It's on the way up! Syn-exhumation paragenesis of glaucophane-phengite-quartz veins

T. A. Ducharme[1], D. A. Schneider[1], B. Grasemann[2], M. Bukała[3], A. Camacho[4], K. Larson[5], K. Soukis[6]

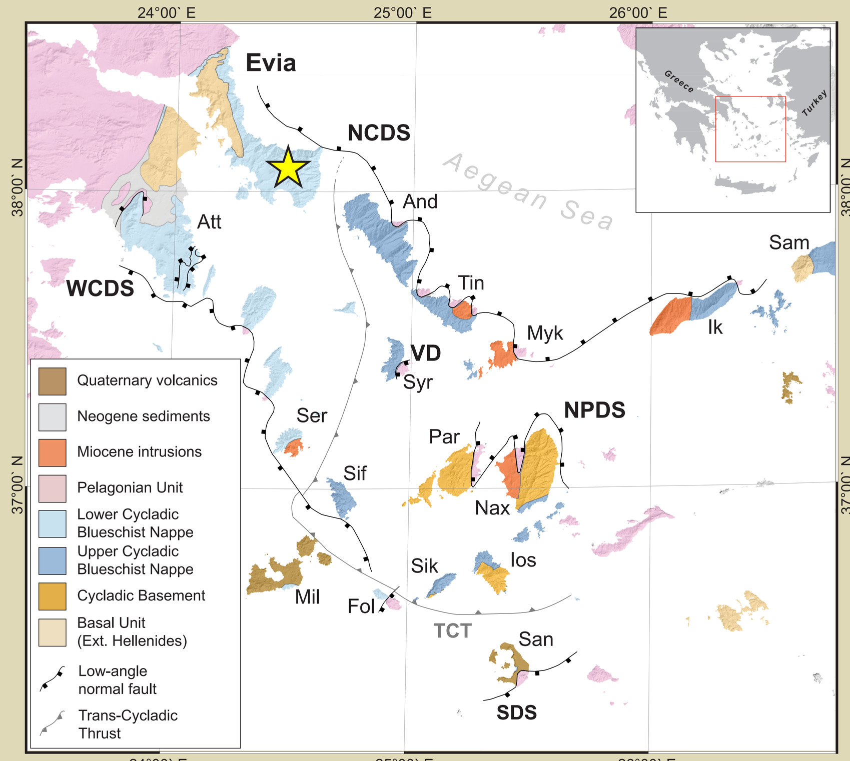
[1]University of Ottawa, Ottawa, Canada • [2]University of Vienna, Austria • [3]Instituto Andaluz de Ciencias de la Tierra, Spain • [4]University of Manitoba, Canada • [5]University of British Columbia Okanagan, Canada • [6]National and Kapodistrian University of Athens, Greece

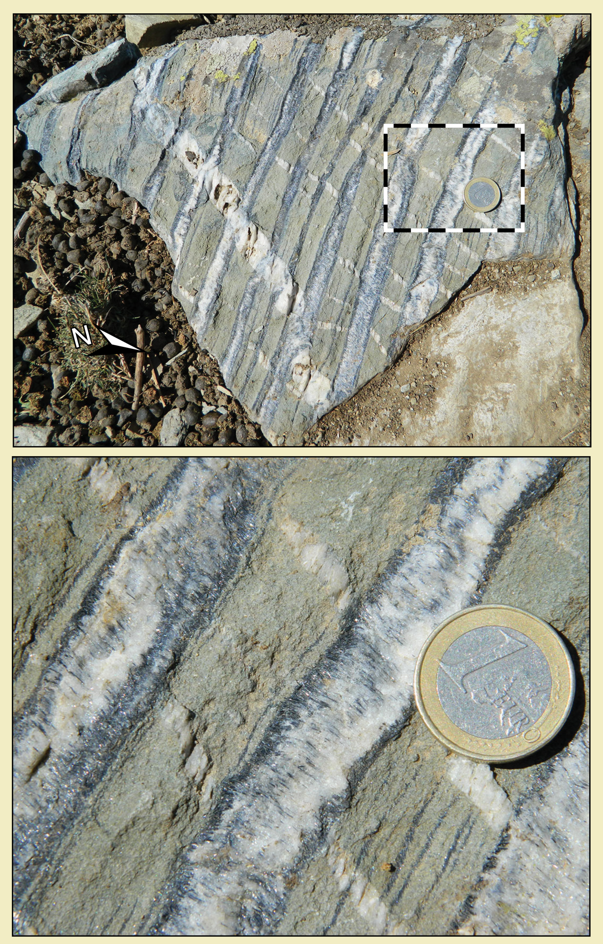
The Mt. Ochi Veins (Evia, Greece)

Southern Evia Island in the Aegean Sea (see map at right) marks the northwestern exposure limits of the Attic-Cycladic Crystalline Massif, including the high pressure-low temperature (HP-LT) Cycladic Blueschist Unit (CBU). The CBU sustained **early Eocene (c. 50-40 Ma) HP-LT metamorphism.**

Glaucophane- and phengite-bearing quartz veins occur due SW of the peak of Mt. Ochi (star at right). Veins are hosted in interlayered metabasalt and quartzite comprising part of a HP-LT ophiolitic subunit within the CBU.

(Micro-)structural data, mineral chemistry, and combined $^{40}Ar/^{39}Ar$ and $^{87}Rb/^{87}Sr$ geochronology (see blue boxes at right) indicate that **vein-hosted HP minerals crystallized during regional greenschist facies metamorphism in the early Miocene.**



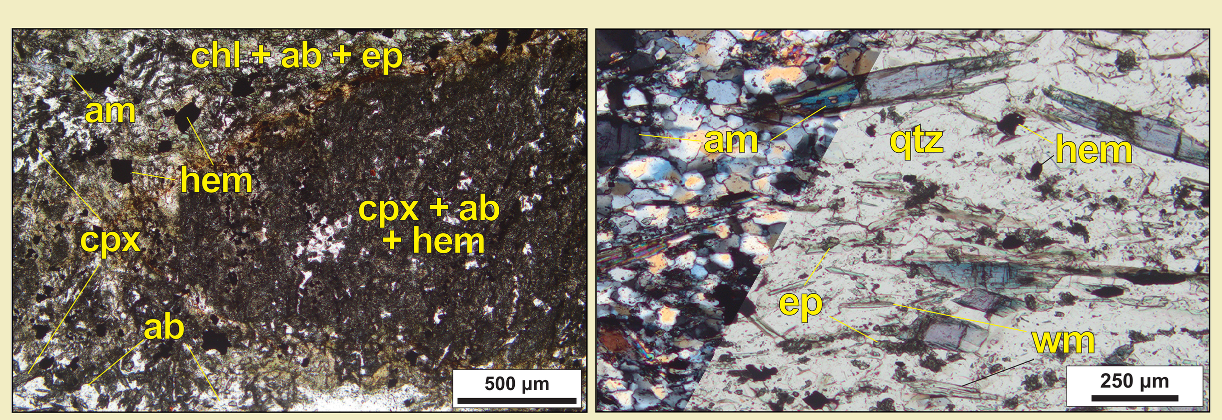


At left: field photographs of the Mt. Ochi veins. 1€ coin used for scale is 2.3 cm in diameter.

Top: representative exposure of the glaucophane-bearing quartz veins. A prominent ~1-2 cm wide planar vein set (V_4) spaced at intervals of ~2-4 cm obliquely cross-cuts an earlier set of narrower veins parallel to a single wider oblique vein (V_3).

Bottom: close-up of area within the box in the photo above. Note the prismatic glaucophane in uniformly normal orientation to the vein walls and inside cores of veins. Several narrow fractures parallel to V_4 cross-cut V_3 veins (orange arrow). Less abundant glaucophane is also hosted in V_3 (white arrow).

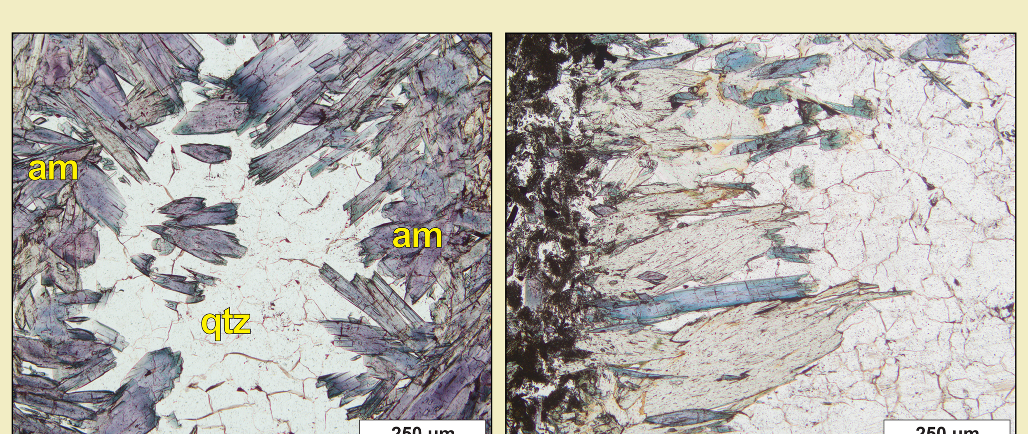
Above: sample EV19-15C. Vein set nomenclature was based on veins in this sample, as shown on the annotated photograph.



At left: representative micrographs of the host rocks to the Mt. Ochi veins.

Left: Na-clinopyroxene metabasalt

Right: white mica + glaucophane quartzite

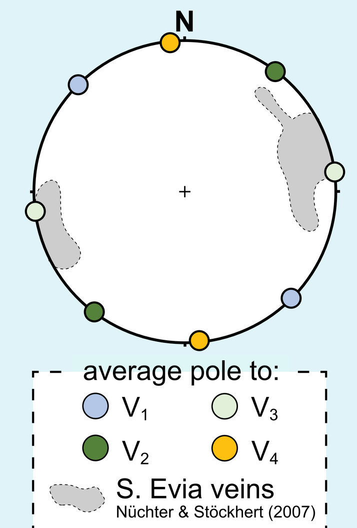


At left: representative micrographs of the Mt. Ochi veins.

Left: centre of a V_4 vein. Euhedral prismatic glaucophane grows inward toward a quartz-rich core.

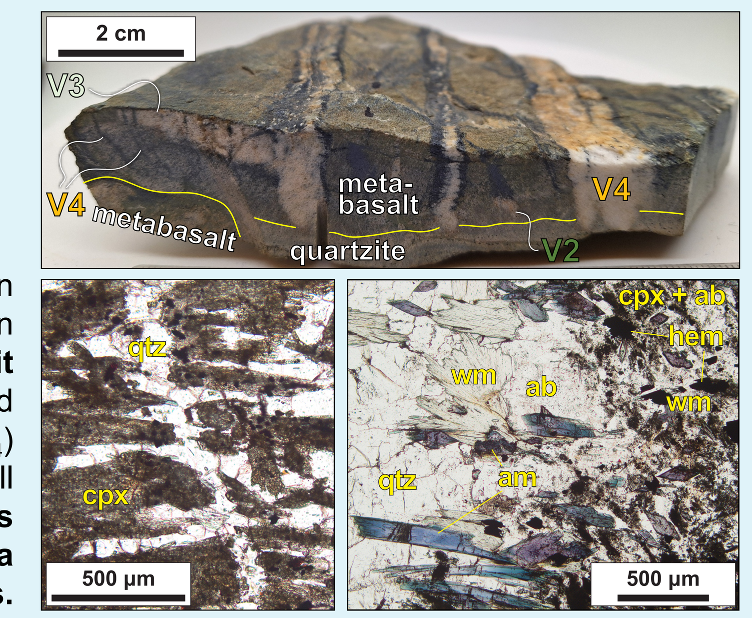
Right: margin of V_3 vein. Note the inward growth of phengite and glaucophane from the vein margin into a vein core composed predominantly of quartz.

Structure



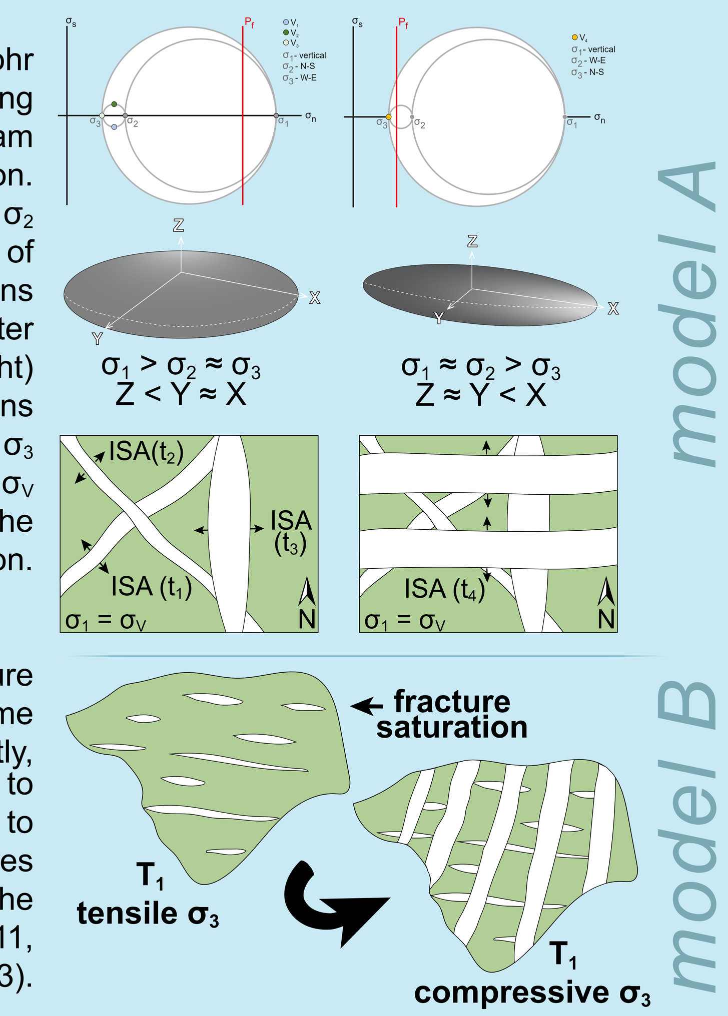
Above, left: coexistence of multiple (some conjugate) vein sets cross-cut by a latest single vein set (oriented vertically in photo; striking ENE-WSW). The Mt. Ochi vein sets **exhibit orthorhombic symmetry** (see stereoplot, above right) and sub-vertical dips. The two most abundant vein sets (V_3 and V_4) are orthogonal to one another. The planar geometry of all vein sets **suggests minimal post-sealing deformation, as any non-coaxial strain component would impose a resolved shear strain on at least one of the vein sets.**

Below: structural features of the Mt. Ochi veins. (top) Cross-section view of the veins in hand sample. Veins show abrupt rounded terminations at the intersection with the ductile quartzite. (bottom left) Photomicrograph showing a narrow tensile (mode I) vein with jigsaw-like margins. (bottom right) Wall of a V_3 vein showing locally radial habit of vein-hosted phengite. Growth textures are consistent with syntaxial growth into an open fluid-filled space.

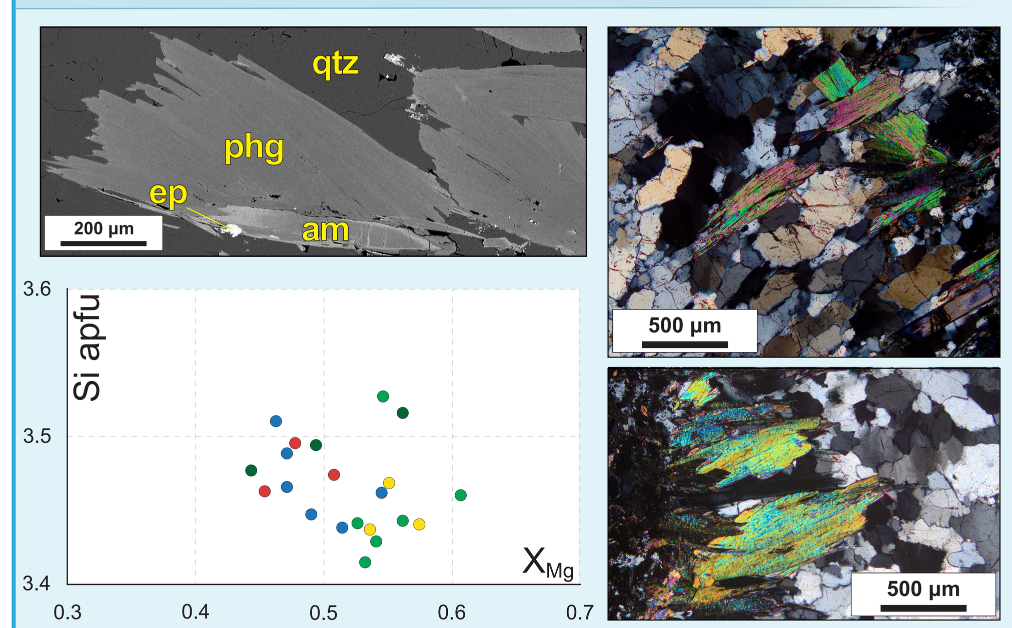


Model A (top to bottom): 3D Mohr circle construction, corresponding strain ellipsoid, and diagram depicting resultant vein formation. Initially (left), $\sigma_1 > P_f >> \sigma_2$ permitting fracturing in a range of instantaneous stretching directions within the horizontal plane. Later reduction of P_f to $\sigma_3 > P_f > \sigma_2$ (right) yields prolate strain and veins exclusively oriented normal to σ_3 (i.e., V_4). Under this model, $\sigma_1 = \sigma_V$ is fixed for all veins, implying the veins formed under tension.

Model B: V_3 veins achieve fracture saturation in the available volume of metabasalt (T_1). Consequently, σ_3 (oriented ENE-WSW, parallel to L_s) transitions from tensile to compressive. Additional fractures (V_4) thereafter form normal to the strike of V_3 (e.g., Zulauf et al. 2011, J. Struct. Geol. vol 33).

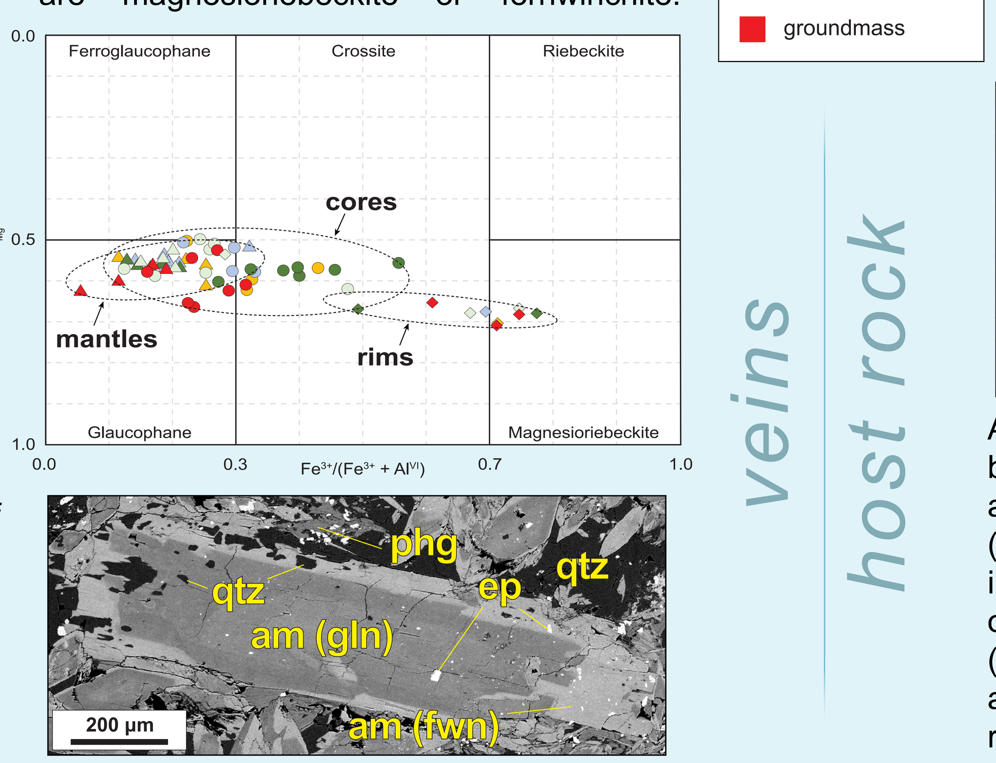


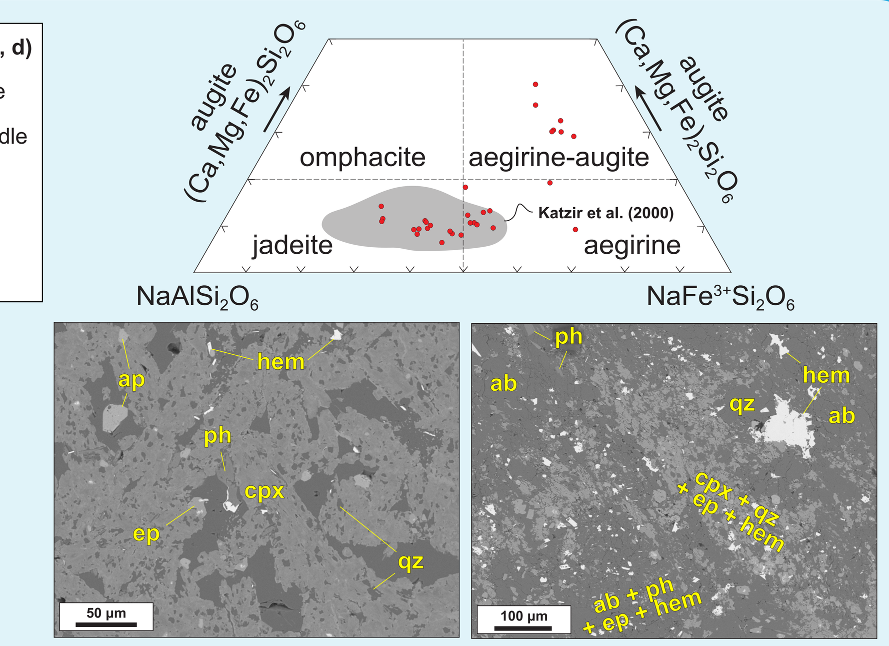
Mineral chemistry



Above: (top left) Representative backscatter electron image of phengite and (bottom left) white mica Si apfu vs X_{Mg} plot vein-hosted white mica. White mica display broadly homogeneous compositions with Si apfu between 3.4 - 3.55 and X_{Mg} between 0.45 - 0.61. Mica are unzoned. (right) Photomicrographs of phengite grown along the margins of V_3 veins. Large phengite crystals are optically continuous and show no evidence of kinking or recrystallization.

Below: Na-amphibole chemistry plot (top) and representative backscatter electron image (bottom) of zoning in vein-hosted amphibole. Cores are glaucophane and more Al-rich from core to mantle. Rims have elevated Fe^{3+} and are magnesioriebeckite or ferriwinchite.



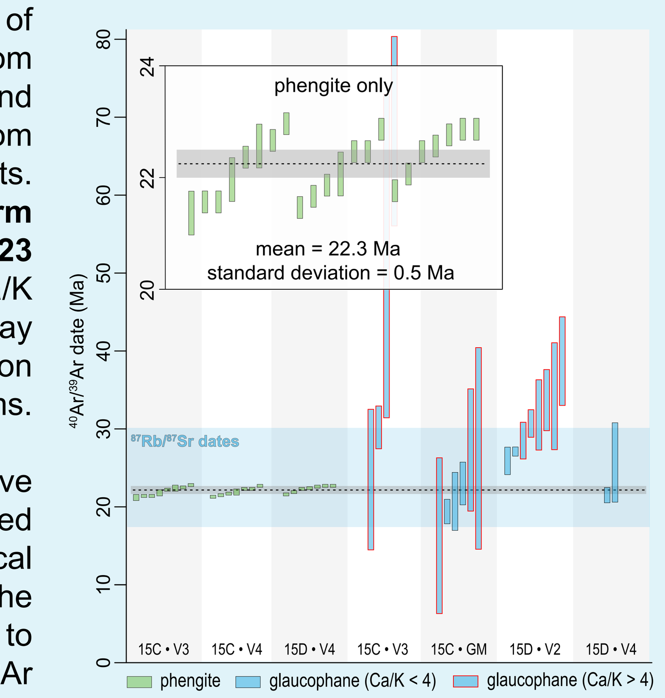


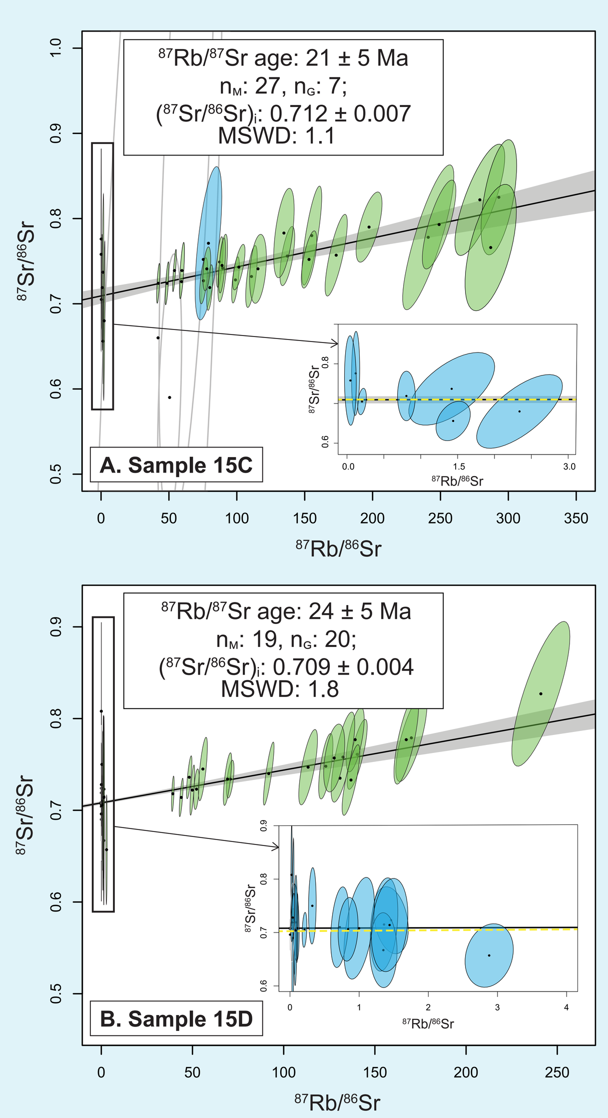
Above: (top) abridged clinopyroxene chemistry plot from the basaltic host rock. Specimens are mostly sodic with (Na apfu > 0.9) and intermediate between jadeite and aegirine. (bottom left) clinopyroxene oikocrysts surrounding quartz inclusions, possibly representative of prograde breakdown of albite. Rims are enriched in aegirine compared to cores. (bottom right) Clinopyroxene undergoing replacement by albite, epidote, and hematite, suggesting local retrogradation via the reaction albite = jadeite + quartz.

Geochronology

Figure at right: summary of total-fusion $^{40}Ar/^{39}Ar$ dates from phengite (green boxes) and glaucophane (blue boxes) from different Mt. Ochi vein sets. Phengite exhibits a **uniform distribution between 21 - 23 Ma.** Glaucophane with Ca/K values < 5 (red outline) may indicate less contamination from Ca-rich (winchite) rims.

Glaucophane routinely gave low $^{40}Ar^*$ yields and dispersed dates with high analytical uncertainties. As such, the phengite data are interpreted to provide the only robust $^{40}Ar/^{39}Ar$ data from the Mt. Ochi veins.





At left: isochrons calculated using *in situ* $^{87}Rb/^{87}Sr$ data from phengite (green ellipses) and glaucophane (blue ellipses) from the Mt. Ochi veins.

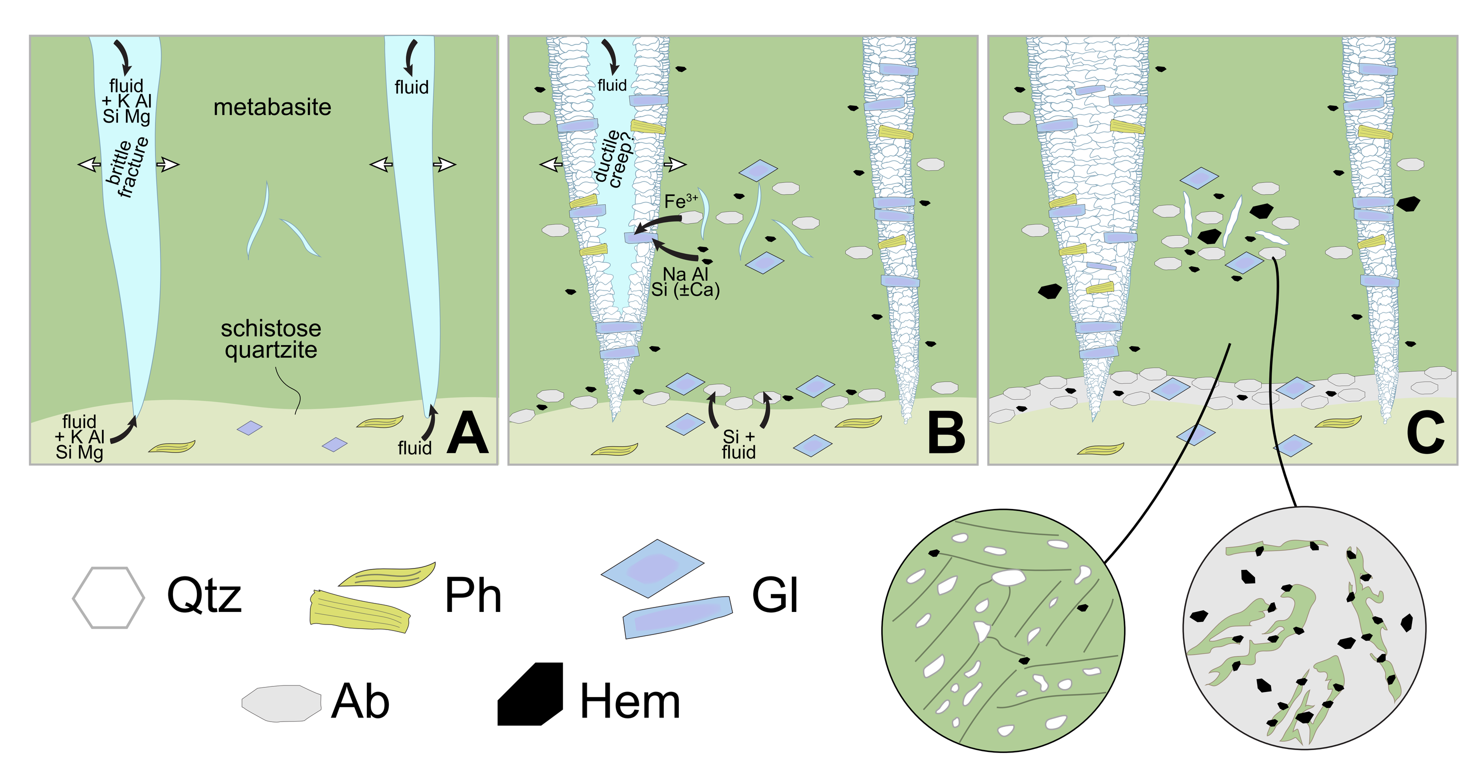
Phengite exhibits a wide distribution of $^{87}Rb/^{86}Sr$ values. Glaucophane is comparatively Sr-rich and Rb-poor, and plots closer to the $^{87}Sr/^{86}Sr$ axis.

Insets: Detailed view of glaucophane data. Yellow dashed line shows isochron regression calculated using only phengite data, suggesting the minerals in the veins likely coexist in isotopic equilibrium.

Both $^{87}Rb/^{86}Sr$ isochron dates are indistinguishable within error of the phengite $^{40}Ar/^{39}Ar$ dates (above). Alongside a lack of (micro-)structural evidence of strain or recrystallization, the dates most likely **reflect the timing of crystallization, coinciding with extensional exhumation of the CBU.**

Paragenetic Model

- Oxygen isotope data for quartz and phengite from V_1, V_3, and V_4 veins yielded $\delta^{18}O$ values of 14.9‰, 18.5‰, and 15.9‰ (quartz); 10.7‰, 11.9‰, and 11.5‰ (phengite), producing corresponding T estimates (Zheng, 1993) of **335 ºC, 172 ºC, and 315 ºC (± 40ºC)**, respectively.
- Amphibole and pyroxene compositions imply pressures of ~6-7 kbar (amphibole cores), ~4-5 kbar (amphibole rims), and ~8 kbar (pyroxene; Maruyama et al. 1986, Geol Soc Am Mem 164; Liu and Bohlen 1995, Contrib Mineral Petrol 119). Conversely, amphibole zoning and vein microstructure indicate **one uninterrupted growth interval.**
- **Oxidized fluids** with dissolved Si, Mg, and K (± Al, Fe, Na) likely altered local bulk composition to produce the observed vein assemblages. Microstructures suggest some Al, Fe, and Na must have originated locally, from **breakdown of clinopyroxene to hematite and/or albite.**



Implications

- Nominally blueschist facies mineral assemblages in the Mt. Ochi veins (i.e., high-Si phengite and glaucophane) **crystallized during early Miocene exhumation** of the Cycladic Blueschist Unit.
- Quartz-phengite oxygen isotope thermometry and amphibole and Na-clinopyroxene geobarometry yieldt PT estimates of **315 ± 40ºC and 7 ± 2 kbar, resembling typical Miocene retrograde greenschist facies conditions in the Cyclades.**
- Oxidizing fluids interacting with an initially jadeite-rich basaltic host rock modified the local reactive bulk chemistry, **stabilizing Na-amphibole species at lower pressures during exhumation.**
- Fluids encountered during exhumation **may routinely stabilize qualitatively blueschist facies assemblages in less conspicuous structural contexts than the Mt. Ochi veins.** Such assemblages pose a risk for misinterpretation in the field.

Read the full paper in Contributions to Mineralogy and Petrology!