Structural architecture of mineralized veins in a Cenozoic orogenic gold deposit along the North Cycladic Detachment System, Greece

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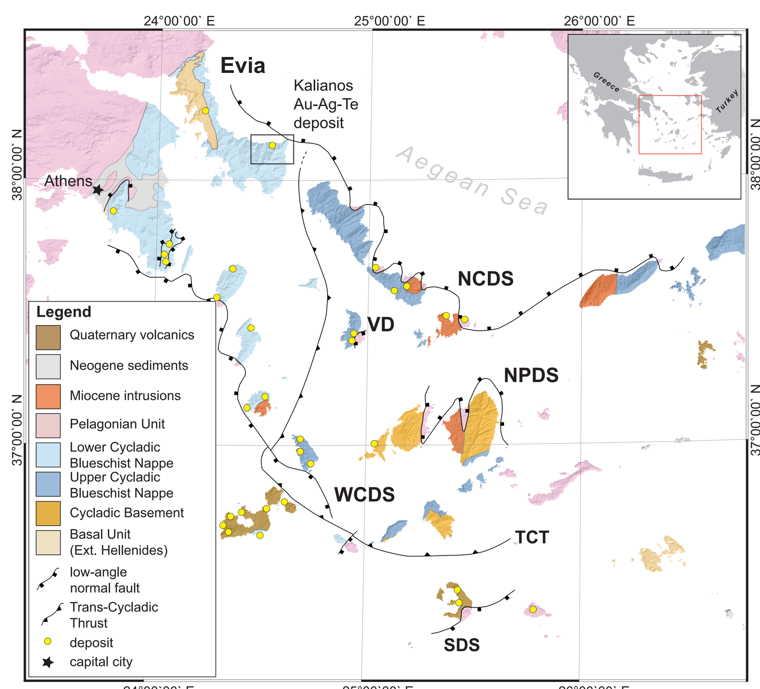
RESEARCH OBJECTIVES

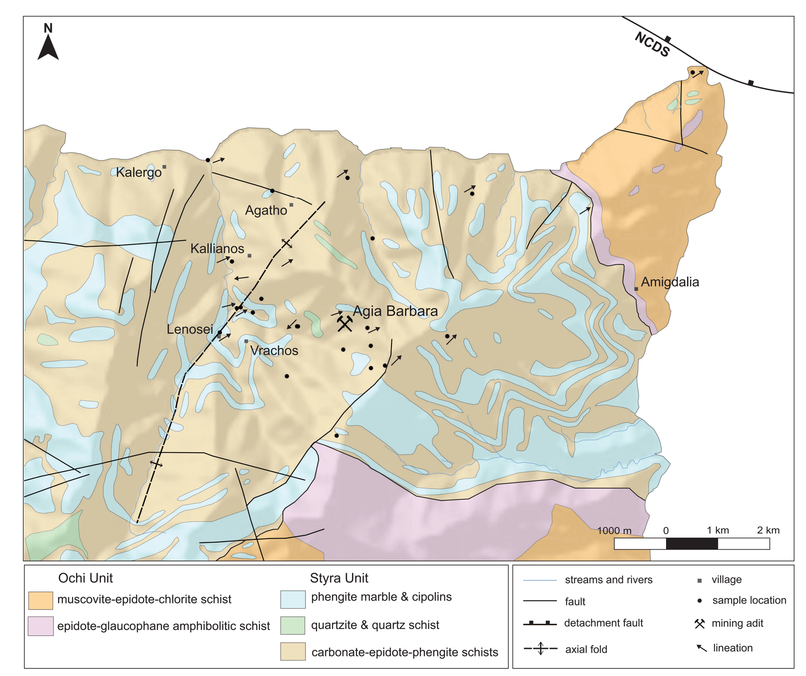
Southern Evia Island in the NW Aegean Sea exposes the Ochi and Styra Unit, both part of the larger Cycladic Blueschist Unit (CBU), which are Eocene high pressure-low temperature (HP-LT) metamorphic rocks of previously subducted crust. The CBU underwent greenschist facies overprint during Miocene back-arc extension that was accommodated by a low angle normal faults, such as the North Cycladic Detachment System (NCDS).



Simplified geological map of the Cyclades, Greece. Ore deposits (yellow circles) include epithermal, carbonate replacement, skarn, vein type and hydrothermal vent type deposits. Modified after Ducharme et al. (2022, Tectonics).

The Cycladic Mineral District is an extensive and important metallurgical area yet hosts a handful of deposits, which have been greatly overlooked in discussions of ancient Greek mining districts (Vaxevanopoulos, 2022, J. Archeological Sci.). One of these deposits is the Kallianos Au-Ag-Te deposit, a Cenozoic orogenic gold deposit hosted in the Styra Unit in the footwall of the NCDS.

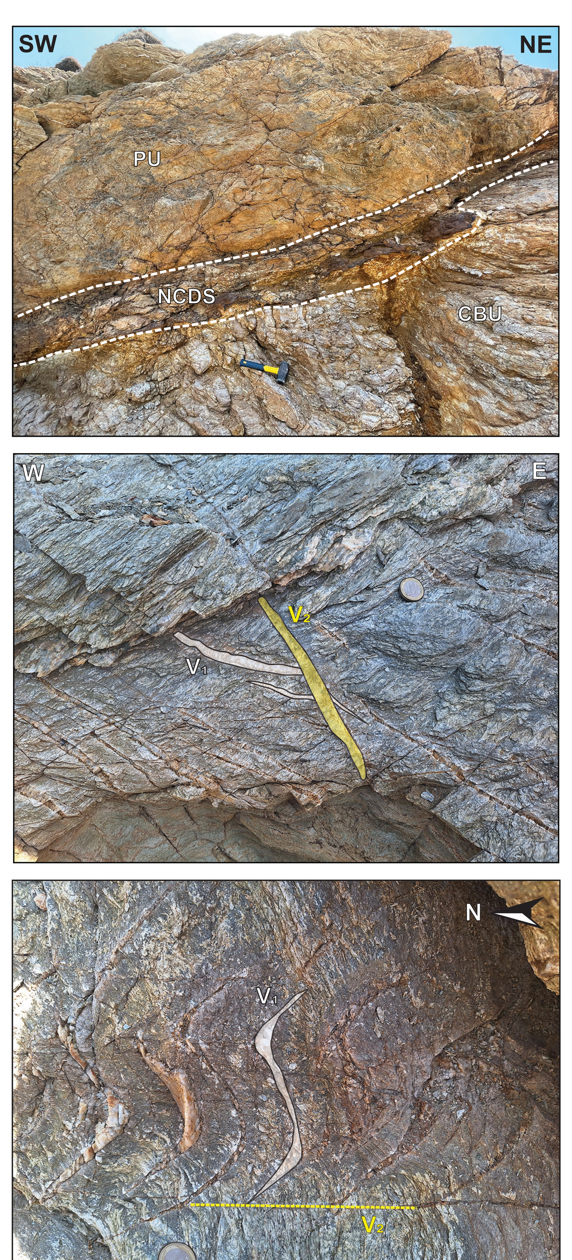
Previous models indicate that the deposit formed at c. 8 Ma and is proposed to be derived from magmatic fluids originating during post-orogenic extension (Tombros et al., 2020, Miner. Deposita). However, the late Miocene age does not seem plausible when considering the regional context, such as the timing of nearby crustal scale post-orogenic structures like the NCDS, as well as the timing of host rock deformation which occurred around 25 Ma (Jolivet et al., 2013, Tectonophysics; Ducharme et al., 2022, Tectonics). Notably, Evia and the nearby islands lack exposures of late Miocene plutons.



Geological map of the Kallianos Ore Deposit, modified after Latsoudas et al. (1997, Inst. Of Geology and Min. Exploration). Agia Barbara (mining adit) contains the most abundant mineralization in the vein sets of the deposit.

With new field observations and structural analyses, we can tie the structural architecture that hosts mineralization to deformation associated with the post-orogenic structures, such as the NCDS. The comprehensive study of the structural architecture of younger Cenozoic orogenic deposits like the one on Evia, where mineralizing structures sustained minimal subsequent deformation, will clarify the original structural controls of older polydeformed systems such as many Precambrian orogenic gold deposits.

NORTH CYCLADIC DETACHMENT SYSTEM

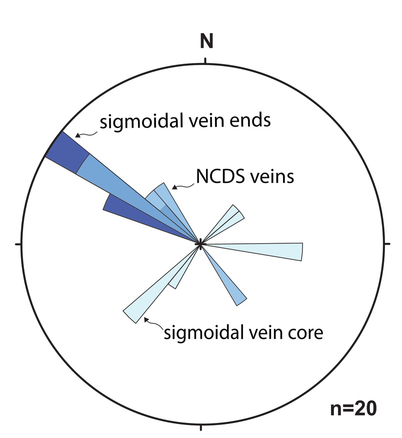


At left: Field photos at the NCDS location.

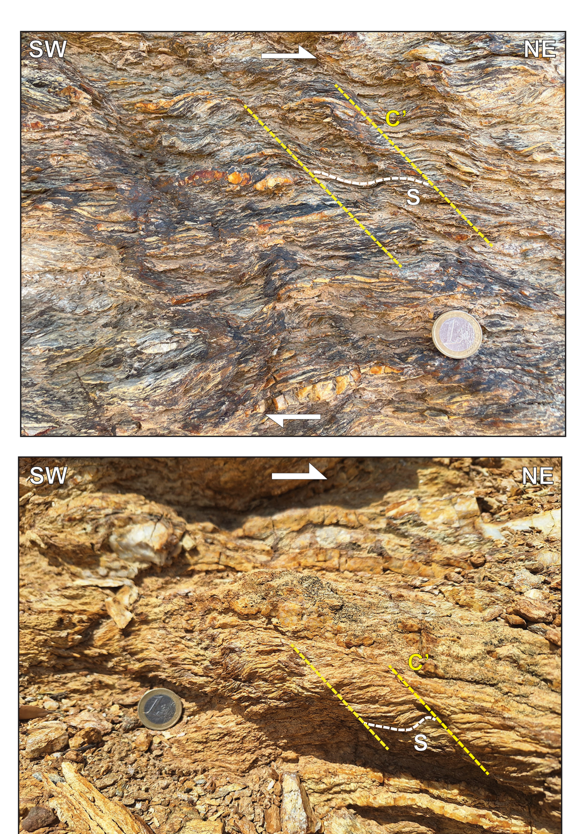
Top: The footwall of the NCDS is a cataclasite underlain by mylonite in the Cycladic Blueschist Unit (CBU). The upper unit is the heavily altered Pelagonian Unit (PU) which exhibits brittle-ductile deformation. Hammer in the same direction as lineation.

Middle: Quartz and albite unmineralized NNW striking vein (V_2) cross-cutting the NW vein set (V_1) in the footwall of the CBU near the NCDS, representing the same sequence observed in the Kallianos deposit veins. The veins and fractures display bleached margins. Fractures in the photo have a NW facing direction, showing brittle deformation.

Bottom: (Plan view) Sigmoidal tension gashes (V_1) with quartz in the immediate footwall of the NCDS, showing brittle-ductile deformation. The tips of the veins are oriented NW-SE and the core shows sinistral shear rotation into a NE-SW direction. Note the vein set is cut by a later NNW striking fracture (V_2).



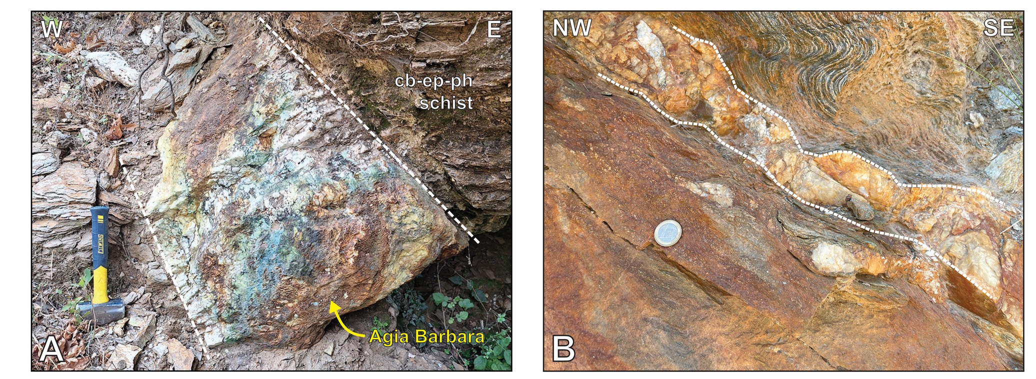
Top left: Rose diagram showing directions of veins in the NCDS footwall. The tips of the sigmoidal vein strike NW, whereas the vein cores are oriented ~perpendicular to this direction. The NCDS have a NW to NNW strike, which are also observed in the Kallianos deposit.



Top and middle left:

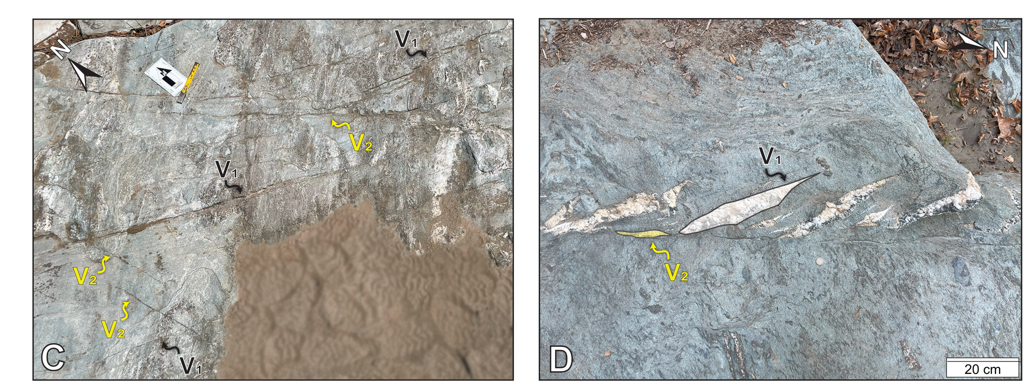
Field photos showing examples of shear sense direction. Shearbands showing top-to-the-NE in the muscovite-epidote-chlorite schist in the footwall of the NCDS, which is evidence of brittle-ductile deformation.

KALLIANOS Au-Ag-Te DEPOSIT



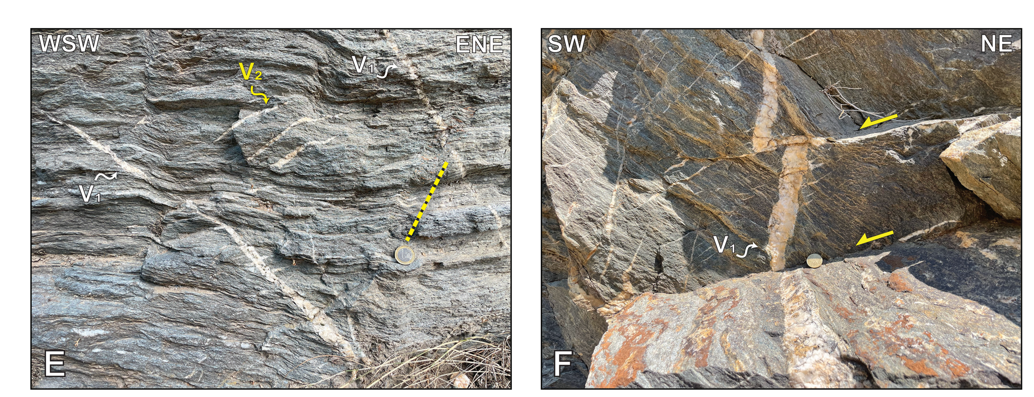
A - Photo of Agia Barbara quartz-albite vein hosted in the carbonate-epidote-phengite schist of the Styra Unit containing mineralization of pyrite, chalcopyrite, galena and covellite. The vein cross-cuts foliation along a strike of NNW with a thickness of 60 m. Abbreviations: cb: carbonate, ep: epidote, ph: phengite.

B - Photo of layer-parallel carbonate replacement vein present in carbonate-epidote-phengite schist of the Kallianos ore deposit. Vein composed of quartz and calcite hosting pyrite mineralization.



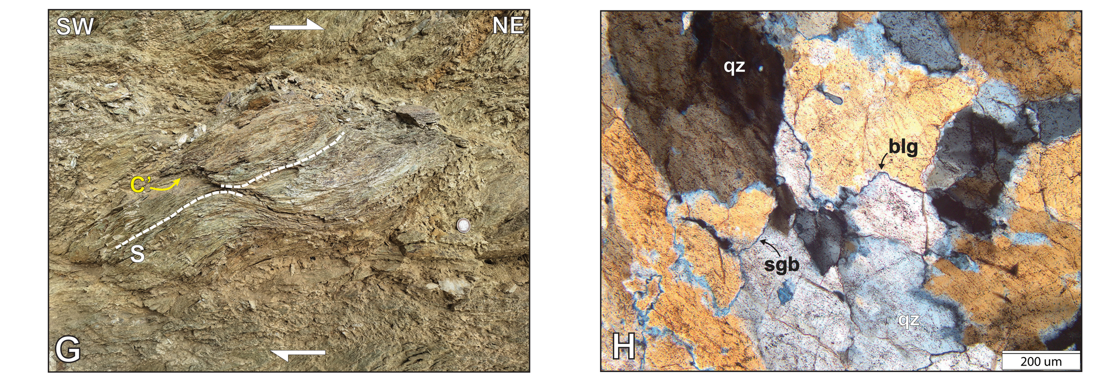
C - (Plan view) Cross-cutting relationships between two pervasive unmineralized vein sets in the carbonate-epidote-phengite schist of the Styra Unit. The NNW-striking set (V_2) crosscuts the NW-striking vein set (V_1) showing brittle deformation.

D - (Plan view) Within the deposit, the vein relationships are the same as those exposed at the NCDS outcrops where NNW striking veins (V_2) cross-cut the NW oriented veins (V_1). These quartz-albite, unmineralized veins show brittle-ductile deformation and are hosted in the carbonate-epidote-phengite schist.



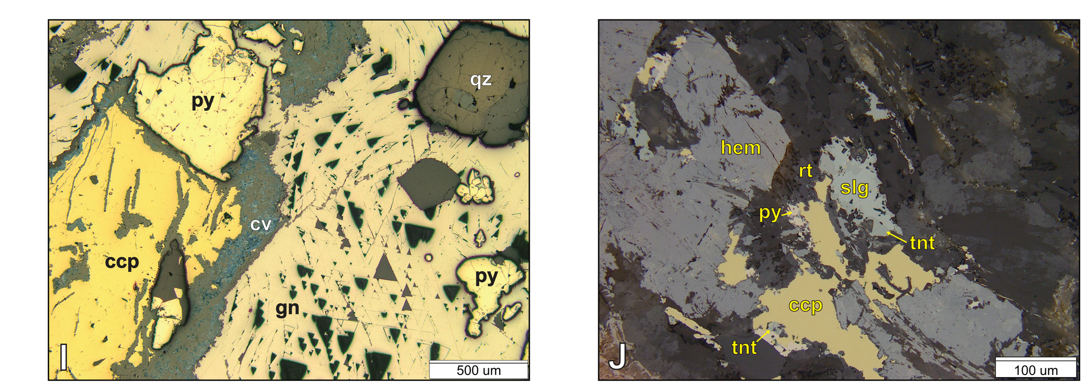
E - Cross-cutting relationships between brittle NNW-striking vein set (V_2) and brittle NW-striking vein set (V_1). Kink bands (yellow and black dashed line) strike parallel to V_1 but dip oppositely.

F - Unmineralized NW-striking vein displaced by late top-to-the-SW brittle faults. Small conjugate veins strike parallel to the larger vein set.



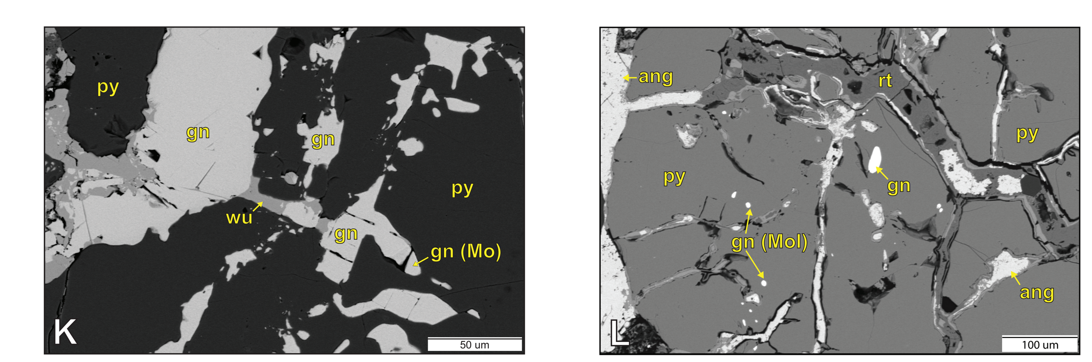
G - Field photos showing shear sense direction in the footwall of the CBU in the Kallianos deposit. Shearband shows top-to-the-NE direction in the carbonate-epidote-phengite schist, evidence of brittle-ductile deformation.

H - Photomicrograph in cross-polarized light of the Agia Barbara vein composed primarily of quartz. Sutured vein boundary and bulging depicts very low temperature-pressure ranges during the formation of the vein and time of mineralization. Abbreviations: qz: quartz, blg: bulging quartz grain, sgb: sutured grain boundary.



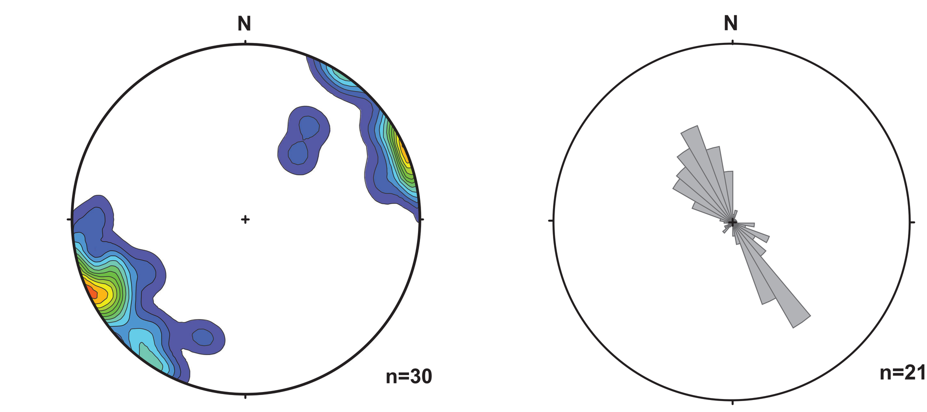
I - Photomicrograph in reflected light of representative mineralization found in the Agia Barbara vein, which strikes NNW. Mineralization include pyrite, chalcopyrite, galena and covellite in a quartz vein. Abbreviations: py: pyrite, cpp: chalcopyrite, gn: galena, cv: covellite, qz: quartz.

J - Photomicrograph in reflected light of representative mineralization found in veins striking NNW. Ag impurities are common in seligmannite (slg) and tennantite (tnt). Abbreviations: py: pyrite, cpp: chalcopyrite, hem: hematite, rt: rutile, tnt: tennantite($(Cu, Ag, Zn, Fe)_{12}As_4S_{13}$), slg: seligmannite ($PbCuAsS_3$).



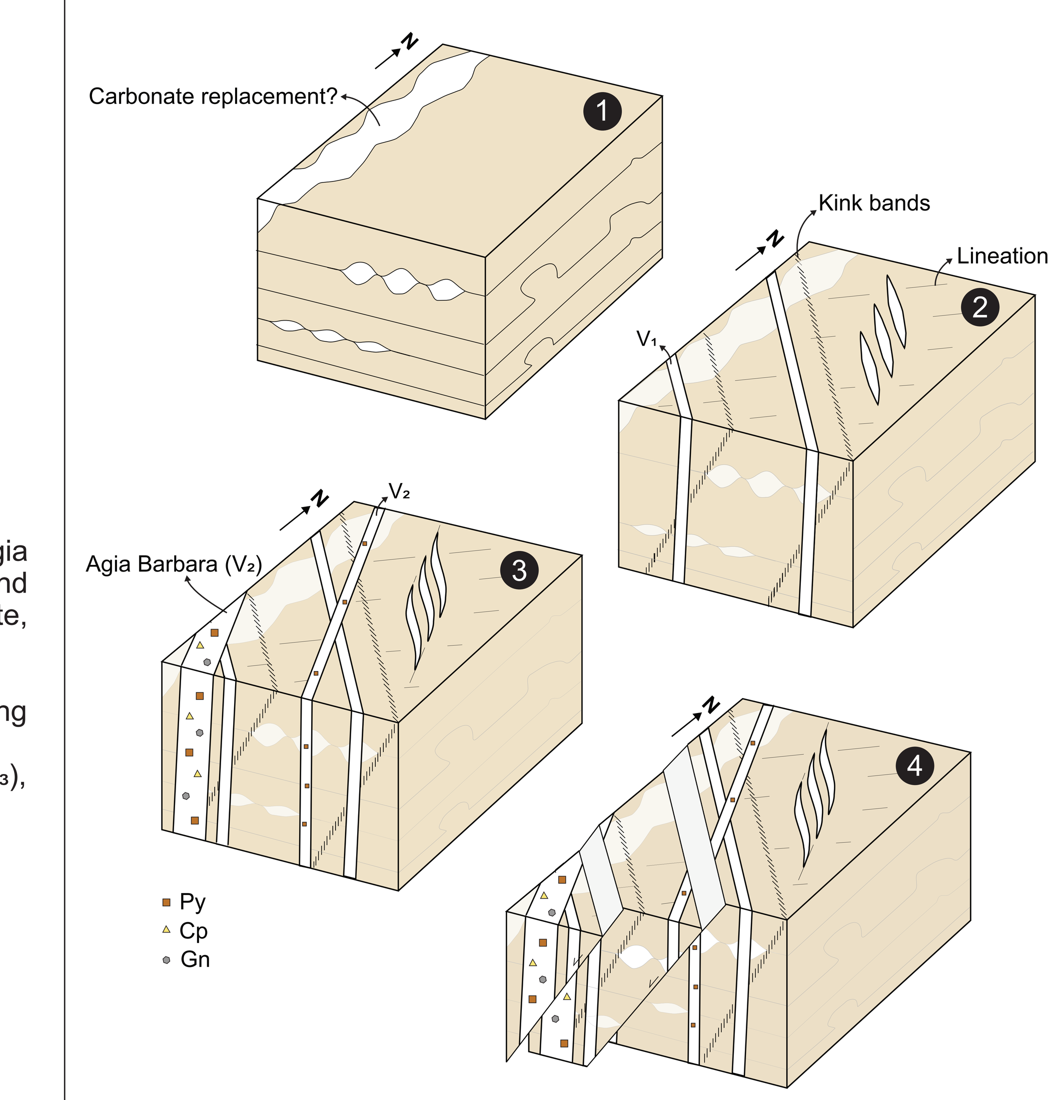
K - Back-scattered electron photomicrograph of the Agia Barbara vein. Some galena inclusions in the pyrite and chalcopyrite contain ~10% molybdenum, with infill wulfenite. Abbreviations: py: pyrite, gn: galena, gn (Mo): galena with Mo, wu: wulfenite ($PbMoO_4$).

L - Back-scattered electron photomicrograph of the Agia Barbara vein. More Mo-rich galena inclusions visible. Abbreviations: py: pyrite, gn (Mol): galena with Mo, ang: anglesite ($PbSO_4$).



Left: Stereonet depicting the stretching lineations within the Kallianos deposit. Lineations trend NE-SW and are perpendicular V_1 and parallel to the vein cores found at the NCDS, indication that the stretching lineation are syn-kinematic with the opening of the sigmoidal vein cores.

Right: Rose diagram depicting the vein orientations of the Kallianos deposit. The two vein strikes are non-resolvable with data alone but shows a NW to NNW trend.



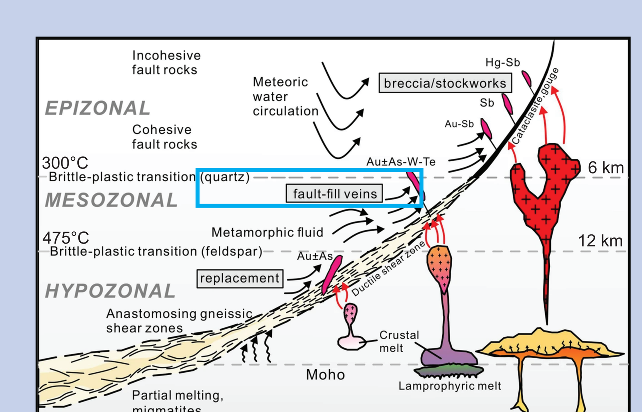
Above :
1 - Styra Unit before formation of the Kallianos deposit veins. Boudinaged quartz veins are seen throughout the field area parallel to foliation. Boudinaged carbonate replacement mineralization observed.

2 - Brittle unmineralized NW-striking veins (V_1) develop coeval with SW-NE stretching lineation.

3 - NNW mineralized veins (V_2) cross-cut NW veins (V_1). Brittle-ductile deformation deflects opening orientation of the tension gash tails from NW to NNW.

4 - Late top to the SW brittle faulting.

IMPLICATIONS



Above: Model showing depth and PT conditions for the veins of the Kallianos ore deposit in the britte-plastic zone (blue box), depicting how extensional vein networks can form in the brittle-plastic regime in metamorphic conditions. Model modified from Goldfarb & Pitcairn (2023, Miner. Deposita).

The vein orientations of the Kallianos deposit trend NW-SE and NNW-SSE, which is generally orthogonal to the sub-horizontal ~NE stretching lineations related to crustal extension and thinning accommodated by the NCDS, showing brittle-ductile deformation. Structural data strongly imply a connection between mineralized veins of the Kallianos Au-Ag-Te deposit and the regional stress field imposed by displacement along the NCDS.

Fluids that generated the deposit were channelized by crustal-scale post-orogenic structures, driven by deformation along the NCDS, which facilitated early Miocene exhumation(?) of the CBU into the brittle crust. Additional work will be conducted with stable isotope geochemistry to understand the source of the fluids.

Currently conducting zircon (U-Th)/He and mica Ar-Ar and Rb-Sr geochronology to date the timing and duration of fluid flow. Preliminary white mica Ar-Ar dates suggest Eocene-Oligocene ductile and brittle-ductile deformation and do not support a middle Miocene paragenesis of the deposit.

new geochronology

abstract