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Numerical simulation of the Kallianos Au-Ag-Te-bearing ore fluid flow along the CBU detachment, Attico-Cycladic Metallogenetic Massif

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Abstract

The Kallianos deposit is located in south Evia at the northern part of the Attico-Cycladic Metallogenetic Massif and consists of carbonate-replacement and vein-type ores. The Au-Ag-Te vein mineralization associates with sixteen ore-bearing syntaxial quartz-I and -II type veins that intersect the schists and marbles of the Cycladic Blueschist Unit. The veins comprise two hypogene ore stages which involve the deposition of stage I-pyrite, and stage II-chalcopyrite, galena and tellurides. Zones of muscovite-chlorite alteration surround the quartz-I and -II type veins.

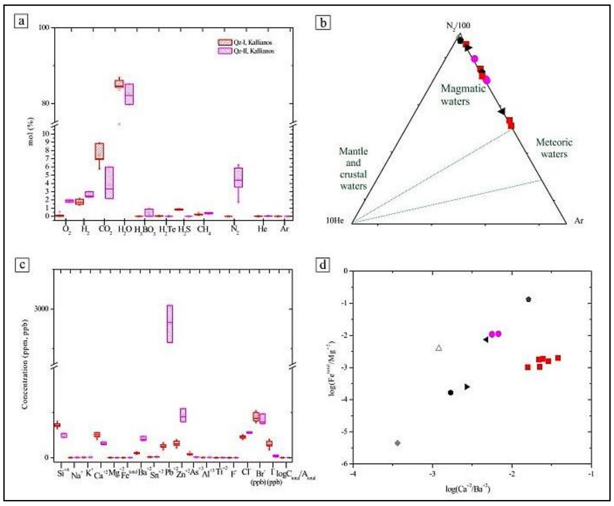

Figure 1. Fluid chemistry of the Kallianos ore fluids: (a). Box-and-whisker plot for the L-V fluid inclusions displaying their gaseous phase content (in mol fractions %) in quartz-I and quartz-II for Kallianos ore fluids, (b).Ternary N2, He and Ar diagram of fluid inclusion gaseous compositions. End-member gaseous fluid compositions and compositional ranges are from Wilkinson (2001), (c). Box-and-whisker plot for the L-V fluid inclusions showing the liquid phase content (in ppm and ppb) in quartz-I and quartz-II, and (d). Log(Ca+2/Ba+2) versus log(Fetotal/Mg+2) plot for the fluid inclusion liquid phase. In this plot for comparison, we have also added data from Plaka, Daskalio, vein 80 and Sounio, Lavrion, Aspros Kavos, Makronisos and Volax, Tinos. The magmatic values are from Williams-Jones et al. (2010).

Bulk chemical analyses of the quartz-I and quartz-II veins and related sulfides from Kallianos suggest that they are enriched in Au, Ag and Mo. They also display Th/U values ≤ 7.8, $(La/Sm)_N$ ratios of ~ 0.2 to 0.7 and moderate negative Ce/Ce* and Eu/Eu* anomalies. Raman and chromatographic analyses suggests ore-fluid gaseous phase contains mostly CO_2, N_2, and H_2S, minor H_3BO_3, O_2, H_2, CH_4, and H_2Te and traces of He and Ar (Fig 1a, b). Bulk composition of the ore fluid liquid phase indicates that Cl^- is the dominant anion in the ore solution and Si^{+4}, Mg^{+2}, Ba^{+2}, Pb^{+2}, $Fe^{+2(total)}$ and Zn^{+2} the dominant cations (Fig. 1c). Stage I-ore fluid bears $\log(Ca^{+2}/Ba^{+2})$ values in respect to the stage II-ore fluid which is characterized by higher $\log(Fe^{total}/Mg^{+2})$ values (Fig. 1d). He, Ar and Ne isotope compositions were also obtained from fluids extracted from the same samples. Their $^3He/^4He$, $^{40}Ar/^{36}Ar$, $^{20}Ne/^{22}Ne$ and $^{21}Ne/^{22}Ne$ compositions range from 0.02-0.08 R_A, 1139-1809, 8.94-9.71 and 0.05-0.15, respectively (Figs. 2a, b). A magmatic origin is deduced for the ore fluids in equilibrium with quartz-I and -II based on measured noble gas isotopic compositions.

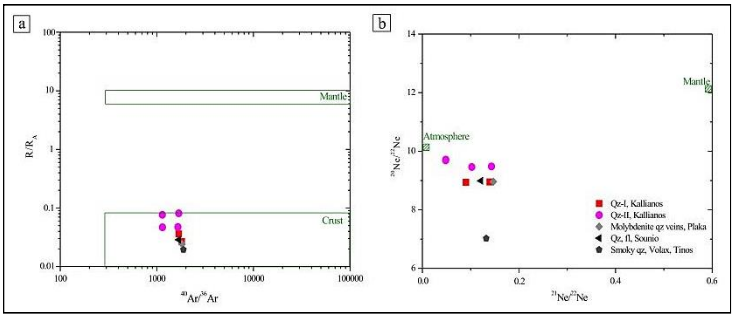

Figure 2. Helium, argon and neon isotopes: (a). R/RA versus 40Ar/36Ar, and (b). 20Ne/22Ne versus 21Ne/22Ne isotopic compositions of primary fluid inclusions in vein quartz from Kallianos ores. For comparison we have also analyzed inclusions from molybdenite quartz veins from Plaka, and quartz crystals from a fluorite vein from Sounio. The "Mantle", "Crustal" and "Atmosphere" fields are from Ballentine and Burnard (2002).

The Upper Continental Crust-normalized REE profiles of the Kallianos quartz veins and vein-type ores appear mildly enriched in the LREE relative to HREE. The Kallianos REE patterns, share many common features to the granodiorite of Plaka and related aplites, carbonate-replacement and vein-type ore deposits (Berger et al., 2013). Moreover, these REE patterns have some similarities with the Tinos leucogranite, aplites and smoky quartz from Volax and quartz veins from Panormos Bay (Tombros et al., 2007, 2010). However, Tinos REE patterns appear with some differences in their LREE patterns relatively to Kallianos.

On the N_2-He-Ar plot (Fig. 1b) the gaseous phase of both stage I and II ore fluids plots in the magmatic waters field. The linear trend observed on the same plot (i.e., on the N_2-Ar join, Fig. 1b) indicates simple cooling of the ore fluids. The Kallianos ore fluids, based on noble gases isotopic compositions resemble to both Lavrion and Tinos ore fluids, even Tinos has lower $^{20}Ne/^{22}Ne$ isotopic values (Fig. 2a, b). Fluid chemistry of the liquid phase suggests that the Kallianos ore fluids mainly plot close to the ore fluids exsolved from the Plaka granodiorite (Lavrion), and more infrequently close to Tinos (Fig. 1b and d). Moreover, in the $\log(Ca^{+2}/Ba^{+2})$ versus $\log(Fe^{total}/Mg^{+2})$ plot the quartz-II ore fluid lies on the mixing line defined between Tinos and Lavrion end-members (Fig. 1d).

An important issue addressed in our study is that a possible magmatic source is indicated from the bulk geochemistry of the quartz-I and-II veins, fluid chemistry and noble gas isotopic compositions (Figs. 1, 2). In order to estimate the possible distance from where the ore fluid could have been exsolved and then transported, we have applied a convective heat-transfer flow model. This model considers as sources the Lavrion and Tinos granitoids, which are the closest to the Kallianos ores (e.g., currently at ~60 and 85 km). It is also based on steady-state fluid flow and simple cooling of the ore fluids, using as a pathway the CBU secondary detachment between the schists and marbles. In the fault damage zone the driving flow mechanism was horizontal fluid convection that resulted in the fluctuations of temperature of the ore-fluid over distance and time. For the simplest case (fluid velocity $\approx 9 \cdot 10^{-3}$ km/Ma, by analogy to Panormos Bay, Tinos, Tombros, 2011), the equation is: $T(x) = x\ln t + bv(\frac{x_0 - t_0 \ln t}{T_0})x$ (1).

Modelling parameters are T(x) = 230ºC, t = 2 Ma for Plaka's granodiorite, Lavrion and 4 Ma for Volax, Tinos, and x_0 = 0, i.e., the Plaka and Volax sites. At t_0 = 9.4 Ma, the ore fluid from Lavrion (T_0 = 460ºC, P ≤ 200 bars, salinity of ~ 55 wt. % equivalent NaCl, Bonsall et al., 2011) or at t_0 = 10 Ma, the fluid from Tinos (T_0 = 320ºC, P ≤ 200 bars, salinity of ~ 5 wt. % equivalent NaCl, Tombros et al., 2007) commenced to flow in the fault zone. Pressures obtained from fluid inclusions for Kallianos are P ~ 125 bars, nevertheless, the temperatures are lower due to the greater distance from the granitoid source and simple cooling of the ore fluids. Solving equation (1) for distance, we conclude that if the fluid moved in the marbles-schist interface it would have flown for a distance of 22.4 to 27.6 km away from Plaka, Lavrion or 23.9 to 29.4 km away from Volax, Tinos.

Based on our geochemical results and numerical simulation of temperature over distance we examine two possible scenarios about the source of the Kallianos ore fluids. The first involves the granodiorite of Plaka in Lavrion area. Bradley et al. (2013) reported that Attica and Evia have experienced ~ 25º ± 6.5º of post-Middle Pliocene clockwise rotation which is linked to acceleration of the Aegean subduction slab retreat and the subsequent initiation of the Evia and Corinth Gulf rifting. In a pre-rotational setting at ~ 9 to 8 Ma the areas of Kallianos, Plaka-Sounio in Attica could have been at a distance of ≤ 20 to 25 km, i.e., the calculated distance that the ore fluid had travelled along the CBU detachment or the WCDS. The second scenario implicates the Tinos leucogranite as a source of the ore fluids exsolved from Volax site. In a similar case at Panormos Bay, Tinos (Tombros et al., 2007, 2010), the Au-Ag-Te mineralization was linked to the volatile evolution of the Tinos pluton, which at surface is ~ 16 km from the leucogranite. Channelized flow at depth may have occurred along the damage zone of the detachment interface between the BU marbles and the CBU or alternatively along the contact between the CBU and the UCU. However, for the Au-Ag-Te bearing ore fluid originated from Tinos the calculated distance that the ore fluid may had moved along the CBU detachment or the NCDS was ~ 24 to 30 km. It seems that Tinos leucogranite could only have promoted mineralization up to Panormos Bay, as recommended by Tombros et al. (2007, 2010). Herein, we propose that Kallianos is an outlier or satellite ore deposit of the Lavrion hydrothermal system with Plaka's granodiorite as the major source for the Au-Ag-Te ore fluids. A possible subsurface pluton with similar characteristics cannot be excluded but there are not any data for its presence so far.

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