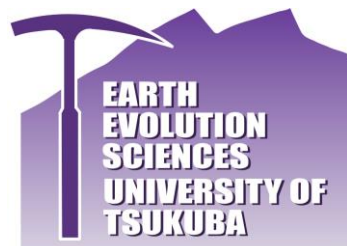


Spatial changes in inclusion band spacing as an indicator of temporal changes in slow earthquake recurrence intervals

Naoki Nishiyama¹ Kohtaro Ujiie¹, & Masayuki Kano²

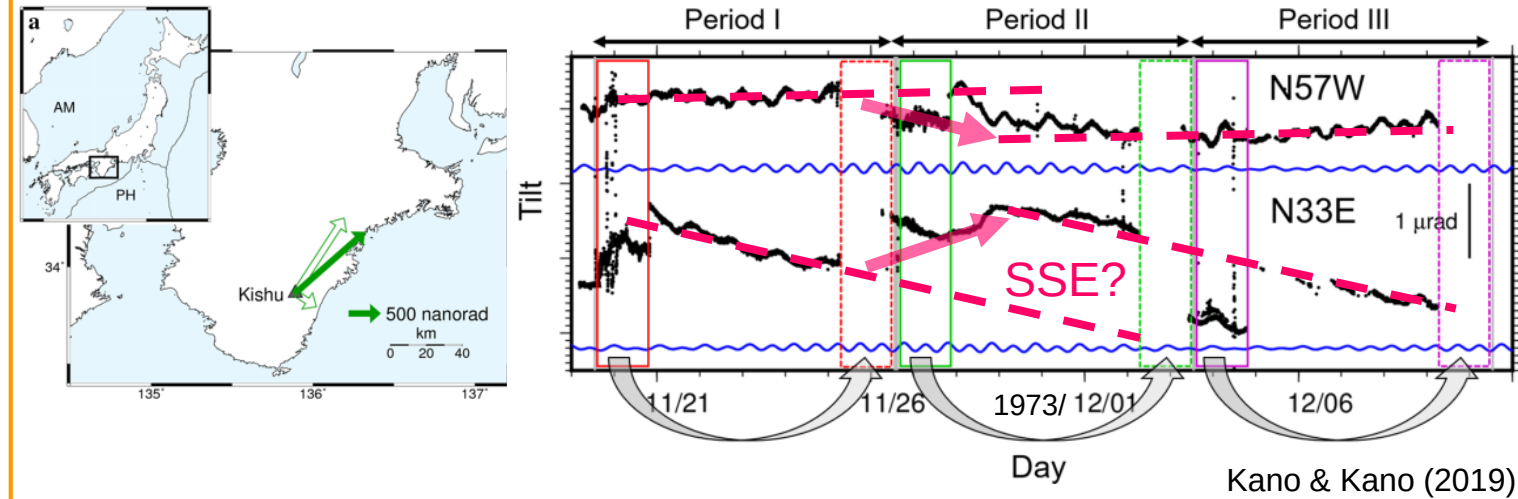
¹University of Tsukuba, ²Tohoku University



Science of Slow Earthquakes

Recurrence intervals of slow earthquakes during megathrust earthquake cycles

Short-term slow slip events (S-SSEs) below the Kii Peninsula



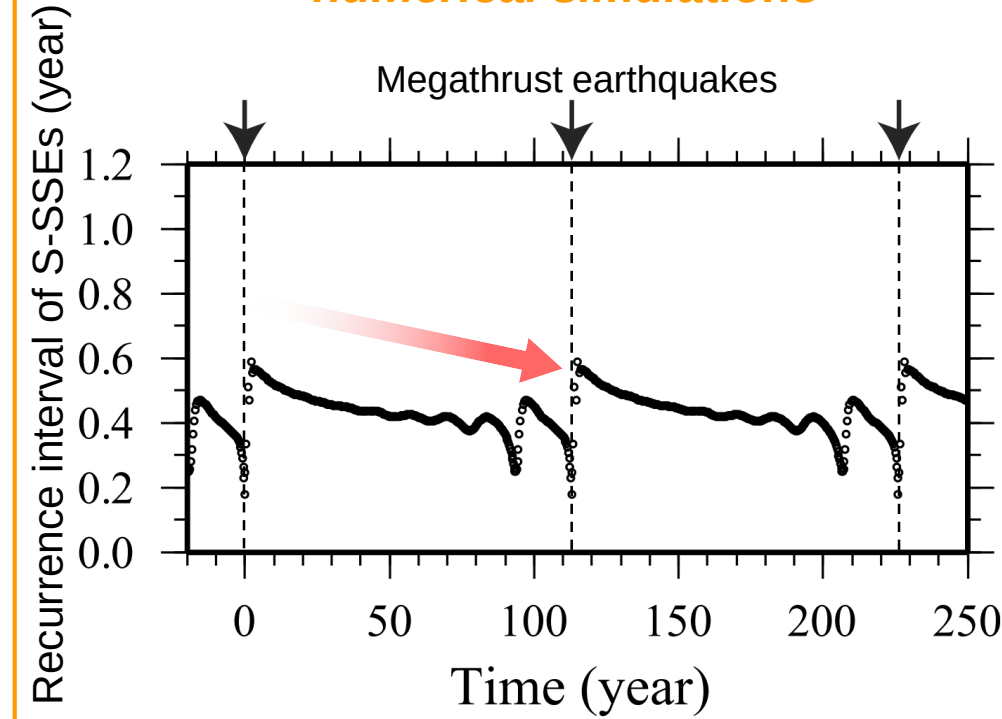
S-SSE recurrence intervals:

>5 years at 1973 **→** **~1 year** during 1996-2012

Kano & Kano (2019)

Nishimura et al. (2013)

S-SSEs by numerical simulations



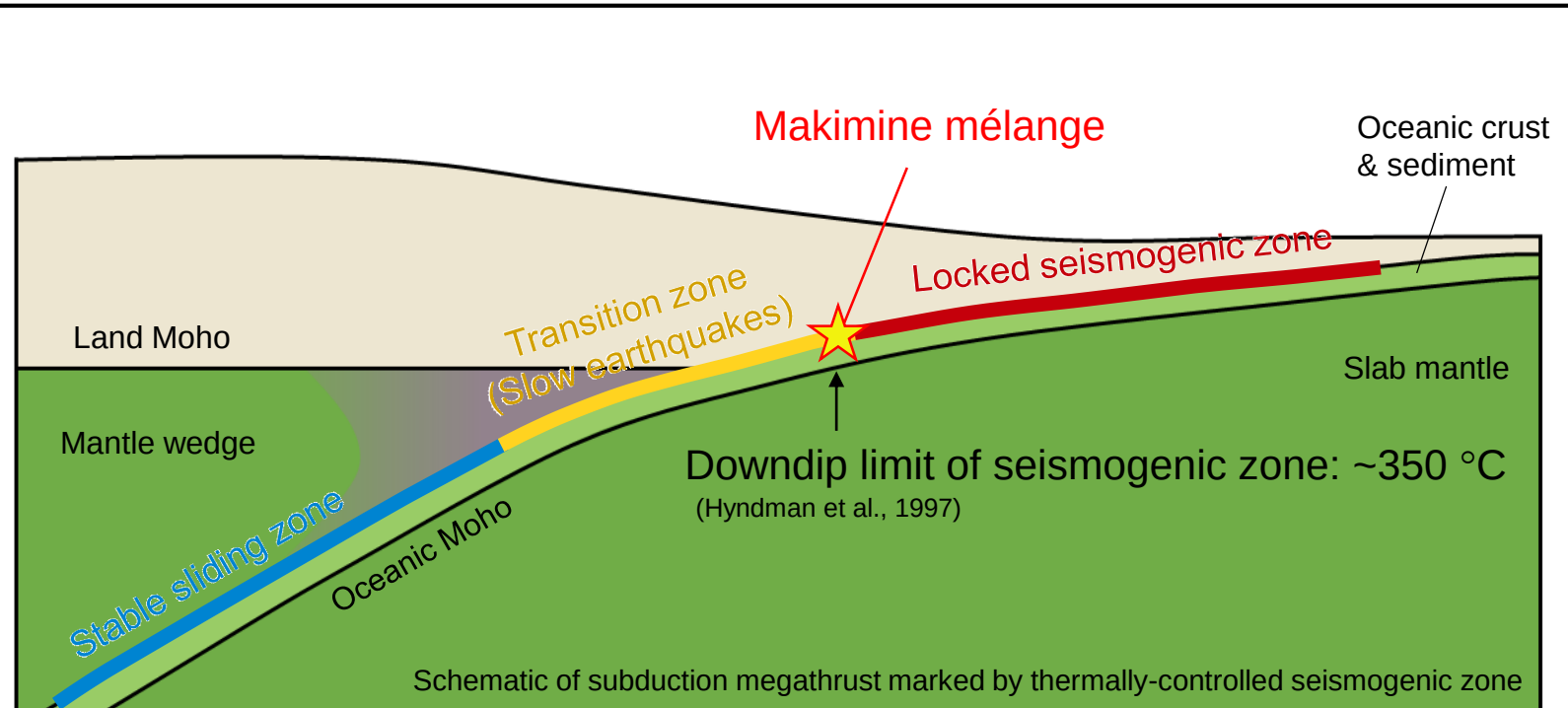
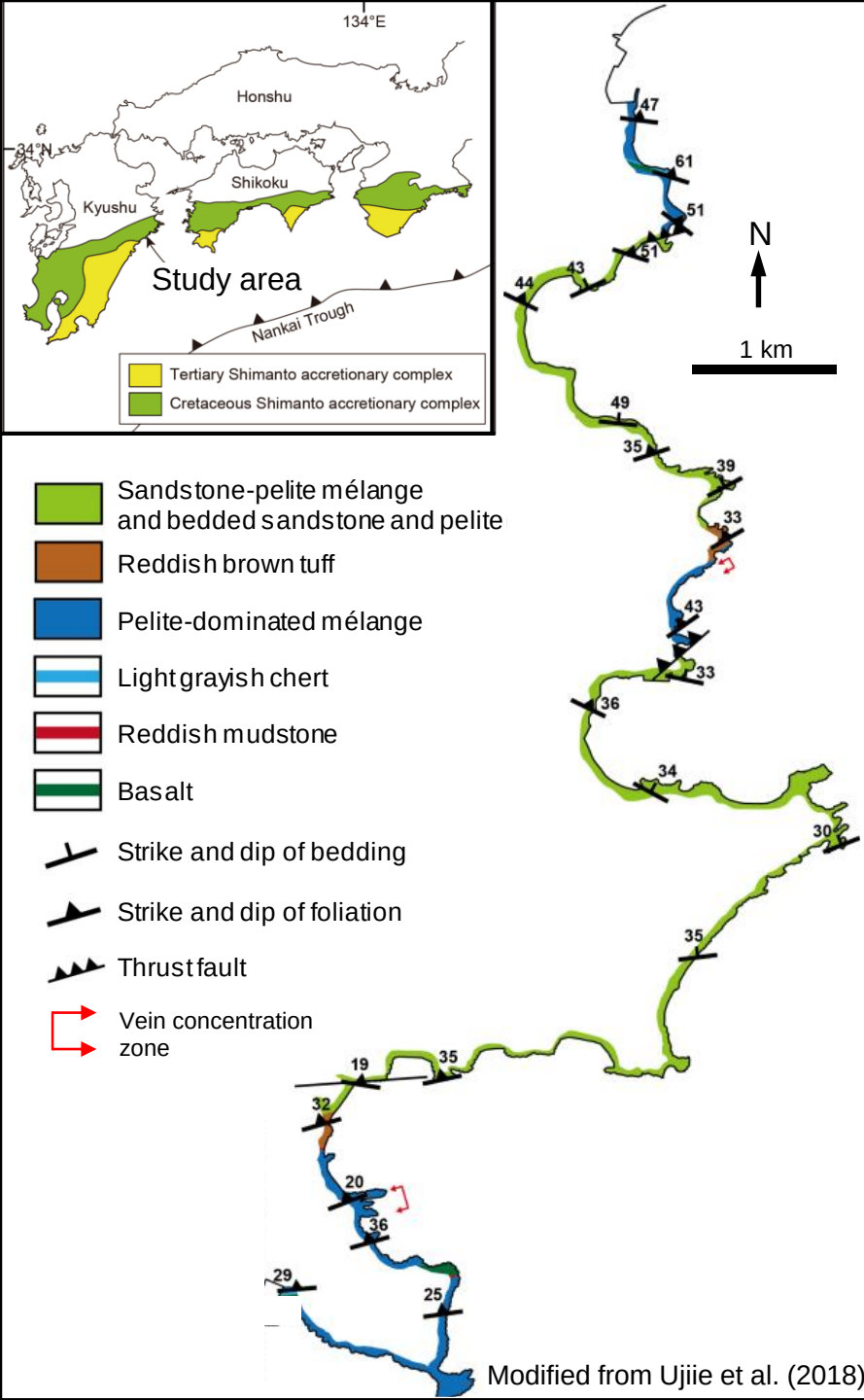
modified from Matsuzawa et al. (2010)

- Recurrence intervals of S-SSEs may decrease toward a next megathrust earthquake
- However, temporal change in slow earthquake recurrence intervals during megathrust earthquake cycles remains poorly understood

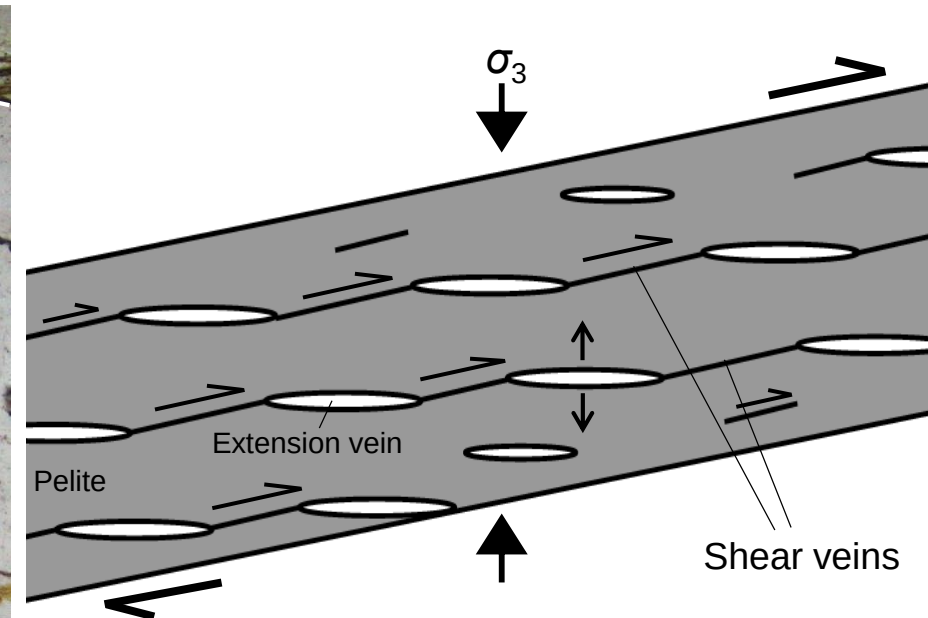
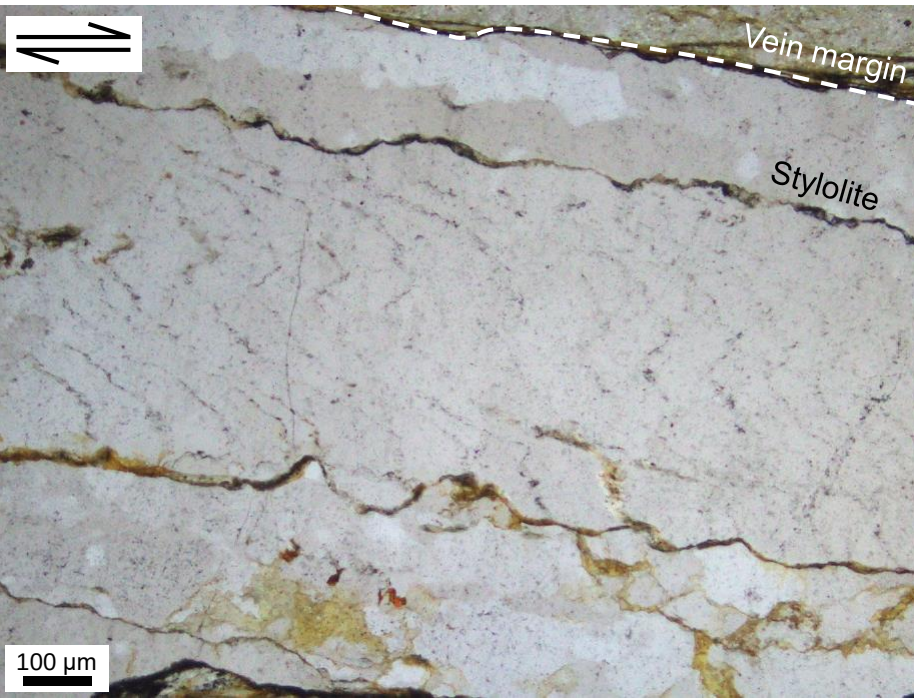
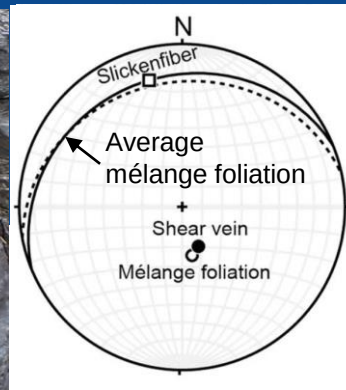
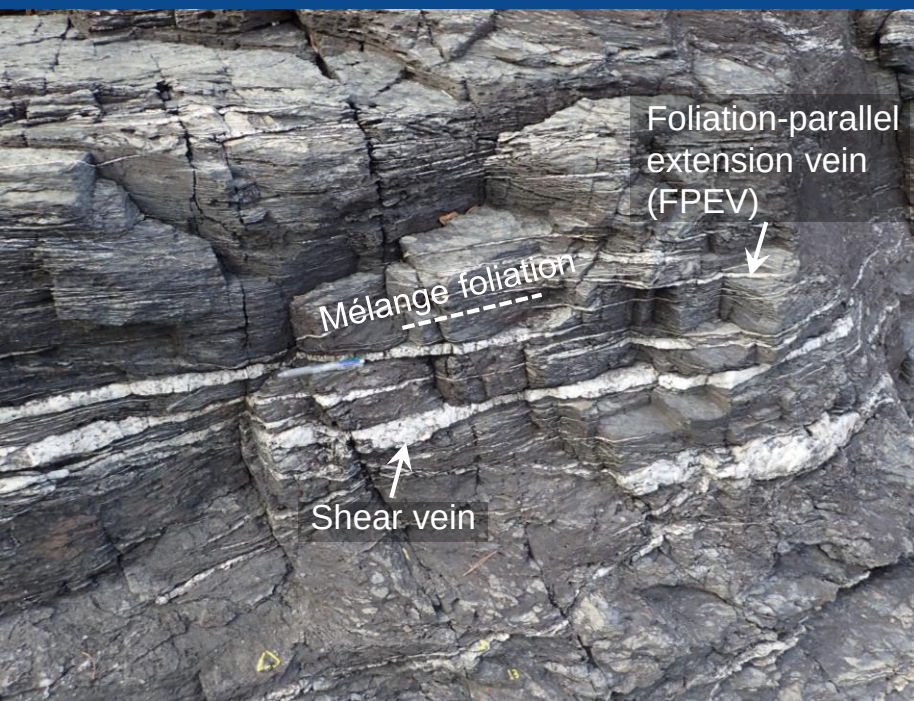
Makimine mélange in the Late Cretaceous Shimanto accretionary complex, Kyushu, Japan

- Plate boundary deformations at frictional-viscous transition zone
- Prehnite-actinolite to greenschist facies metamorphism
- Depth: 10-15 km
- Maximum temperature: 300-350 °C

Toriumi & Teruya (1988); Hara & Kimura (2008); Palazzin et al. (2016)



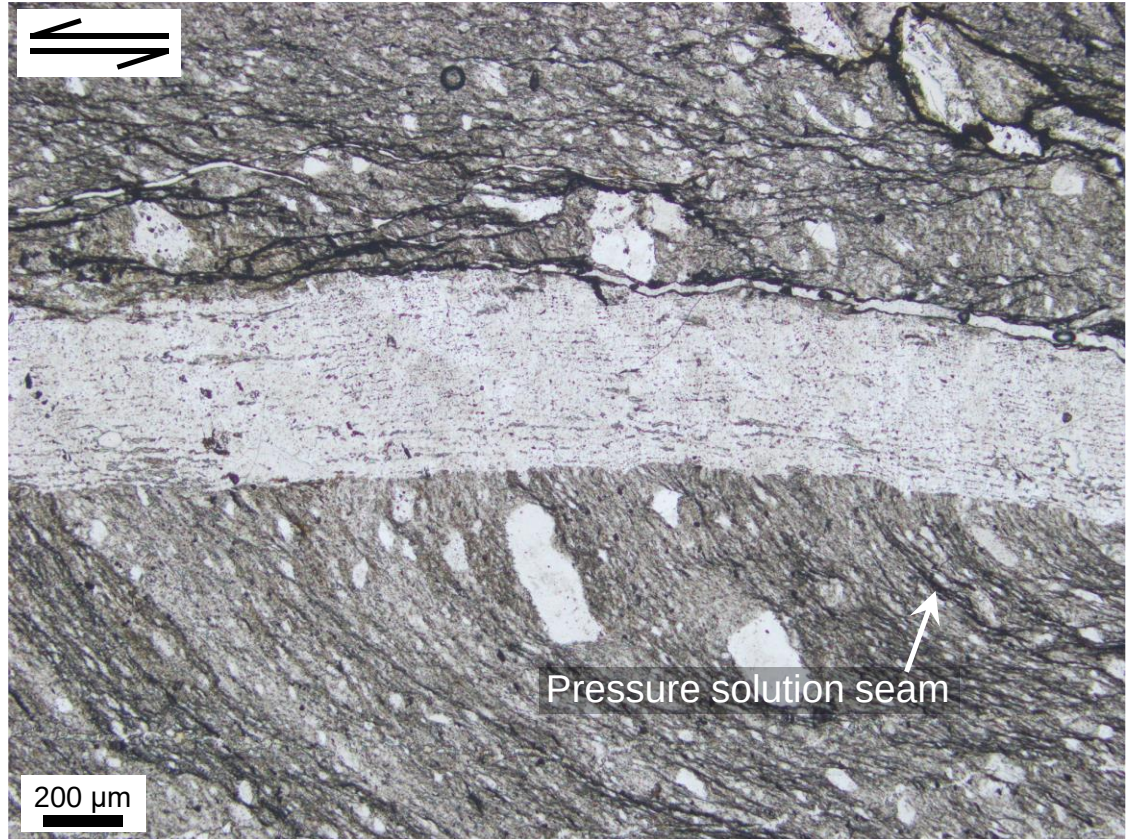
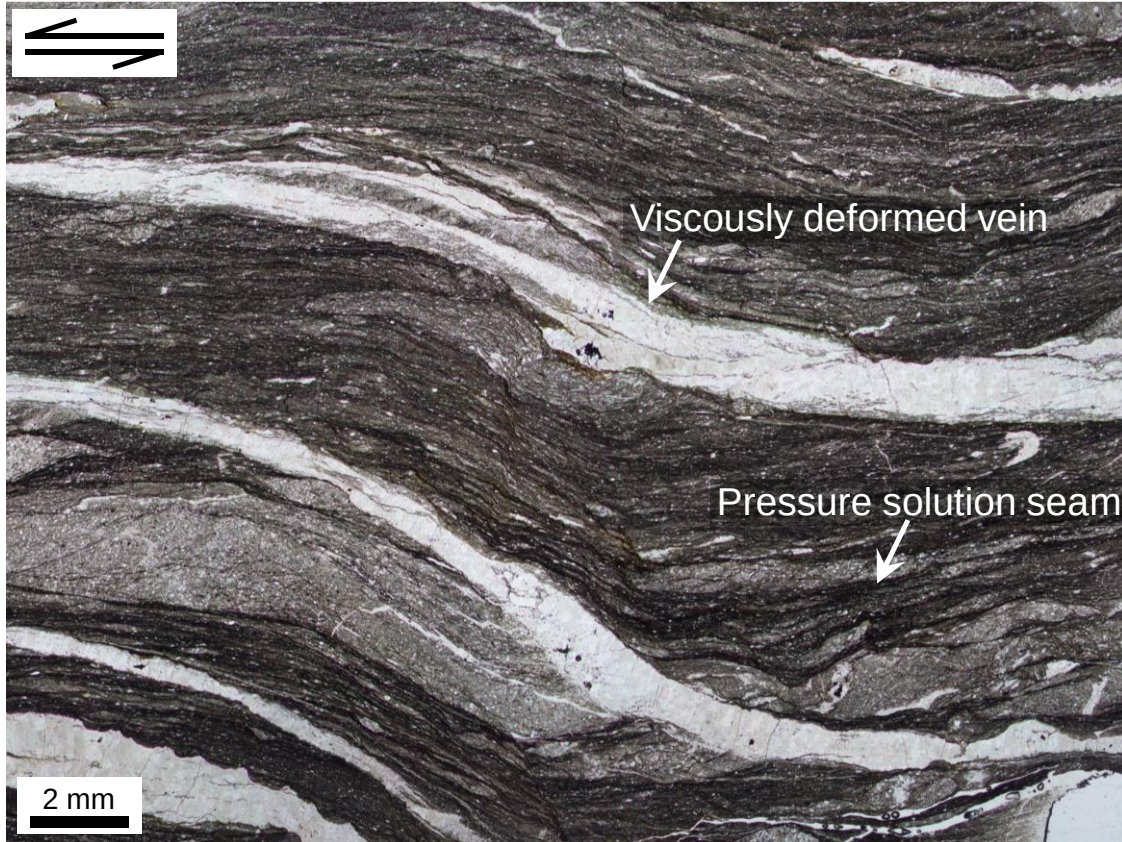
Occurrence of vein concentration zone



Modified from Ujiie et al. (2018)

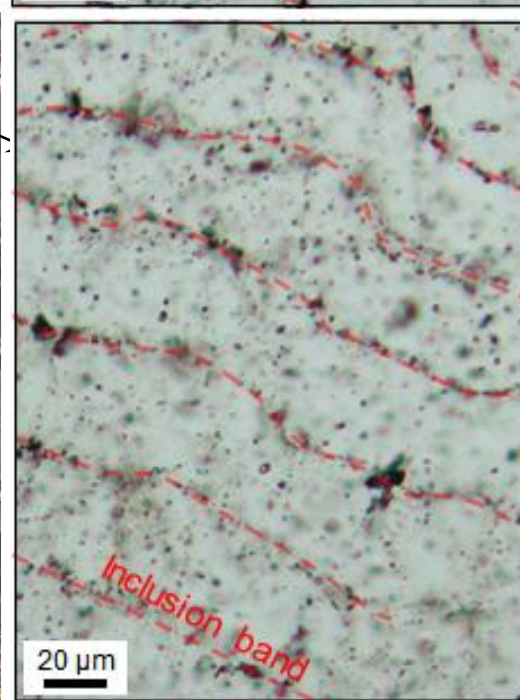
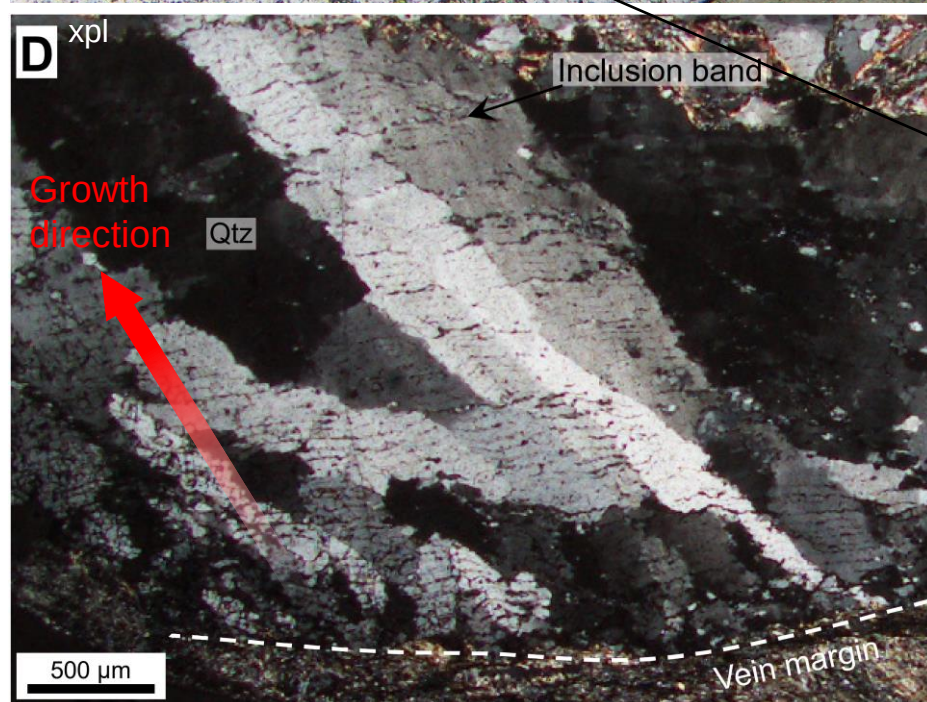
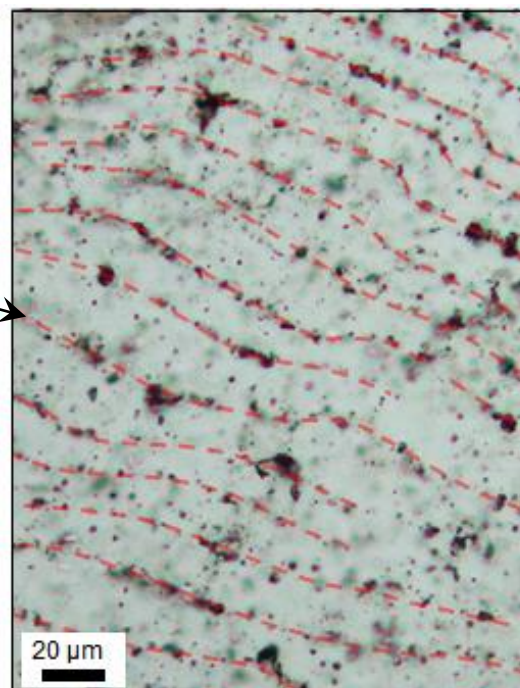
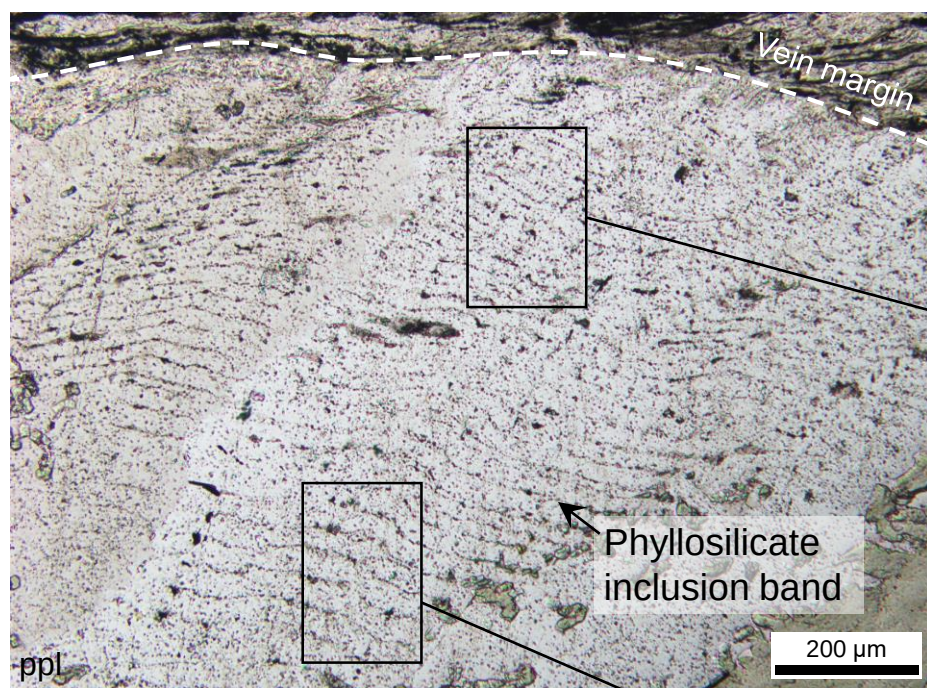
- Shear veins subparallel to foliation parallel veins
- fault-fracture meshes in the mélange deformed at nearly perpendicular to the vertical stress
- generation of shear veins under near-lithostatic fluid pressure
- top-SSE shear, consistent with megathrust shear in the Late Cretaceous
- Slip increments of a single thrusting: ~0.1-0.2 mm

Occurrence of vein concentration zone



- Viscously deformed veins
 - Veins cutting viscous fabrics formed by pressure solution creep
- Contemporaneous occurrence of brittle thrusting and viscous shear

Microstructure of shear vein



Later event

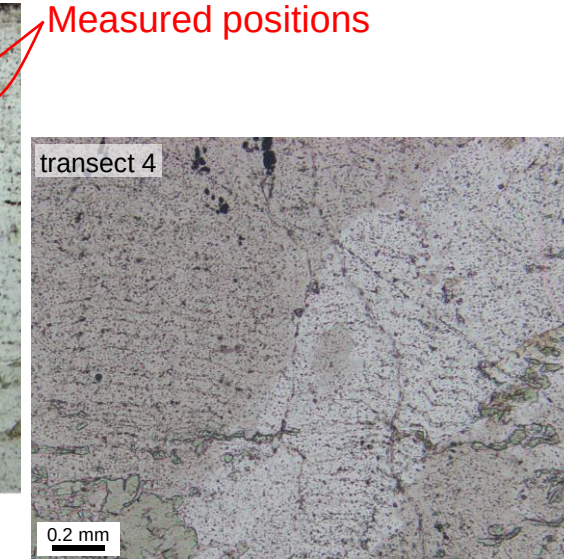
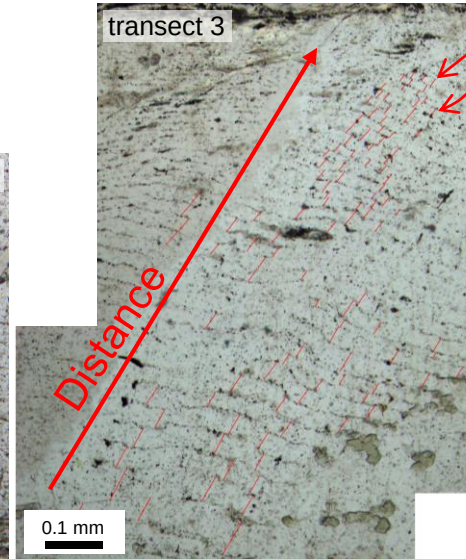
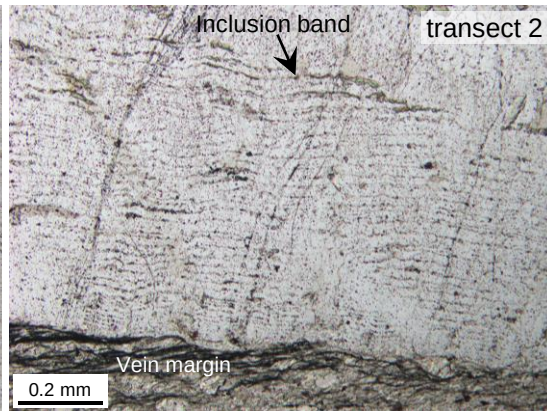
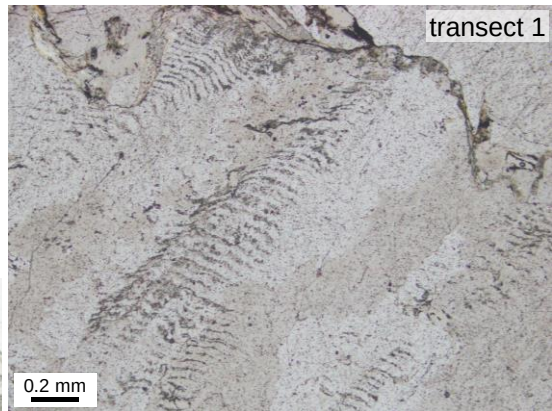
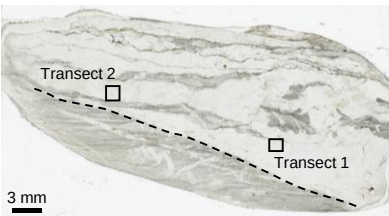
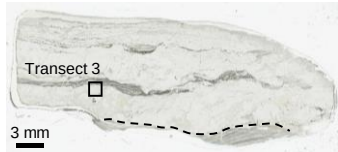
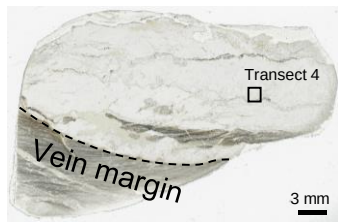
Time

Earlier event

- Crack-seal texture defined by alignment of phyllosilicate inclusion bands
- ➔ repetition of brittle thrusting and crack sealing by quartz precipitation
- Elongate-blocky quartz with grain sizes increasing upward from the lower vein margin
- ➔ spatial variations in inclusion band spacing suggest temporal variations in band spacing

Measurement of inclusion band spacings

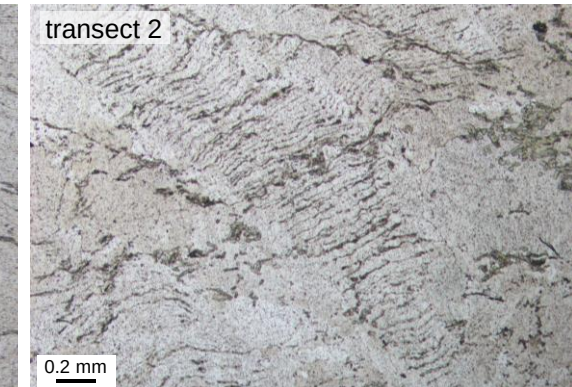
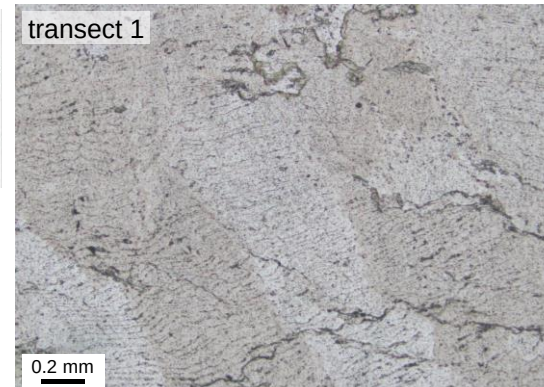
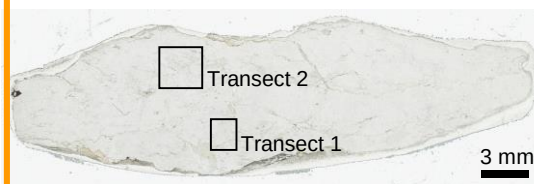
Sample1: SV-R2



Measured positions

Distance

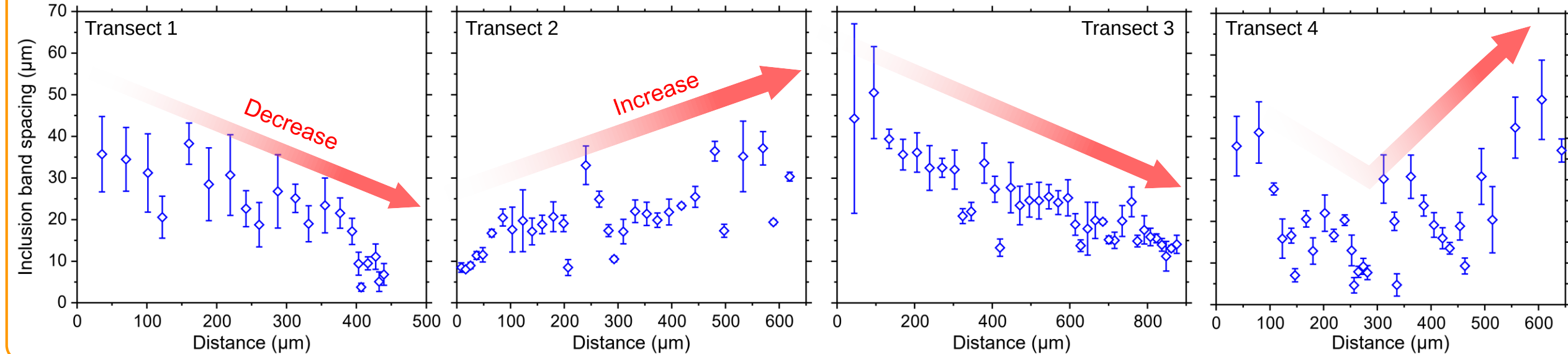
Sample2: SV-R1



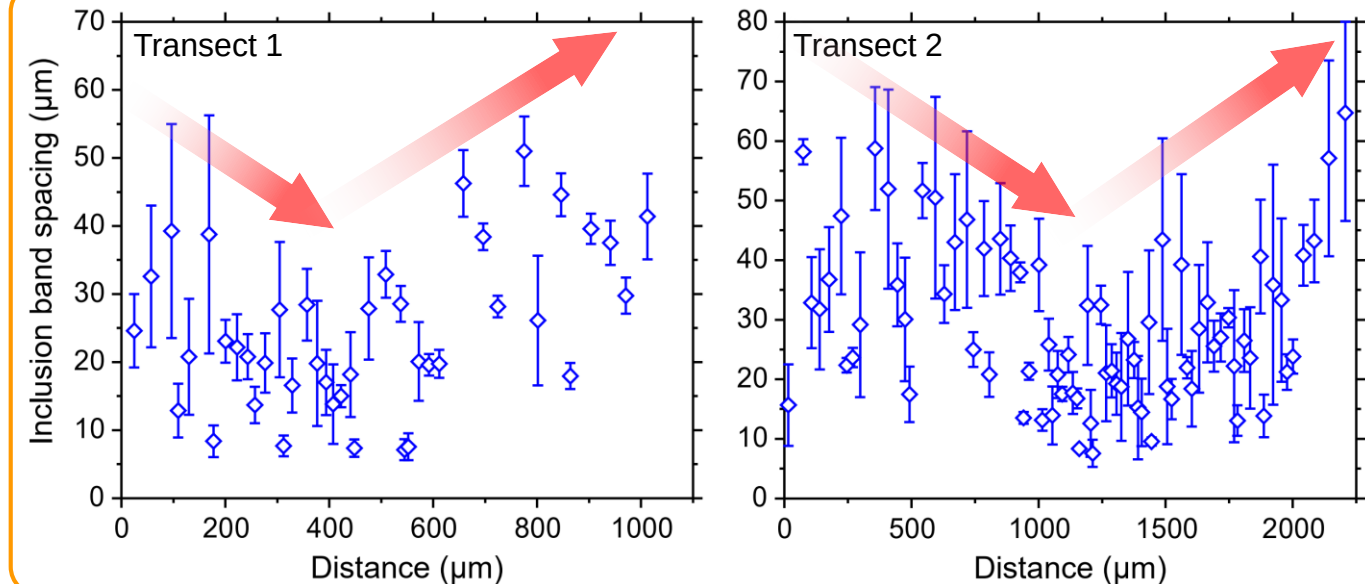
Measurement of inclusion band spacing as a function of distance for six transects from two shear veins

Spatial changes in inclusion band spacing

SV-R2



SV-R1



- Cyclic decrease and increase in inclusion band spacing in the range of 4-65 μm
- At least, two cycles of spatial changes in inclusion band spacing are recorded in a single shear vein

Estimation of sealing time by quartz precipitation driven by fluid pressure drop

Kinetic model of quartz precipitation (Rimstidt & Barnes, 1980)

$$\frac{\partial C_{\text{SiO}_2}}{\partial t} = k \frac{A_{\text{H}_2\text{O}}}{M_{\text{H}_2\text{O}}} (C_{\text{SiO}_2, \text{eq}} - C_{\text{SiO}_2})$$

C_{SiO_2} : SiO_2 concentration in fluid

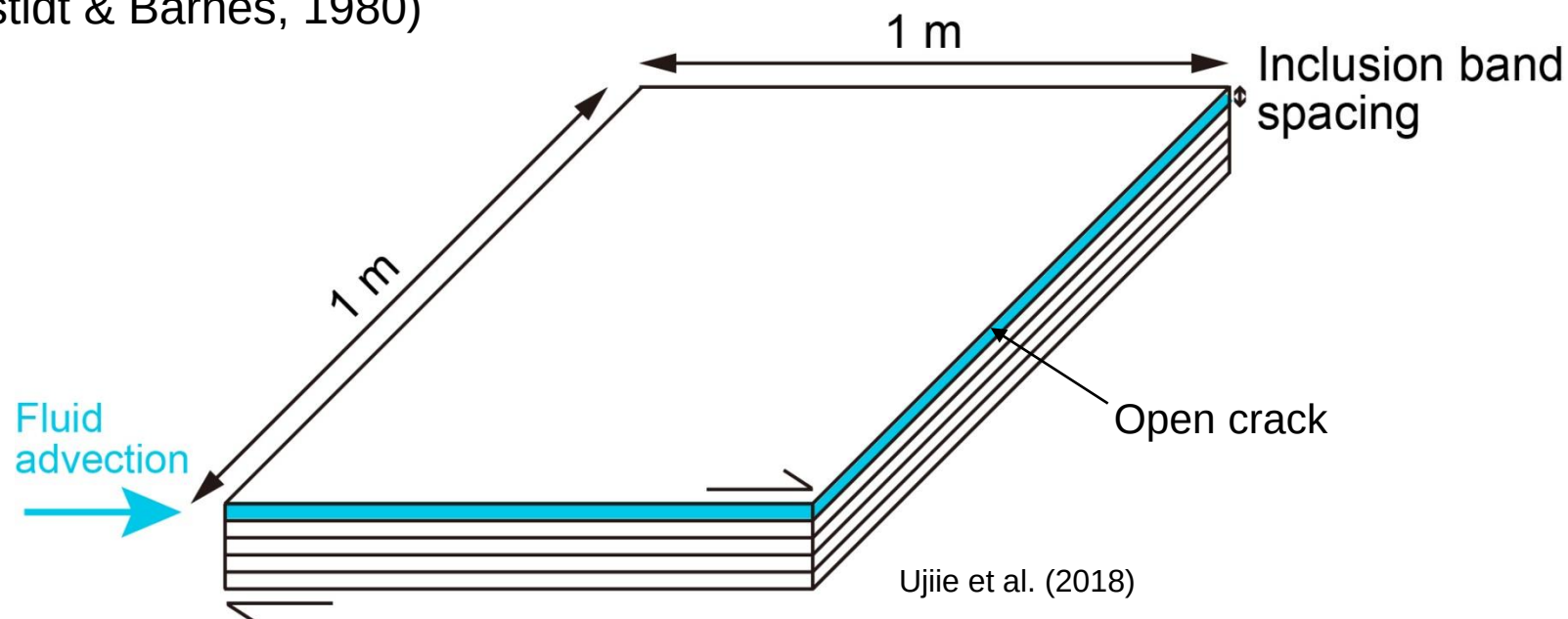
$C_{\text{SiO}_2, \text{eq}}$: solubility of quartz in fluid at hydrostatic pressure

t : time

k : quartz precipitation rate ($\log k = -0.0886 - 2638/T$ (Okamoto et al., 2010))

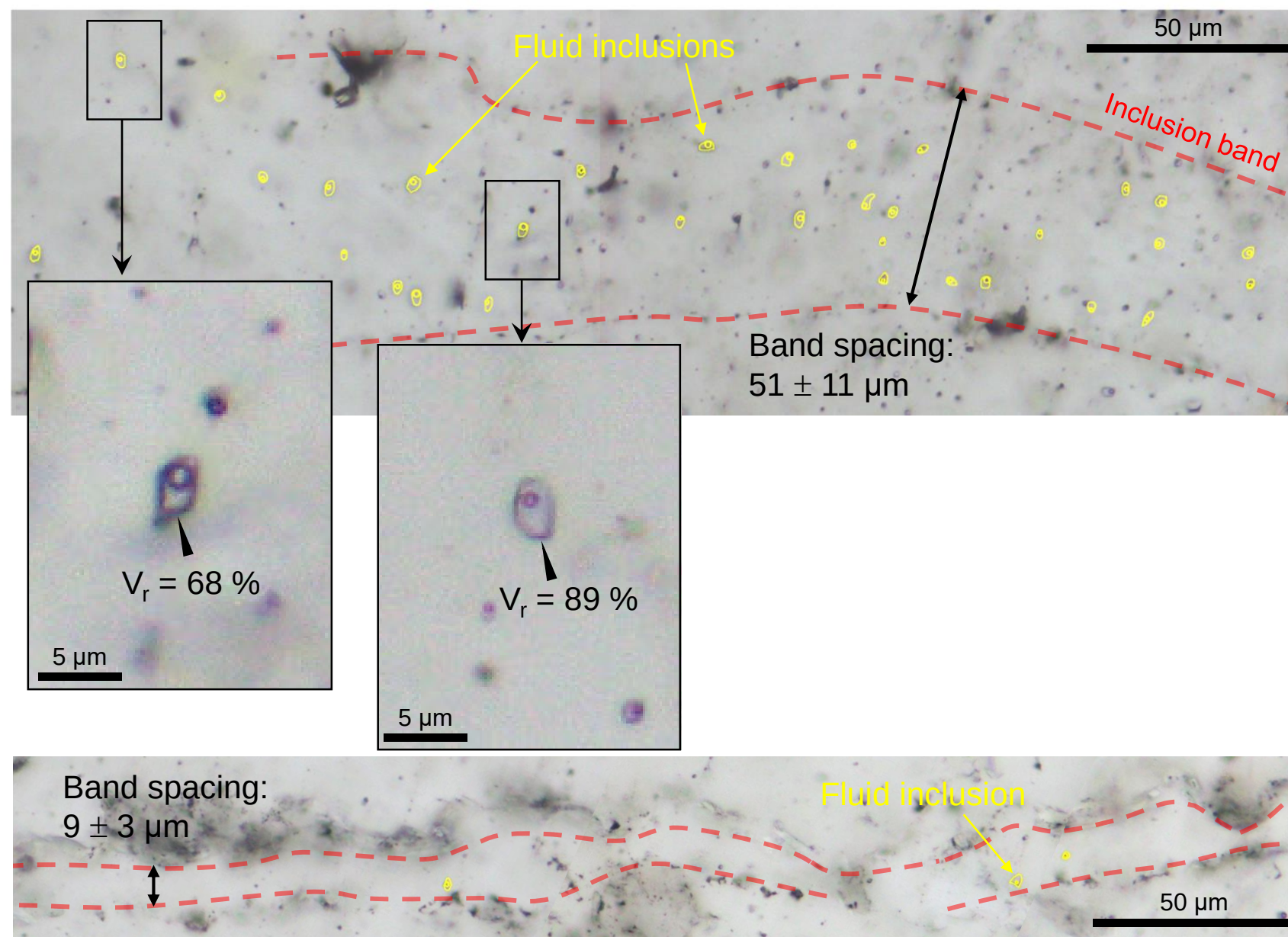
$A_{\text{H}_2\text{O}}$: reactive surface area

$M_{\text{H}_2\text{O}}$: H_2O mass in crack



Parameter	Value
Vein length	1 m
Inclusion band spacing	Measured values
Temperature (T)	330 °C (Ujiie et al., 2018)
Fluid pressure drop	lithostatic minus hydrostatic pressures at 15 km depth
Quartz solubility	calculated by LonerAP (Akinfiev & Diamond, 2009)

Estimation of fluid pressure drop during a single crack-seal event



(1) Measurement of vapor/liquid ratio (V_r) in two-phase primary fluid inclusion between inclusion bands using micrograph

(2) Estimation of water density (ρ_h) at homogenization temperature

$$\rho_h = \rho_r \frac{V_r}{V}$$

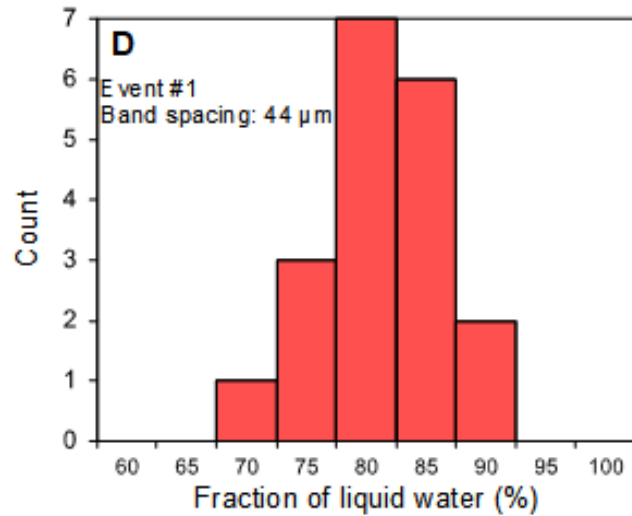
V : volume fraction of liquid water at homogenization temperature ($= 1$)

ρ_r : water density at room temperature ($\sim 1 \text{ g/cm}^3$)

(3) Estimation of fluid pressure using isochore with ρ_h

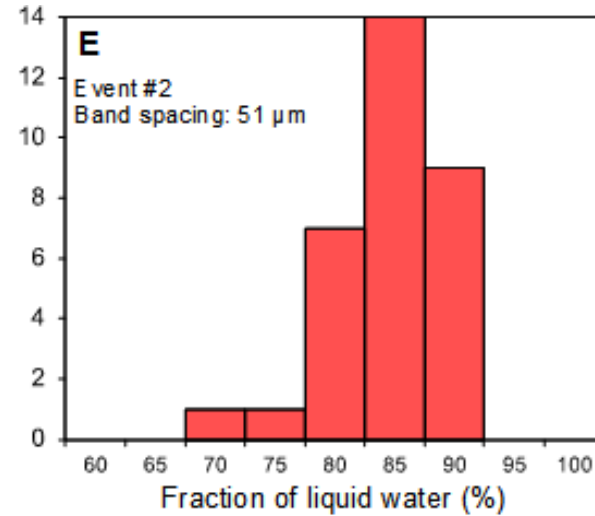
Variation in vapor/liquid ratio during a single crack-seal event

Band spacing: 44 μm



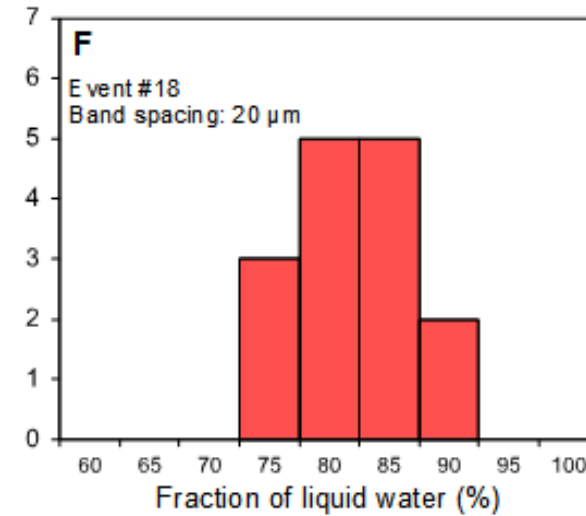
Vapor/liquid ratio: 66-89%

51 μm



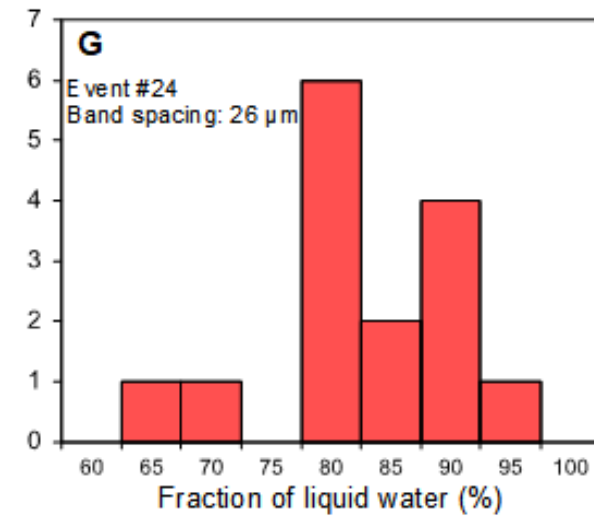
68-89%

20 μm



70-89%

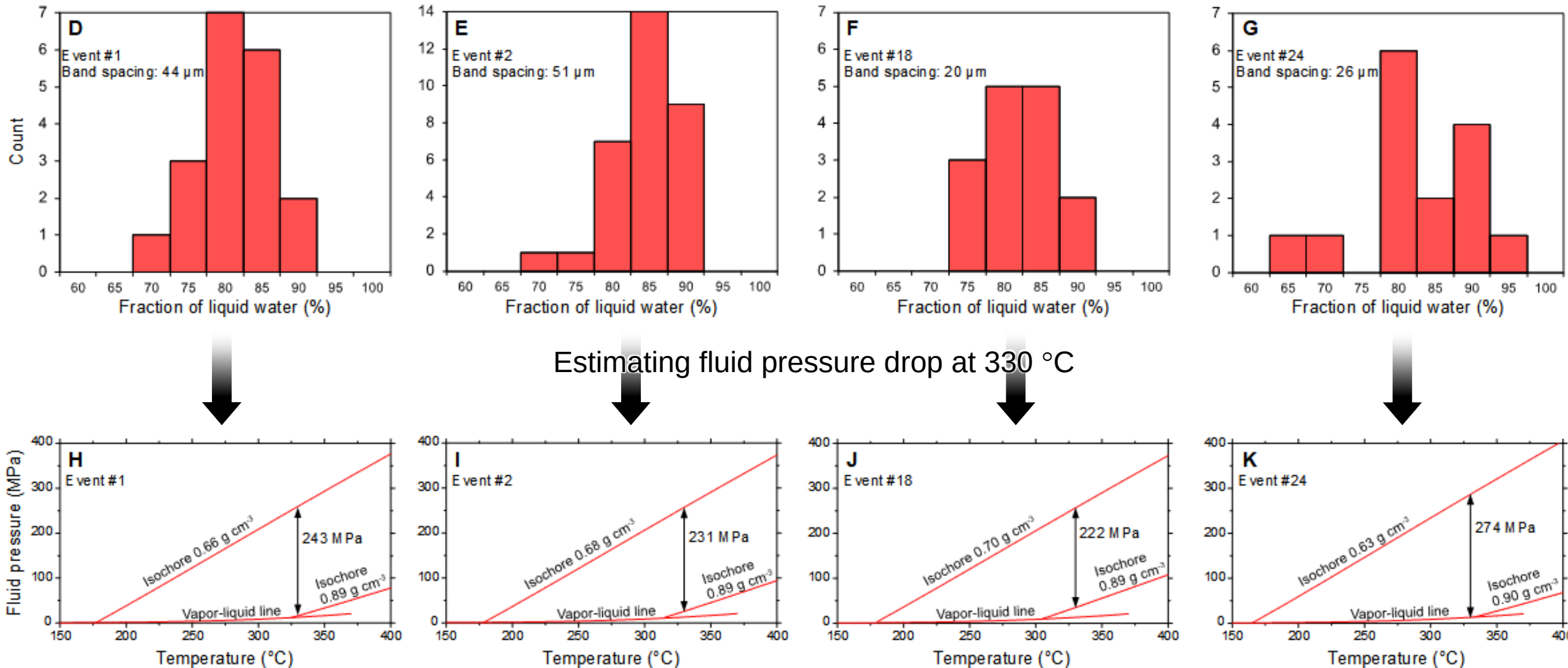
26 μm



63-90%

- Large variation in vapor/liquid ratio in a single crack-seal event
- The range of vapor/liquid ratio does not correlate to inclusion band spacing

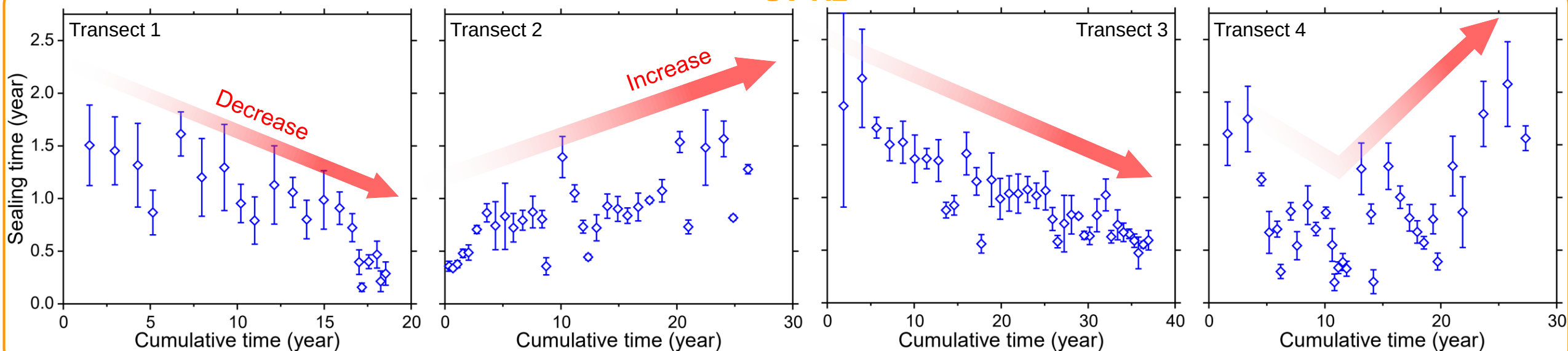
Possible fluid pressure drop during a single crack-seal event



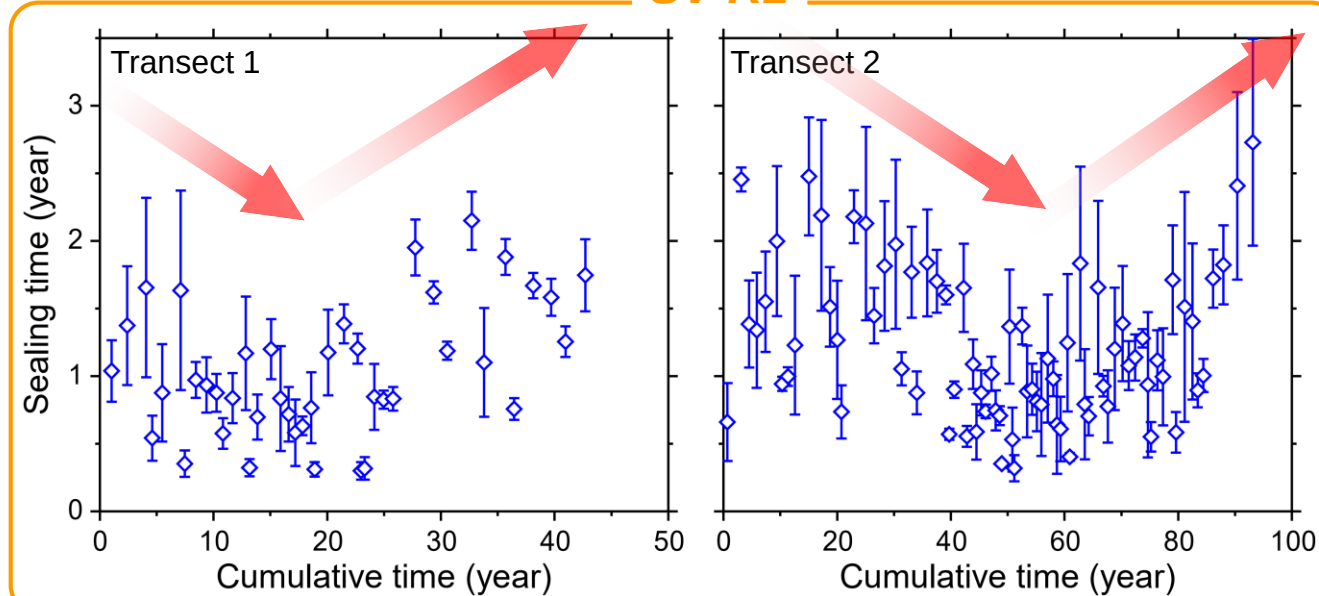
Fluid pressure drop comparable to that from lithostatic to hydrostatic values at 15 km depth (235 MPa)

Temporal variations in sealing time

SV-R2

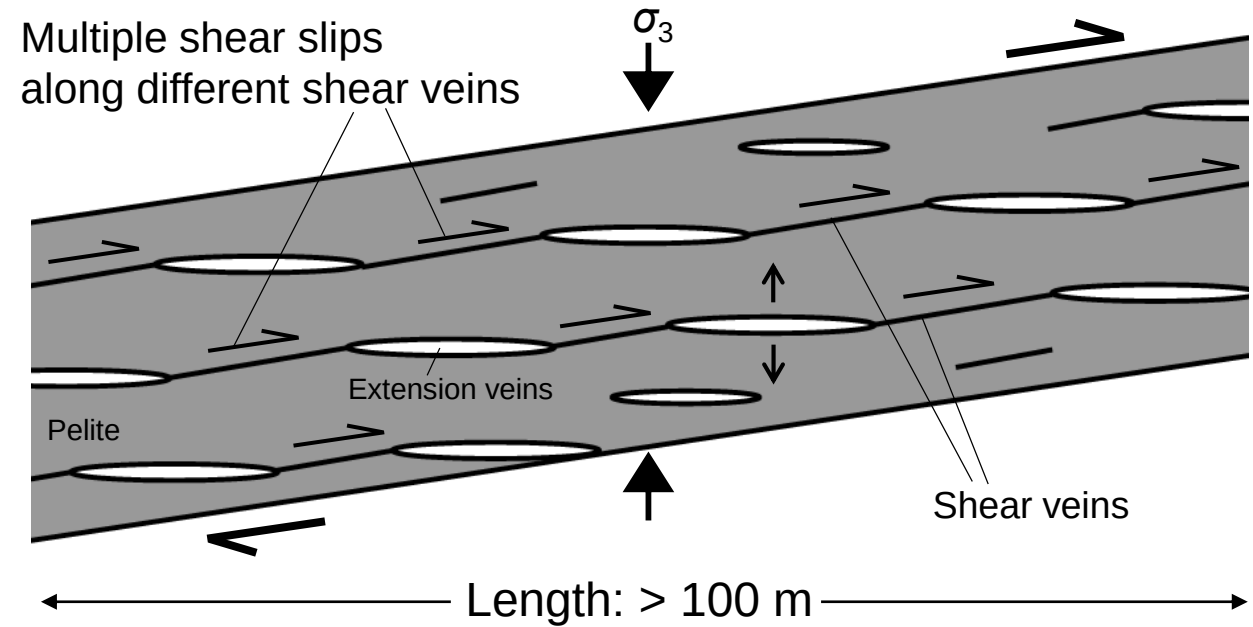
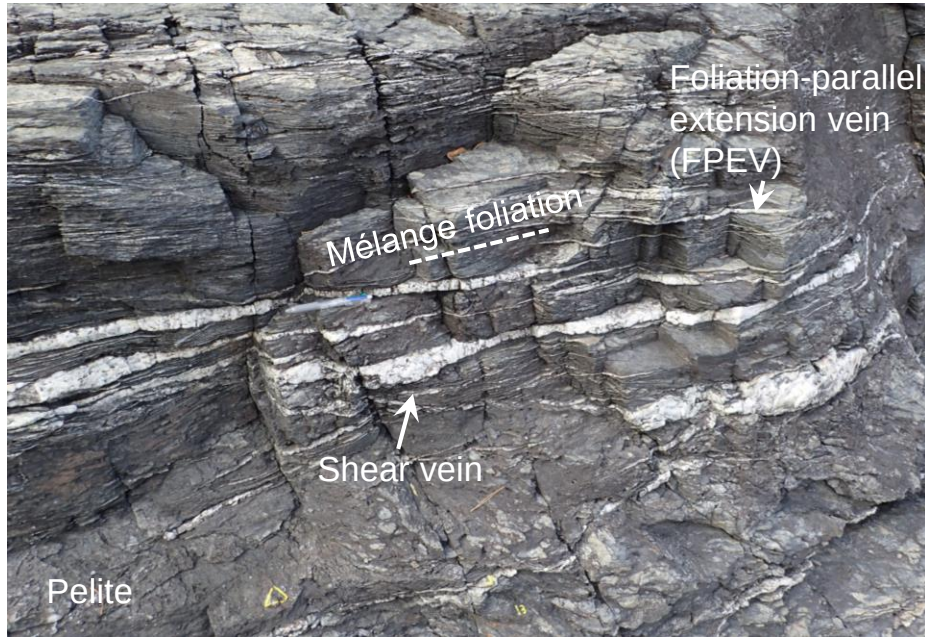


SV-R1



- Sealing time of crack-seal event cyclically decreased and increased at least twice
- Range of sealing time: 0.2-2.7 years

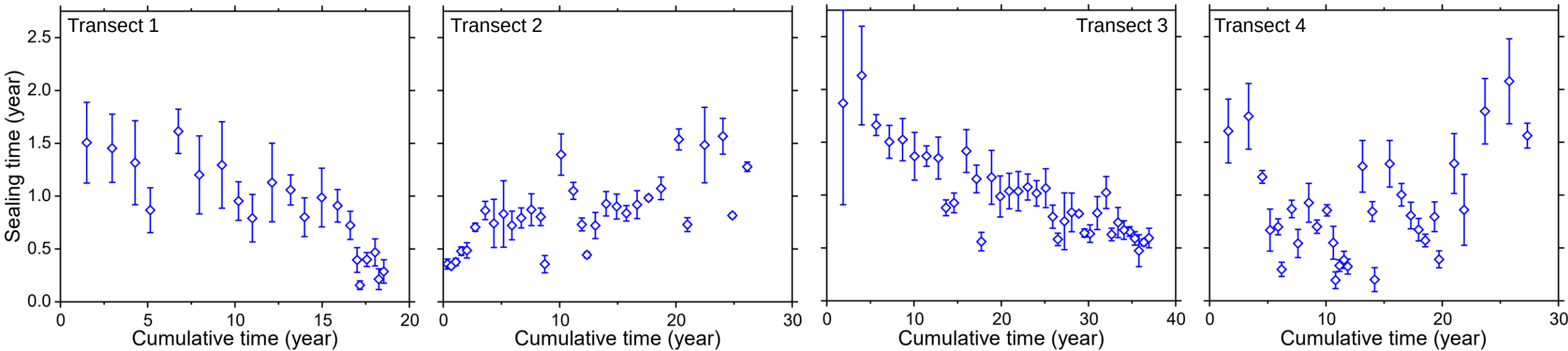
Crack-seal shear veins: a possible record of tremor-generating deformations



- Shear veins constitute fault-fracture meshes in vein concentration zone
 - Length scales of vein concentration zone (> 100 m)
 - Low angle brittle thrusting under near-lithostatic fluid pressures
 - 0.1-0.2 mm slip increments during a single thrusting event
- consistent with characteristics of low-frequency earthquakes (LFEs)
- Sealing time of crack-seal event (0.16-2.7 years) → longer than recurrence intervals of LFEs but comparable to episodic tremor and slip (ETS)

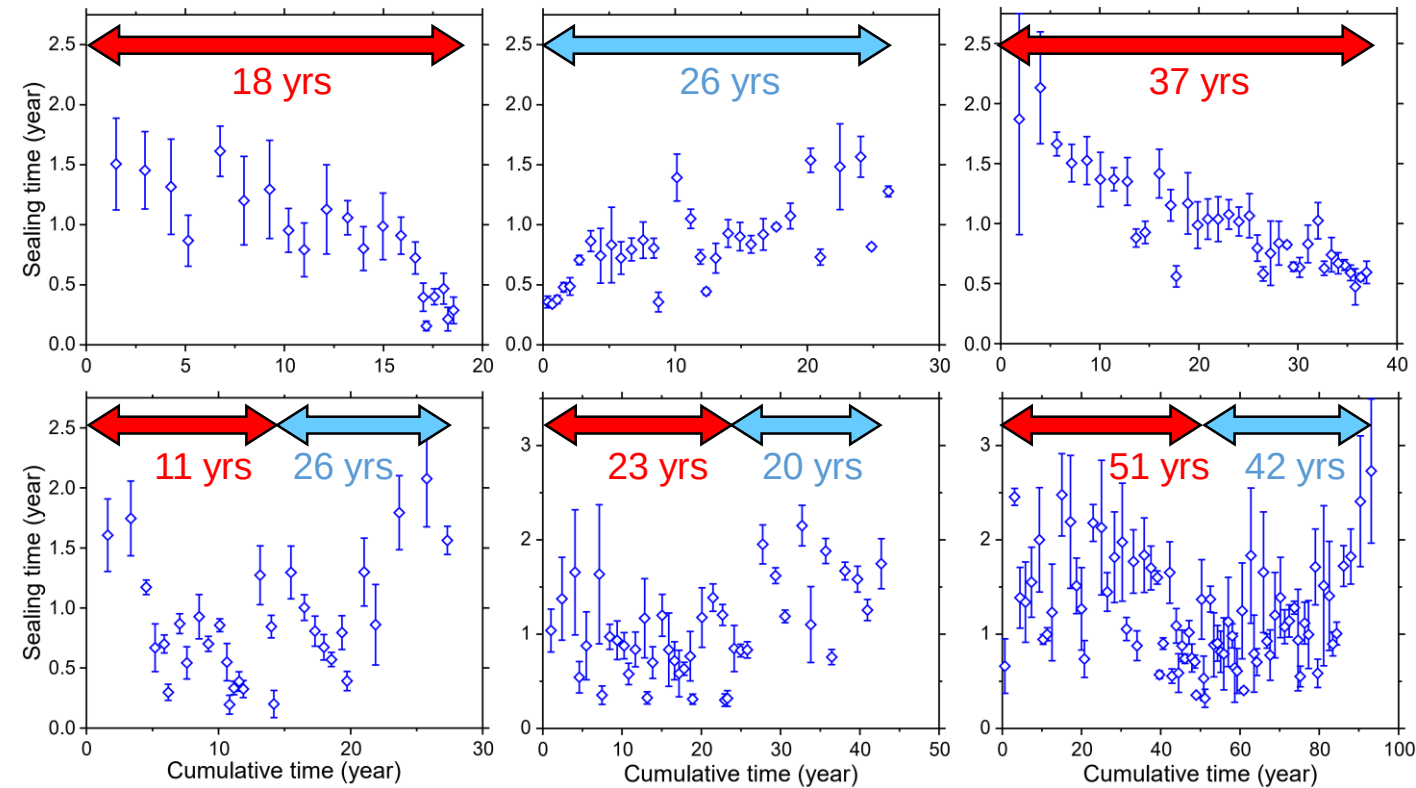
➡ Shear vein may represent a small component of tremor composed of LFEs, which concurrently occurred in different shear veins

Implications for temporal change in ETS recurrence interval



If inclusion band spacing in the analyzed veins represents ETS recurrence interval, our results suggest that ETS recurrence interval temporally decreases and increases

Implications for temporal change in ETS recurrence interval



➤ Duration of temporal decrease: 11-51 yrs

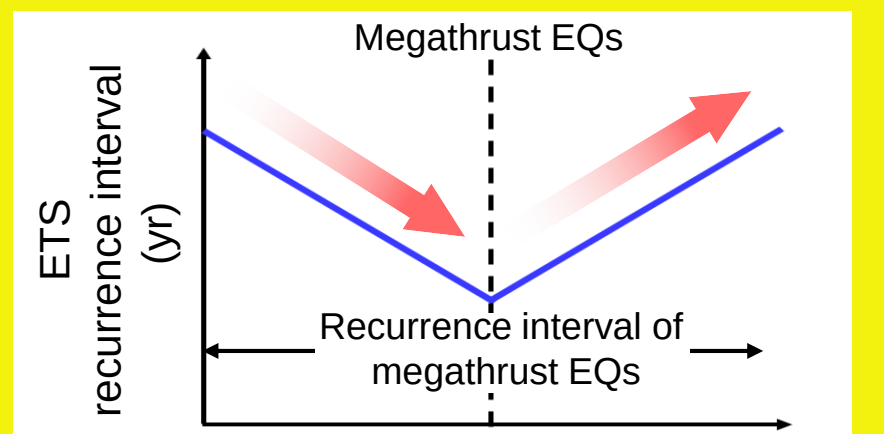
➤ Duration of temporal increase: 20-42 yrs

→ One cycle duration: $\geq 31-93$ yrs

→ within recurrence intervals of megathrust earthquakes for subduction zones

Subduction zone	Recurrence interval of megathrust earthquake	References
Nankai	90-200 yrs	Ando (1975)
Sumatra	63-157 yrs	Bilham et al. (2005); Malik et al. (2019)
Chile	128-300 yrs	Lomnitz (1970); Cisternas et al. (2005)

Our results may represent cyclic decrease and increase in ETS recurrence interval during megathrust earthquake cycles



Summary

- Crack-seal shear veins in the Makimine mélange deformed near the downdip limit of the seismogenic zone recorded the cyclic decrease and increase in inclusion band spacing.
- Sealing time during crack-seal events and duration of decrease-increase cycle are comparable to recurrence intervals of ETS and megathrust earthquakes, respectively.
- Spatial change in band spacing is a potential geologic indicator of temporal change in ETS recurrence intervals during megathrust earthquake cycles, when large fluid pressure drop occurred during crack-seal events.