Ma)
rhyolitic pumice-cone volcanoes/rhyolitic lavas, andesitic-dacitic pillow lavas

Phase IV (0.5-0.08 Ma)
rhyolitic lavas, pyroclastics, phreatic activity

Fytikas et al. (1986), Stewart & McPhie (2006)
Geological map of western Milos

Alfieris (2006)
Three intrusive phases: magmatic products in a submarine-subaerial setting (Upper Miocene-Lower Pleistocene/ ~ 3.5 - 1.4 Ma)

Alfieri 2006
Volcanosedimentary products (3-2.7 Ma), emplacement of dacitic-rhyodacitic-andesitic domes (Anda, Dado) in submarine to subaerial environment (2.7-1.4 Ma)

Reworked volcanosedimentary horizon (ep) at contact with in situ hyaloclastite subvolcanic dacitic breccia at Triades

Dacite(Anda) domes emplaced along a quasi E-W direction at Triades. The coherent and hyaloclastic components are very well visible.

The coherent and the fragmented components of extrusive domes. From McPhie et al. (2003)

Alfieris 2006
Hydrothermal alteration zones

Alfieris 2006
Two orthogonal fault sets (the first one with NW/SE and NE/SW directions and the second one with N-S and E-W directions), have influenced magmatism, hydrothermal alteration and mineralization.

Alfieris 2006
Profitis Ilias - Chondro

Vouno: Au-Ag-telluride IS mineralization in quartz-adularia veins hosted by brecciated dacite-rhyolite flow dome (Rhyda). Au-Ag mineralization extends into overlying ash and pumice tuffs.

Alfieris 2006
Profitis Ilias deposit

Precious metal mineralization in drillhole material from the deeper levels of the deposit (elevation 220m above sea level). This mineralization is characterized by pyrite followed by an assemblage composed of hessite, altaite, petzite, native gold, chalcocite, galena and chalcopyrite and finally by sphalerite.

Alfieris 2006
Ternary Au-Ag-Te diagram (atomic proportions) for mineral compositions analyzed in the present study. Theoretical compositions are shown as open squares, whereas solid lines indicate compositions of coexisting phases.

Alfieris 2006, Alfieris and Voudouris 2006
Profits Ilias deposit: a second mineralizing event introduces copper sulfides, galena overprints tellurides and earlier sulfides. Evidence of seawater oxidation.

Alfieris 2006, Alfieris and Voudouris 2006
Triades-Galana: Pb-Zn-Ag-Cu HS mineralization hosted in submarine pumiceous lapilli tuffs (Lmp), fossiliferous tuffs (Ftt), tuffaceous and epiclastic marine sediments (ep) and in flow-banded andesitic-dacitic-rhyodacitic subvolcanic bodies (Anda, Dado). Multistage breccia zones and quartz-baryte veins.
**Triades-Galana:** py + Fe-rich sl → cpy + ga + Fe-poor sl + tn/tt → en + cv. Gangue minerals are barite, kaolinite, sericite, adularia and quartz. Late framboidal pyrite

Alfieris 2006, Alfieris and Voudouris 2006
Kondaros-Katsimouti: Pb-Zn-Ag-Mn mineralization in brecciated and crustiform/colloform banded quartz-carbonate-barite-adularia veins, hosted in dacite flow dome (Dado) and partly in the pumiceous lapilli tuff unit (Lmp).

Alfieris 2006
Kondaros base-Katsimouti: Early deposition of sl → py + ga + pbs/prc + Ag-tt + hm + cpy. Gangue minerals are barite, calcite, adularia, and quartz.

Alfieris 2006, Alfieris and Voudouris 2006
Kondaros upper level: high-sulfidation mineralization

Alfieris 2006, Alfieris and Voudouris 2006
Vani Mn-Pb-Zn deposit: stratiform mineralization hosted in volcaniclastic sandstones, tuffs underlain by Anda, Dado lavas and domes. Seafloor deposition - White smokers (Plimer 2000)
Distribution of Au, Ag

Alfieris 2006
Distribution of Pb, Zn

Alfieris 2006
Distribution of As, Sb

Alfieris 2006
W, Mo, Bi enrichment at Triades-Galana

Alfieri 2006
Evolution of magmatism and mineralization in western Milos (Phase I)

- Pyroclastic units after felsic explosive volcanism
- Neogene sediments
- Metamorphic basement
- Magmatic chambers
- Paleo sea floor

Phase I (3.5 - 3.1 Ma)

Alfieris 2006
Evolution of magmatism and mineralization in western Milos (Phase II)

Alfieris 2006
Evolution of magmatism and mineralization in western Milos (Phase III)

- Breccia pipes / hydrothermal explosion breccias
- Submarine to subaerial hot springs

Steam heated advanced argillic alteration
- Argillic alteration
- Adularia - sericite alteration

Phase III
(1.4 - 0.5 Ma)

Alfieris 2006
Simplified geologic map of the Hellenides (I.G.M.E. 1983) and location of the gold-bearing mineralization in the Attico-Cycladic complex.
Reduced Intrusion-related Mo-W-Au-Bi systems
Kimmeria/Xanthi, Kavala, Lavrion
Oligocene-Miocene magmatic rocks (plutonic and volcanic) in Southern Balkan peninsula
Distribution of the Tertiary ore districts and deposits within the Rhodope and the Serbomacedonian metallogenic provinces in the southern Balkan peninsula.

RM=Rhodope Massif  
SMM=Serbomacedonian Massif  
CRB=Circum Rhodope Belt  
AZ=Axios Zone  
SG=Srednogorie Zone

1. Esymi  
2. Kirki-Sapes  
3. Kavala  
4. Thasos  
5. Thermes-Madan-Luky  
6. Spahievo,  
7. Lozen  
8. Madjarovo  
9. Zvezdel  
10. Chalkidiki  
11. Kilkis (Doirani-Gerakario-Vathi-Pontokerasia)  
12. Buchim-Damjan  
13. Kratovo-Zletovo  
14. Osogovo-Sasa-Toranica  
15. Borov Dol, 16. Aridea-Kozuf  
17. Balikesir

from Melfos et al. (2002)
Kimmeria/Xanthi
Intrusion-related
Mo-W-Cu-Au-Bi system
The Xanthi pluton intruded the gneisses and marbles of the Palaeozoic-Mesozoic Rhodope metamorphic complex, along the Xanthi-Komotini fault.
Intrusion-hosted Mo-W-Bi-Au-rich sheeted quartz veins
Mo-W-Cu-Au skarn at marble-granodiorite contact

Intrusion-hosted Cu-rich quartz veins
Molybdenite, native Au, chalcopyrite in skarn and intrusion-hosted mineralization
Re-content in Molybdenite from various mineralization types in Greece

Voudouris et al. (2010a)
Kavala
Intrusion-related Au-Bi-Te system
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from Melfos et al. (2002)
The Early Miocene Kavala pluton intruded the gneisses and marbles of the Palaeozoic-Mesozoic Rhodope metamorphic complex, along the Kavala-Komotini fault.
The intrusion-related ore system is dominated by a SE-NW trending system of veins, which crosscut the Kavala pluton (5), 2000 m long and up to 5 m wide, at its northeast border. Mineralized quartz veins are also found at the adjacent gneisses and marbles at Chalkero locality (6).

In addition, four main types of ore mineralization had been distinguished: (1) Pb-Zn-Ag-bearing Fe-Mn-oxidized bodies; (2) Au-bearing Fe-Mn-oxidized bodies; (3) Au-bearing pyrite-chalcopyrite ore bodies and (4) Au-bearing pyrite-arsenopyrite ore bodies.
Pluton: deformed granodiorite, in places: diorite, tonalite, monzogranite. Sometimes it has a porphyritic texture.
Intrusion-hosted sheeted quartz-pyrite veins

Boudins with massive pyrite within the pluton
The mineralogical composition of the veins consists of: pyrite, tetradymite (Bi$_2$Te$_2$S), bismuthinite (Bi$_2$S$_3$), cosalite (Pb$_2$Bi$_2$S$_5$) and Sb-lillianite (Pb$_3$Bi$_2$S$_6$)
Chalkero/Kavala: Metamorphic rock-hosted quartz veins. Shear zone-related Au-Bi-Te mineralization
Chalkero/Kavala: shear-zone related quartz-tetradymite-Au
Chalkero/Kavala: tetradymite, bismuthinite
Palea Kavala: Carbonate rock-hosted oxidized Mn-Fe-Au mineralization
Kavala-Chalkero veins: Fluid inclusion study

Melfos et al. (2008)
The fluid inclusion study shows that two immiscible fluids were present during entrapment:
1. CO₂-H₂O-NaCl fluid with low salinity (6-7 wt% NaCl equiv.) and
2. H₂O-NaCl-CaCl₂ fluid with moderate salinity (17-22 wt% NaCl equiv.)

Melfos et al. (2008)
Spry et al. (2010)
The Kavala ore deposit is characterized as a deep system, according to Baker’s (2002) classification of the intrusion-related systems.

Melfos et al. (2008), Spry et al. (2010)
Lavrion intrusion-related deposit

Intrusion-hosted sheeted Mo-W veins
Skarn W-Bi-Te
Manto Pb-Zn-Cu-Ag-Bi-Au
Vein-type Pb-As-Sb-Ag
Generalized tectonic map of the Aegean region showing major tectonic units and present-day position of the Hellenic subduction zone.

Ring et al. 2007
Lavrion: Regional Geology

Shaked et al. 2000
Lavrion: History

- From earlier than 1000 B.C up to 1980 famous for the silver and base metal production
  - 3500 tonnes of Ag and 1.4 Mt Pb production during ancient times. In modern times 0.92 Mt of Ag-rich Pb
  - More than 1000 shafts and underground working with a total length of more than 2000 km

Conophagos (1980)
Regional geology

Voudouris et al. (2008b) modified after Marinos and Petrachek 1956
Metalliferous contacts

The majority of the ores of Lavrion occur mainly within the autochthon system, particularly at the contacts of the marbles with the schists.

Plaka: Galleries along the contacts I and II

Kamariza: Galleries along the contact III

Conophagos (1980)
Plaka area, geology

Miocene Plaka granodiorite

Voudouris et al. (2008a)
Plaka deposit

Granodiorite-hosted Mo-W ore

Breccia-type ore

Skarn-type ore

Skarn-type ore
Vein-type ore

Manto-type sulfide ores

Vein-type ore

Pb-As-Sb-Ag vein

Hornfels

Pb-As-Sb-Ag vein
Table 1. *Paragenetic sequence of ore and alteration minerals in the Plaka polymetallic deposit*

<table>
<thead>
<tr>
<th>Minerals</th>
<th>Porphry style</th>
<th>Breccia style</th>
<th>Skarn style*</th>
<th>Skarn-free replacement</th>
<th>Vein style</th>
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<td>Quartz</td>
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*Only retrograde stage

**Plaka deposit**

Voudouris et al. (2008a)
Plaka deposit: Re-free molybdenites

Voudouris et al. (2008a)
Kamariza deposit
Distal from Plaka granodiorite. Manto and chimney-type Pb-Zn-Ag-Cu-Au ore deposition in III contact

J. Baptiste  Serpieri  Ilario

Kamariza cross-section modified after Marinos & Petraschek (1956)
Kamariza deposit - Intrusives

Porphyritic dikes of andesitic and dacitic composition are common in the Ilario and Jean Baptiste mines.

The dikes are subvertical, striking E-W and crosscut the autochthonous system.

Most of the dikes are hydrothermally altered.
Kamariza deposit
first occurrence of skarn mineralization
Kamariza deposit: massive sulfide mantos and vein-type ores. Quartz-fluorite-carbonate gangues

Massive sulfide ore

Galena-rich ore

Vein-type Cu-rich ore

Cu-rich ore
Bulk ore analyses

All the samples are characterized by high contents of As (>10000 ppm), and Sb (up to 3650 ppm), and relatively high contents of Bi (up to 300 ppm) and Sn (up to 520 ppm). Te (up to 3.4ppm) and Se (up to 1.8ppm) were also detected (Voudouris & Economou-Eliopoulos 2003)
Paragenetic Sequence

The textural features of the ore indicate that early formed pyrite is followed by:

1. Fe-rich sphalerite, arsenopyrite
2. And then by a copper-rich assemblage composed of:
   - chalcopryite
   - low-Fe sphalerite
   - enargite
   - tetrahedrite series minerals
   - Bi-Cu-Pb-Ag-sulfosalts
   - galena
   - native gold
   - gersdorffite
   - petrukte
### Paragenetic Sequence

**Vein-type Au-Bi-Ni ore**

Voudouris et al. (2008b)

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<td>Bouzoumite</td>
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<td>Semecyte</td>
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<td>Boulangarite</td>
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<td>Stephanie</td>
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<td>Pyragryrite</td>
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<td>Ramdohnite</td>
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</table>

hom homologue, ss sulfosalt
Kamariza/Lavrion deposit
Kamariza deposit: Bismuthinite, native gold, gersdorffite included in galena
Kamariza deposit: Stannite included in pyrite
Kamariza deposit: Stephanite included in galena
Plaka deposit

Voudouris et al. (2008a)
Kamariza deposit

Voudouris et al. (2008b)
Fig. 9. Homogenization temperatures of fluid inclusions from the Plaka/Lairion porphyry- and vein-style mineralizations. Type 1 two-phase liquid-rich aqueous inclusions. Type 2 three-phase halite-bearing liquid-rich inclusions. *Py* pyrite, *mlb* molybdenite

Voudouris et al. (2008a)
Fig. 11. Homogenization temperatures versus salinity plot for the fluid inclusions from the Plaka porphyry and vein mineralization styles. Salinity was calculated using the equation of Potter et al. (1978) and Bodnar (1993). NaCl saturation curve (halite + liquid + vapour curve) and critical point curve of the system H₂O-NaCl are also shown (data from Sourirajan and Kennedy, 1962; Haas, 1976). Trends of decreasing temperatures and salinities are represented by thick grey lines with arrows. Qtz quartz, py pyrite, milb molybdenite, fl fluorite, cal calcite, sid siderite.

Voudouris et al. (2008a)
Kamariza deposit

Voudouris et al. (2008b)
Bonsall et al. (2007)
Shear zone-related (orogenic?) Cu-Au-Bi-Te prospects
Stanos/Chalkidiki:
Shear zone-related Au-Ag-Bi-Te-Cu veins in metamorphic rocks of the Servo-Macedonian Massif

Agostini et al. (2009)
I.G.M.E. (Kockel et al. 1977)
The Cu-Au mineralization of Stanos area is hosted by regional NE-SW trending shear zones within the crystalline Servomacedonian Massif on the Chalkidiki Peninsula, North Greece. The ore bodies are located along the contact between the orthogneisses of Silurian age of the Vertiskos terrane and marbles and garnet-graphite schists of the Svoula series. The copper-gold mineralization of Stanos is structurally-controlled and is restricted to high-strain shear zones within gneisses that developed late during regional ductile shearing. This deformation event is related to southwestward overthrusting of the Vertiskos unit onto the Svoula lithologies under upper-greenschist to lower-amphibolite facies metamorphism.

Voudouris et al. (2010c)
Stanos/Chalkidiki: shear-zone related Au-Cu-Bi-Te prospect
Stanos/Chalkidiki:
Lillianite homologues and bismuthinite derivatives
Stanos/Chalkidiki:
Ikunolite, Joseite-A, Joseite-B, Telluronevskite
Stanos/Chalkidiki: Electrum and native Bismuth

(a) Au, Ccp

(b) Py, Ccp, Lil, Au, Py

(c) Bi, Gn, Ccp, Qtz

(d) Bm-d, Lil, Bi, Ccp, Mtd, Bt
Stanos/Chalkidiki: Bi-sulfosalts, Bi-tellurides

Voudouris et al. (2010c)
Stanos/Chalkidiki: Geochemical environment of ore formation

Voudouris et al. (2010c)
Koronouda-Laodikiono/Kilkis: shear-zone related Cu-Bi-Au

Himmerkus et al. (2006)
Koronouda/Kilkis: joseite-B ($\text{Bi}_{3.92}\text{Au}_{0.05}\text{Te}_{1.93}\text{Se}_{0.04}\text{S}_{0.98}$), pilsenite ($\text{Bi}_{3.80}\text{Te}_{2.85}\text{S}_{0.35}$), tellurobismuthite ($\text{Bi}_{2.05}\text{Te}_{2.78}\text{S}_{0.17}$), hessite
Laodikino/Kilkis: pilsenite (Bi$_{3.97}$Te$_{3.03}$) included in chalcopyrite
Kallianou Evia island

Shear zone-related Au-Ag-Te veins in metamorphic rocks of the Cycladic Blueschist Unit
Generalized tectonic map of the Aegean region showing major tectonic units and present-day position of the Hellenic subduction zone.

Ring et al. (2007)
Tectonic map of southern Evia showing major structures and tectonic contacts between units

Kallianou locality

Ring et al. (2007)
NW–SE cross-section through the nappe pile of southern Evia

Ring et al. (2007)
Kallianou/S. Evia: shear-zone related quartz veins
Au-Ag-Te-bearing milky quartz veins in the Kallianou area are hosted in mica schists and marbles of the Cycladic Blueschist Unit

The quartz veins (up to 3m thick and 100m long) generally strike NW-SE and are discordant with respect to syn-metamorphic structures. The veins were formed under ductile to brittle deformation, and in the footwall block of an exhumed metamorphic core complex.
Ore minerals in the veins occur in masses (up to 10 vol %) to disseminations, filling fractures or cementing brecciated quartz fragments. The ore mineralogy consists of pyrite, arsenopyrite, löllingite, sphalerite, chalcopyrite, tetrahedrite, galena, gold, pearceite, sylvanite and argentite.

The main gangue minerals include quartz and calcite, whereas wallrock alteration consists of chlorite, muscovite, albite and calcite.

Voudouris & Spry (2008)
Kallianou: minerals of the cervelleite-group, Te-polybasite and hessite.

Voudouris & Spry (2008)
Kallianou:
unnamed Ag$_2$CuTeS
and (Ag,Cu)$_2$TeS
minerals

Voudouris & Spry (2008)
Kallianou/S. Evia: electrum

Voudouris & Spry (2008)
Kallianou: Ag-Cu sulfotellurides

This study:
- Kallianou area

Literature data:
- Spry & Thieben (1996), Mayflower Montanta
- Cook & Ciobanu (2003), Large, Ocna de Fier Baita Bihor Romania
- Gu et al. (2003), Funan China
- Novoselov et al. (2006), Gayskoe, Yaman-Kasy Severo-Uvaryazhskoe, Tash-Tau, Babaryk Southern Urals Russia

Voudouris & Spry (2008)
Kallianou/S. Evia: Ag-Cu sulfotellurides, electrum and hessite

Voudouris & Spry (2008)
Conditions of formation for Ag-Cu sulfotellurides

Voudouris & Spry (2008)
References

References

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- Voudouris P., Spry P.G. Mavrogenatos C., Sakellaris G.A. (2010c) Gold-bismuth-telluride-sulfide assemblages at the Stanos shear zone-related prospect, Chalkidiki, northern Greece. 13th Quadrennian IAGOD symposium, Adelaide, South Australia, 6-9 April, 297-298