Unraveling coseismic kinematics of frictional melts in extensive pseudotachylyte networks of the Santa Rosa Mountains, California

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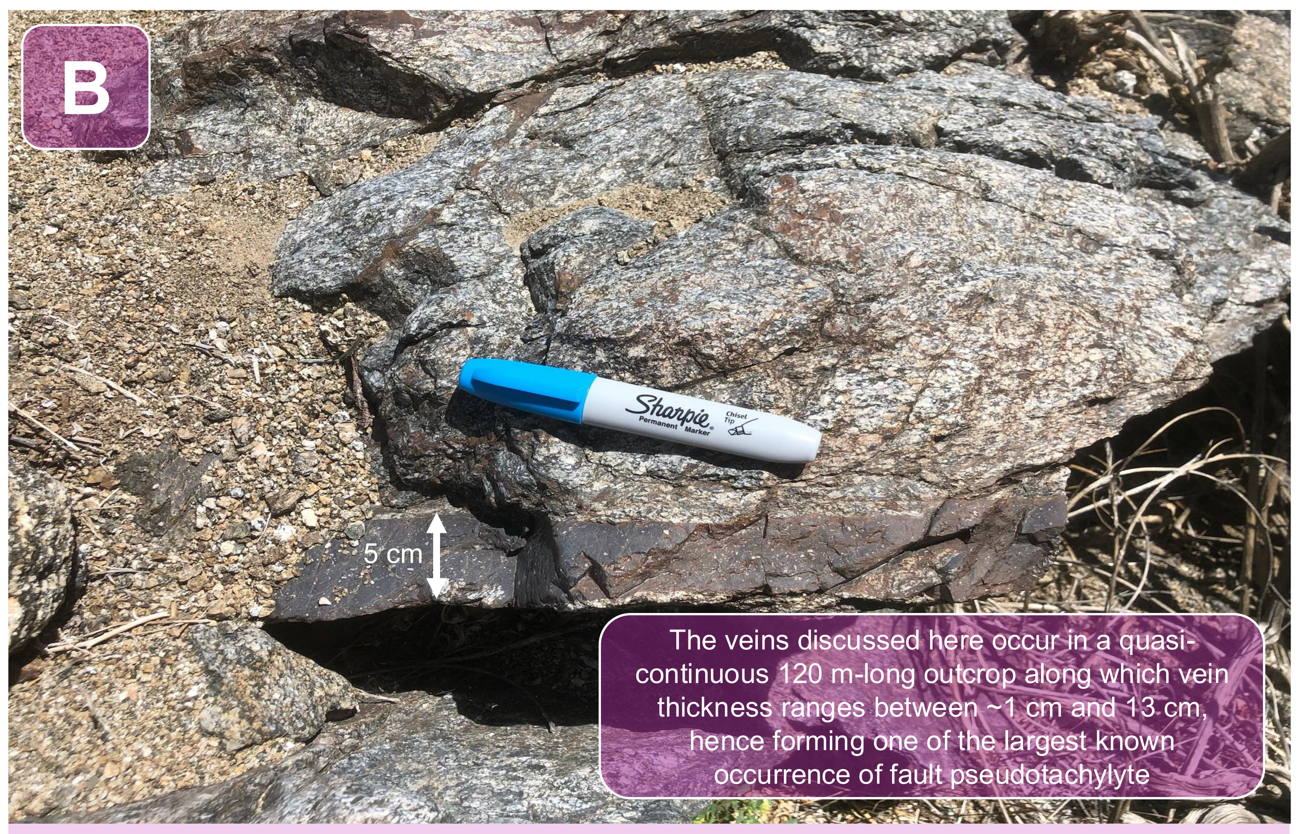
The Santa Rosa pseudotachylytes formed ~59 Ma ago and preserve an extensive record of seismic deformation in the Eastern Peninsular Ranges, showing a broad range of vein geometries (pull-apart, en-echelon tension veins, etc)

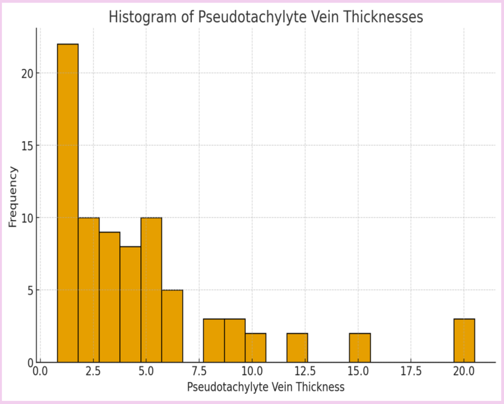


The veins discussed here occur in a quasi-continuous 120 m-long outcrop along which vein thickness ranges between ~1 cm and 13 cm, hence forming one of the largest known occurrence of fault pseudotachylyte


The melt volume in a pseudotachylyte vein can be used to calculate the energy needed to melt the host rock and, with reasonable assumptions, infer earthquake energy though it is often underestimated due to melt loss into injection veins

1. Estimating paleo-earthquake magnitudes

Energy needed to melt the Asbestos Mtn. tonalite



The Guadalupe Canyon locality exposes a quasi continuous array of pseudotachylyte veins, bearing the same attitude, ranging in thickness from 1 to 20 cm.
The variations in thickness of the vein along strike are due to the existence of restraining and releasing bends. We also acknowledge that a small percentage of frictional melt is lost in the form of injection veins and thus the estimated volume is a slight underestimate. The average thickness of these veins was estimated at 80 locations (where the width was measured over a distance of ~1 m) to 5 cm photo B and diagram). To melt the Asbestos Mtn. tonalite and produce a 5 cm-thick layer of frictional melt (*i.e.*, a volume v = 0.05 m^3), we need the thermal energy to melt a mass m of tonalite. Considering the tonalite density r ~2,730 kg/m^3, and the volume of melt produced v = 0.05 m^3, this amounts to melting a mass m = r . v = **136.5 kg** of tonalite per 1 m^2 of fault surface.

Melting heat calculations
The total heat Q_f needed to melt this mass of tonalite is the sum of the heat needed to warm up the tonalite from pre-seismic ambient temperature Q_i plus the heat to completely melt the solid rock up to the liquidus, Q_m (assuming congruent melting).
$Q_f = Q_i + Q_m$
The tonalite mass-specific heat capacity C_p is calculated from the major element oxide composition (Wenk et al., 2000) using published values of heat capacity for each oxide (Robie et al., 1978), at 1 kbar pressure (~3.5 km depth), and a water content of 4.49% (Eves, 2023).
$C_p = 924\ J\ kg^{-1}\ K^{-1}$

To raise the tonalite temperature from ambient
preseismic temperature of ~100ºC, at 3.5 km depth (Wenk et al., 2000) to its melting temperature of 1200ºC requires

$Q_i = C_p \cdot \Delta T = 924 \times 1100 = 1,016,400\ J\ kg^{-1} \sim 1.02\ MJ\ kg^{-1}$

However, C_p is temperature-dependent so integrating Q_i over the 100-1200ºC range yields

$\mathbf{Q_i} = \int_{373}/^{1473}(854 + 0.2349\ T)\ \Delta T = \mathbf{1.178\ MJ\ kg^{-1}}$

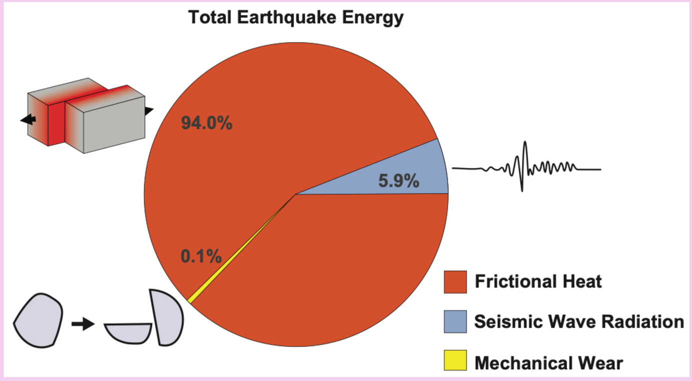
In addition to this heat, the composition-weighed heat of fusion Q_m for the tonalite needs to be considered,

$\mathbf{Q_m = 368\ kJ\ kg^{-1}}$

Frictional heating from 100 to 1200ºC and melting of the tonalite requires a total energy of
$\mathbf{Q_f} = Q_i + Q_m = 1,178,000 + 368,000\ Jkg^{-1} = \mathbf{1.546\ MJkg^{-1}}$

Melting the 136.5 kg mass of tonalite requires the thermal energy
$\mathbf{Q_e} = Q_f\ .\ m \sim 211\ .\ 10^6\ J\ \mathbf{\sim 211\ MJ}$

Considering the percentage of clasts in the veins (~5%), this reduces Q_e by 5%, hence a more realistic value is
Qe' ~ 200 . 10^6 J (a value higher by ~15% compared to Wenk et al. 2000's due to a cooler host rock and smaller clast percentage in our calculations.

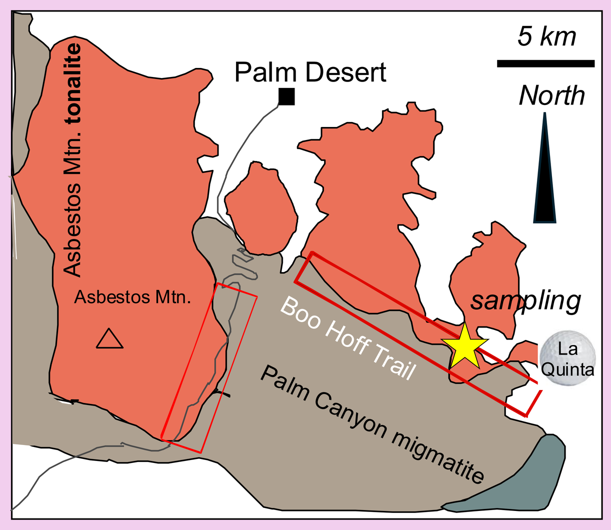


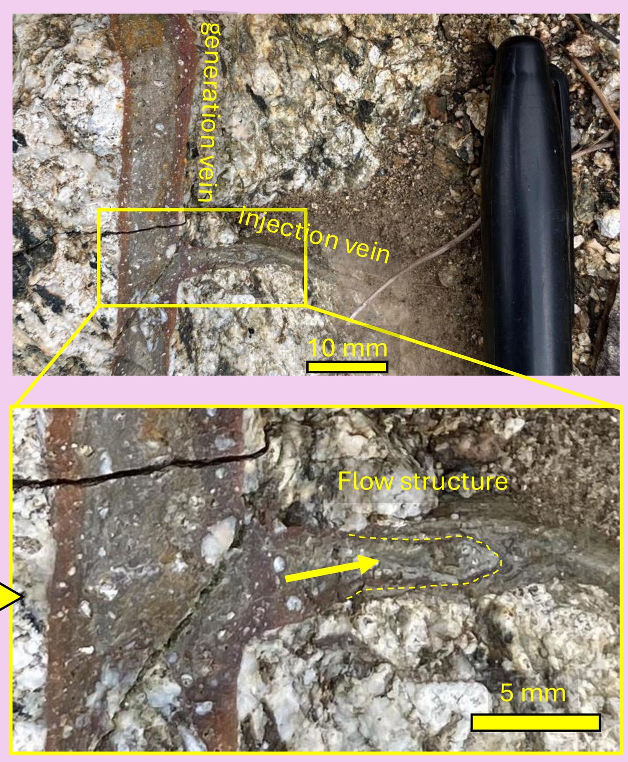
Boatwright and Choy (1986) and Kanamori (2001) considered that radiated seismic energy accounts only for **~5.9%** (seismic efficiency) of an earthquake energy budget. Therefore the total earthquake energy corresponding to the 5 cm-thick vein can be conservatively estimated to E ~212 . 10^6 J / m^2

Considering an average tonalite with strength t = 156 MPa (*e.g.*, Perkins et al., 1970), ignoring any possible dynamic weakening, the **displacement** needed to produce this amount of thermal energy is
D = E / t = 212 . 10^6 / 1.56 × 10^8 = **1.36 m**

This displacement corresponds to seismic events Mw 5.0 to 6.5 depending on the rupture surface area which is comparable to modern seismicity in the area (Mw 6.4 in 1948 and Mw 6.0 in 1986). Thus the Santa Rosa pseudotachylytes are representative of modern seismicity in this region.

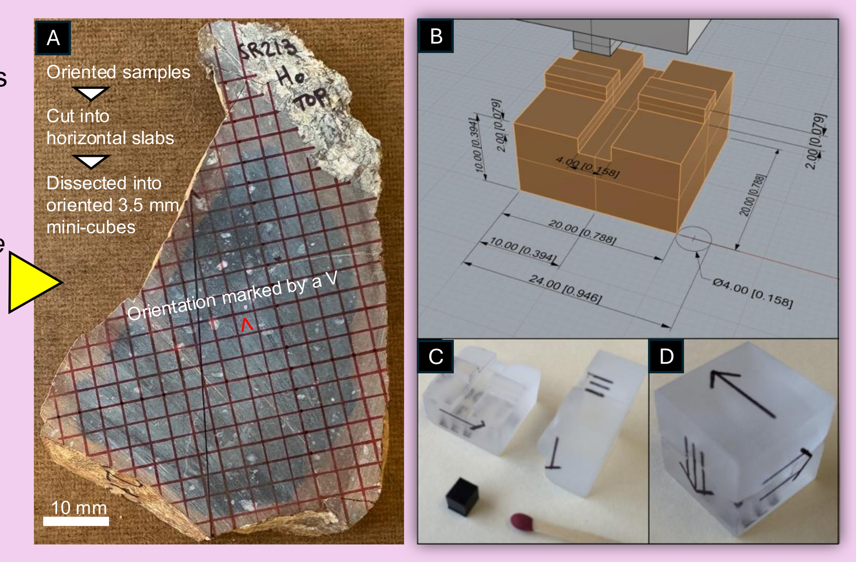
2. Method for determining coseismic kinematics from magnetic fabrics





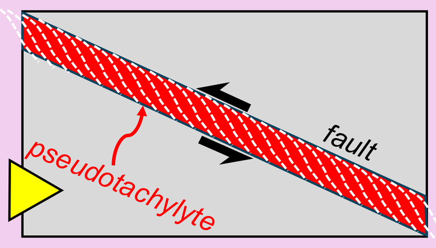
The sampling localities are ~5 km to the West of the La Quinta PGA golf course. Oriented samples for **anisotropy of magnetic susceptibility** (AMS) were collected from fresh exposures of generation veins (Fig. B above), away from injection veins to avoid local flow complication.

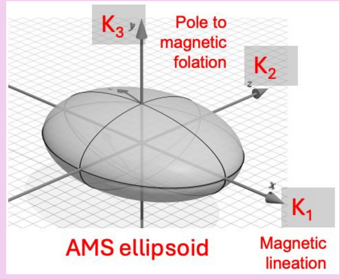
Slabs (3.5 mm thick) were cut along the horizontal plane and cubes were cut from these slabs along NS and EW vertical directions. The mini-cubes (3.5 mm) are measured using custom-made diamagnetic acrylic holders in a *Kappabridge KLY-5S susceptometer*.



The AMS measurements yield the magnetic foliation (K_1-K_2 plane), magnetic lineation (K_1 axis), magnetic susceptibility (K_m), degree of magnetic anisotropy (P') and shape parameter (T) (Jelinek, 1981).

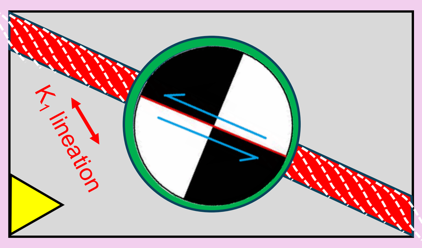
The predicted AMS foliation and lineation follow Jeffery (1922)'s model and are oblique with respect to shear plane.





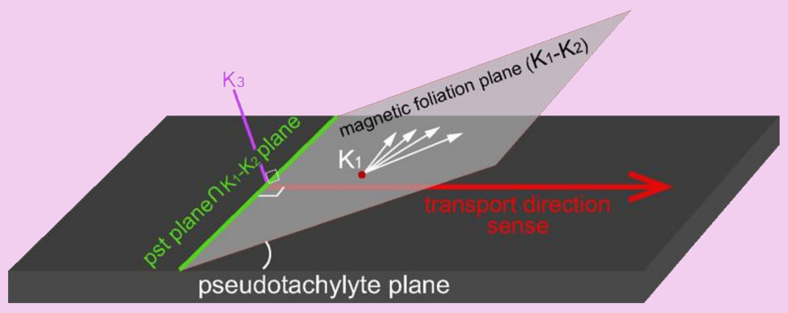
Therefore, the magnetic lineation does not represent the direction of viscous co-seismic slip.

The obliquity of the AMS fabric with respect to the shear plane (pseudotachylyte generation vein) gives the earthquake focal mechanism (Ferré et al., 2015)

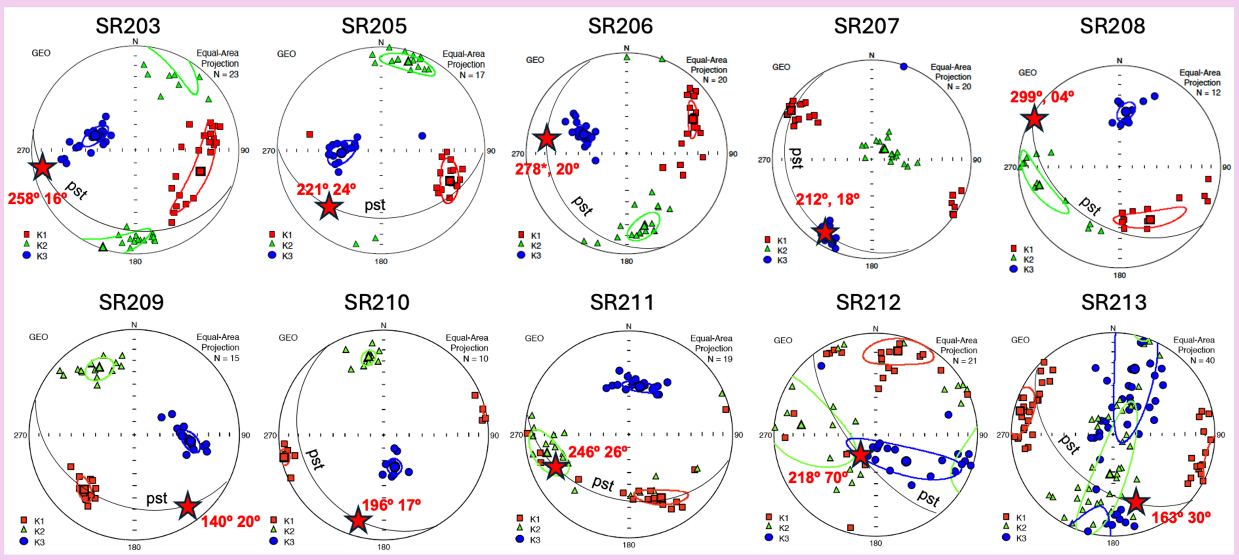


pseudotachylyte lineation is **not** the earthquake slip direction

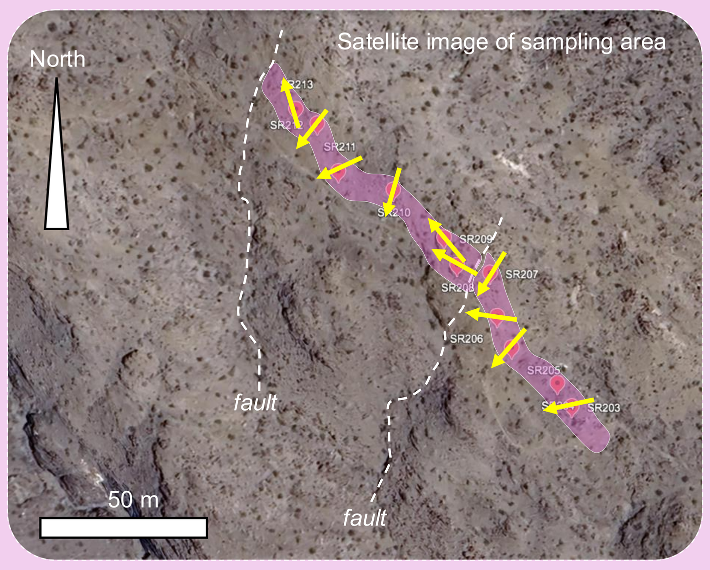
The actual direction of seismic slip is given by Callot et al. (2001)'s model as the line perpendicular to the intersection of the shear plane and the magnetic foliation (K_1-K_2 plane).



3. AMS, paleoseismic slip direction and sense, paleofocal mechanisms

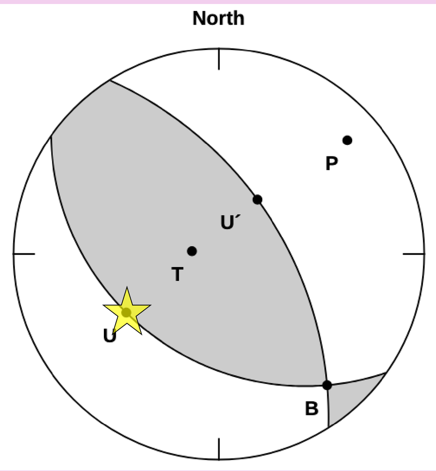


The AMS fabric of **197** minicubes from 10 samples has been measured. Most samples show a clustering of K_3 axes (blue) indicative of **strong planar fabric** / homogeneous viscous strain. In contrast, SR212 & 213 show dispersed K_1, K_3 axes distribution. As the samples are free of post-cooling deformation, the dispersion reflects **heterogenous strain**. The K_1 girdles are consistent between samples suggesting alignment within the flattening plane. The AMS **symmetry is mainly oblate**, suggesting flow in a tabular conduit. Slip direction variations (yellow arrows) show reflect **variations in flow vorticity** due to releasing and restraining bends along the fault.



The lower-hemisphere stereographic plot shows **earthquake focal mechanism** determined from all 10 samples and their AMS fabrics.

This data indicates a **reverse faulting** mechanism along a N233.5º, 36º direction.



Conclusion

The mini-AMS proves to be a powerful method to investigate paleoseismic events that produced frictional melts (pseudotachylytes).

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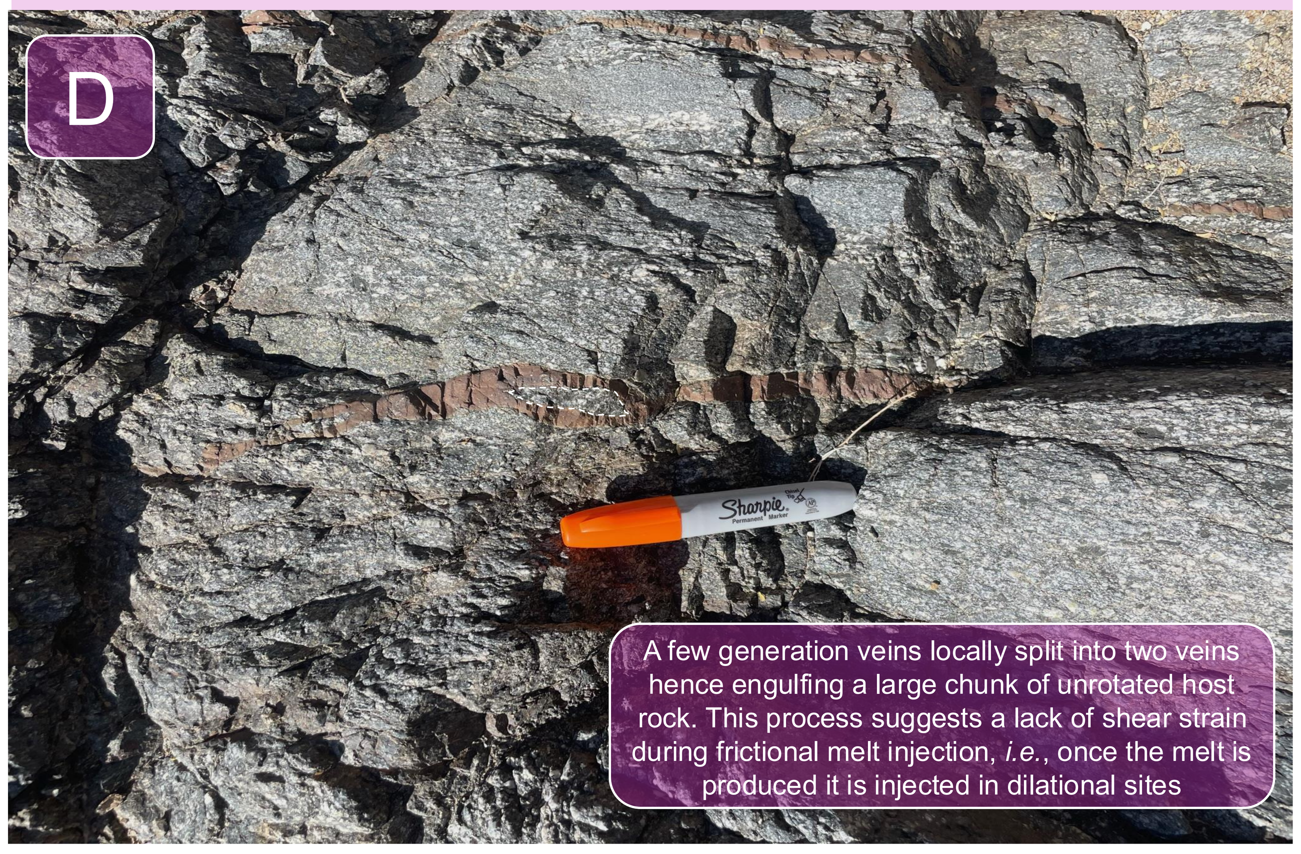
A few generation veins locally split into two veins hence engulfing a large chunk of unrotated host rock. This process suggests a lack of shear strain during frictional melt injection, *i.e.*, once the melt is produced it is injected in dilational sites

Haley M. Benoit completed her MS in Geology at the University of Louisiana at Lafayette in May 2025 and acknowledges the support of the Shreveport Geological Society and the Geological Society of America

Macroscopic criteria for coseismic slip direction or slip sense are exceedingly rare in pseudotachylytes in general including at the Santa Rosa localities. However, a few striations and flow structures at the contact with the host rock deserve further study.

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