Geochemical Study of Fluid Pathways in Dilational Hydroshear Veins: A Record of Fossil Tremor and Slow Slip Events in Subduction Zones

Jan Kulhánek[1], Francesco Giuntoli[1], Chiara Boschi[2], Daniela Rubatto[3], and Enrico Cannaò[4]

[1]*University of Bologna, Department of Biological, Geological, and Environmental Sciences, Italy (jan.kulhanek@unibo.it);* [2]*Institute of Geosciences and Earth Resources, National Research Council of Italy (IGG-CNR), Pisa, Italy*
[3]*Institute of Geological Sciences, University of Bern, Switzerland;* [4]*Department of Earth Sciences "Ardito Desio," University of Milan, Italy*

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

EGU General Assembly 2025

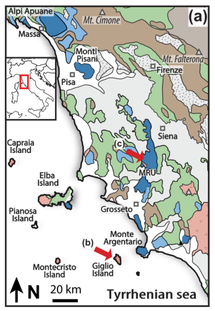
University of Bologna DFT Deformation · Fluids · Tectonics

Research aim

Geophysical studies of subduction zones have revealed deep episodic tremor and slow slip events (ETS), commonly occurring at depths >30 km[1,2]. This study focuses on crack-seal, fluid-mediated vein formation—considered a fossil record of ETS—typical of such settings. We investigated continental metasediments from the Northern Apennines, Italy, where quartz–carpholite crack-seal veins are widespread. The study highlights the composition and origin of fluids trapped as inclusions, and the mobility of major and trace elements during the vein formation and subsequent compositional changes during retrogression.

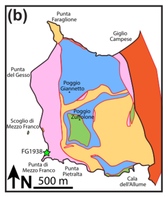
Geological setting

- Study area: Northern Apennines, Italy (**Fig. a**).
- Rocks include oceanic (Ligurian Units) and continental (Tuscan Metamorphic Units, TMU) sequences.
- Metamorphic conditions: 0.8–1.6 GPa, 300–500 °C (27–18 Ma).[2,3,4]
- TMU rocks later juxtaposed against non-metamorphic units.
- Samples collected from Island of Giglio (**Fig. b**) and Monticiano–Roccastrada Unit (**Fig. c**), ~80 km apart across TMU.



Northern Apennines

- Location of the study areas
- Quaternary (a) and late Miocene-Pleistocene deposits (b)
- Plio-Pleistocene intramontane deposits
- Late Miocene magmatic rocks (a) and Plio-Pleistocene volcanic rocks (b)
- Undifferentiated Ligurian and Subligurian Units
- **Tuscan Domain**
- Late Oligocene-early Miocene (a) and Langhian-Messinian (b) Siliciclastic foredeep units
- Mesozoic carbonate sequences
- Tuscan Metamorphic Units

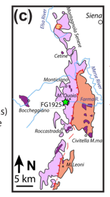


Giglio island

Magmatic rocks
- Granite (Pliocene)

Ligurian Units
- Metabasite (Late Jurassic)

Tuscan Units
- Meta?-Limestone breccia (Calcare cavernoso; Upper Trias)
- Black metalimestone and slate (Upper Trias)
- Verrucano metasediment (Middle-Upper Trias)
- Tectonic contact
- Sample Location; FG1938

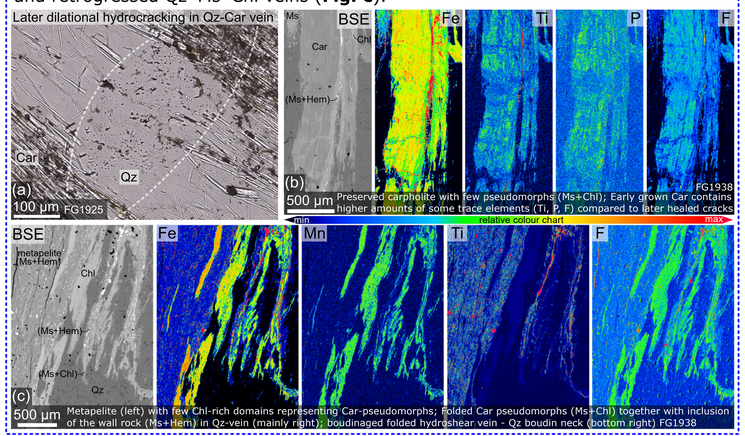


Monticiano-Roccastrada Unit

- Iano subunit
- Monte Quoio-Montagnola Senese subunit
- Monte Leoni-Farma subunit
- Palaeozoic metasedimentary rocks
- Thrust
- Sample Location; FG1925

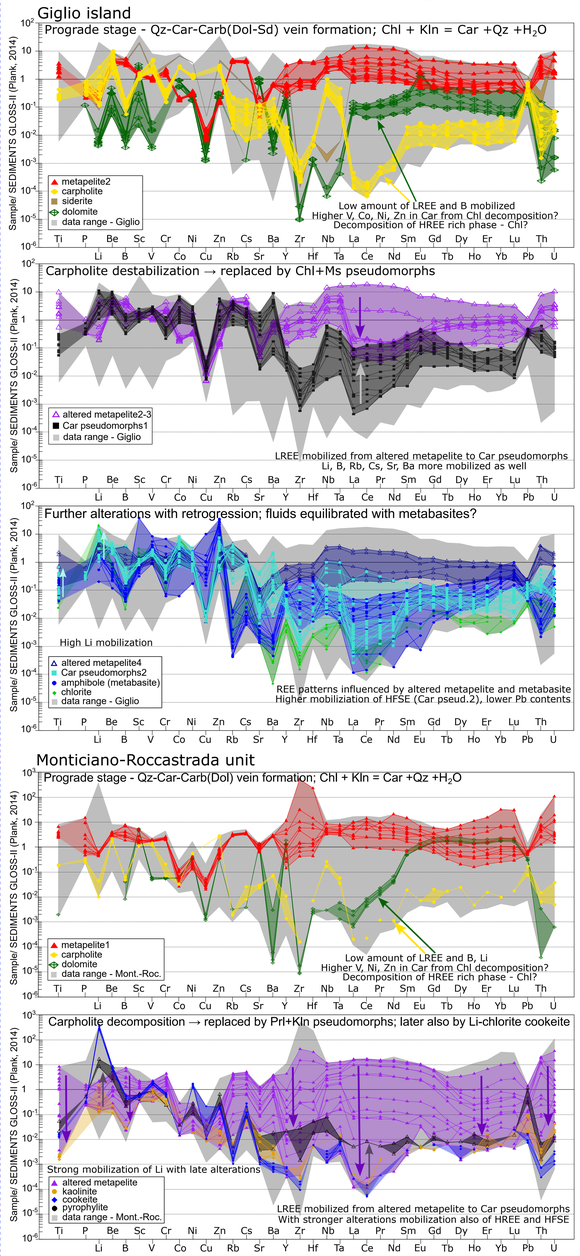
Petrography and compositional mapping

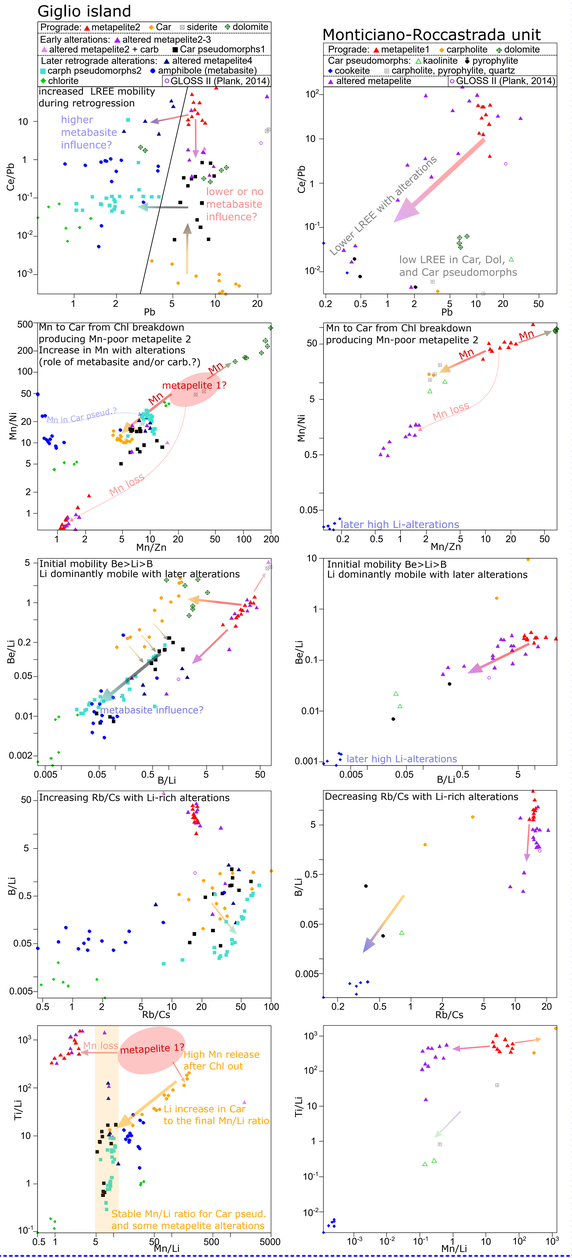
- Metapelites hosting Qz–Car veins show foliation of white mica, quartz, hematite, and carbonate.
- Carpholite preserved from both localities; pyrophyllite, chloritoid and Li-rich chlorite cookeite only at Monticiano–Roccastrada.
- Veins show alternating Qz–Car bands and Ms+Chl pseudomorph bands.
- Quartz fibers contain abundant fluid inclusion trails, oriented perpendicular to fiber elongation, with common later hydroshear cracks crosscutting them (**Fig. a**).
- Early carpholite enriched in Fe, Ti, P, F; later healed cracks depleted (**Fig. b**).
- Carpholite replaced by Ms+Chl pseudomorphs with Fe, F, Mn enrichment (**Fig c**).
- Hematite needles aligned with stretched wall-rock metapelites folded into Qz–Car and retrogressed Qz–Ms–Chl veins (**Fig. c**).



Trace element budget and possible redistribution in vein formation and retrogression

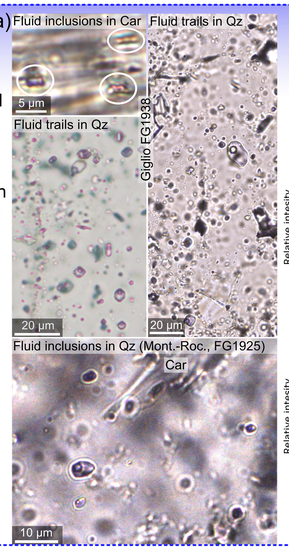
- First detailed study of trace element redistribution during Qz–Car vein formation in subduction setting.
- Metapelite 1 (unaffected) shows higher Mn, V, Co, Zn; possibly released during chlorite-out reaction (fluid production).
- Chlorite breakdown mobilized HREE? → relative LREE/HREE enrichment in metapelite 2?; opposite trend in carpholite and carb.
- Further alteration: LREE decrease in metapelites (3), progressive LREE-enrichement in Car-pseudomorphs 1 (Ms+Chl)?
- Retrograde stages: increased lithium mobilization into more altered metapelite 4 and Car-pseudomorphs 2.
- Late Li mobilization linked to metabasite at Giglio and other rocks (not yet identified) at Monticiano–Roccastrada.

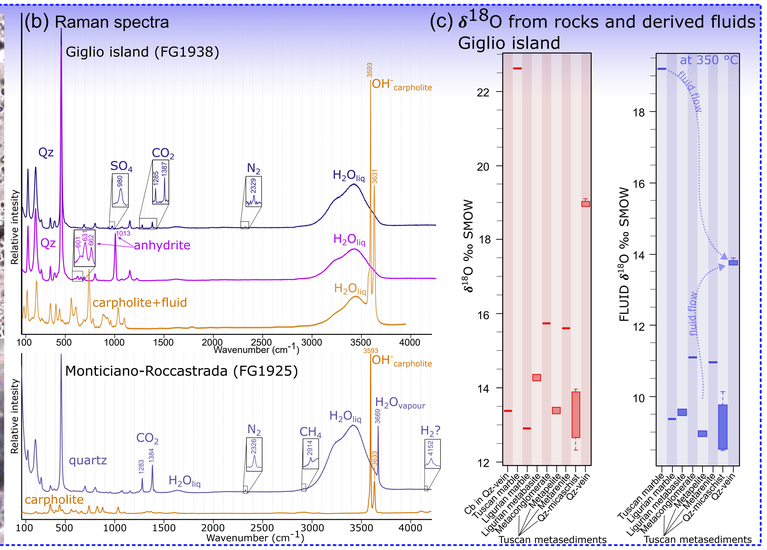




Fluid composition and origin

- Raman spectroscopy shows fluid inclusions containing H_2O, CO_2, SO_4, N_2, H_2, CH_4 and anhydrite crystals (**Fig. a, b**).
- Inclusions differ slightly between Giglio and Monticiano–Roccastrada veins.
- In-situ $\delta^{18}O$ SIMS of quartz fibers: +18.4 to +19.2‰, norm. to SMOW (**Fig. c**).
- Bulk $\delta^{18}O$ of rocks: +12.3 to +15.7‰ (Tuscan meta-sediments), ~+23‰ (Tuscan marble), ~+14‰ (Ligurian metabasites), ~+12‰ (Ligurian marble) (**Fig. c**).
- Fluid $\delta^{18}O$ recalculations at 350 °C suggest equilibration between Tuscan marbles and metasediments.





Preliminary conclusions

- Quartz–carpholite veins formed under HP conditions by fluid release from chlorite breakdown.
- Fluids enabled carpholite, carbonate growth, and CO_2-rich abundant biphasic inclusions.
- Fluids from Giglio Qz-Car veins equilibrated with nearby Tuscan marbles.
- Retrogression shows external inputs from metabasites (Giglio) and potentially other sources (Monticiano–Roccastrada).
- Indicates broader fluid circulation during exhumation and nappe stacking.

Acknowledgements
Giuntoli F. acknowledges financial support under the National Recovery and Resilience Plan (NRRP), Grant Assignment Decree No. MUR 2022X88W2Y_002 by the Italian Ministry of University and Research (MUR). Orlando Olivieri is thanked for his expertise consultations on the Raman spectroscopy topic.

References
1 Behr, W. M. et al. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 379, (2021); **2** Giuntoli, F. et al. Sci. Rep. 12, (2022); **3** Giuntoli, F. et al. Geochemistry, Geophys. Geosystems 22, 1–27 (2021); **4** Giuntoli, F. et al. J. Geophys. Res. Solid Earth 127, (2022)