What can petrology and geochemistry of subduction-related rocks tell us about subduction zone fluids?

Sarah Penniston-Dorland

Will Hoover, Kayleigh Harvey, Gray Bebout, Phil Piccoli, Rich Walker, Julia Gorman, Lukas Baumgartner, Besim Dragovic, Anne-Sophie Bouvier, Michele Locatelli, Samuel Angiboust, Philippe Agard

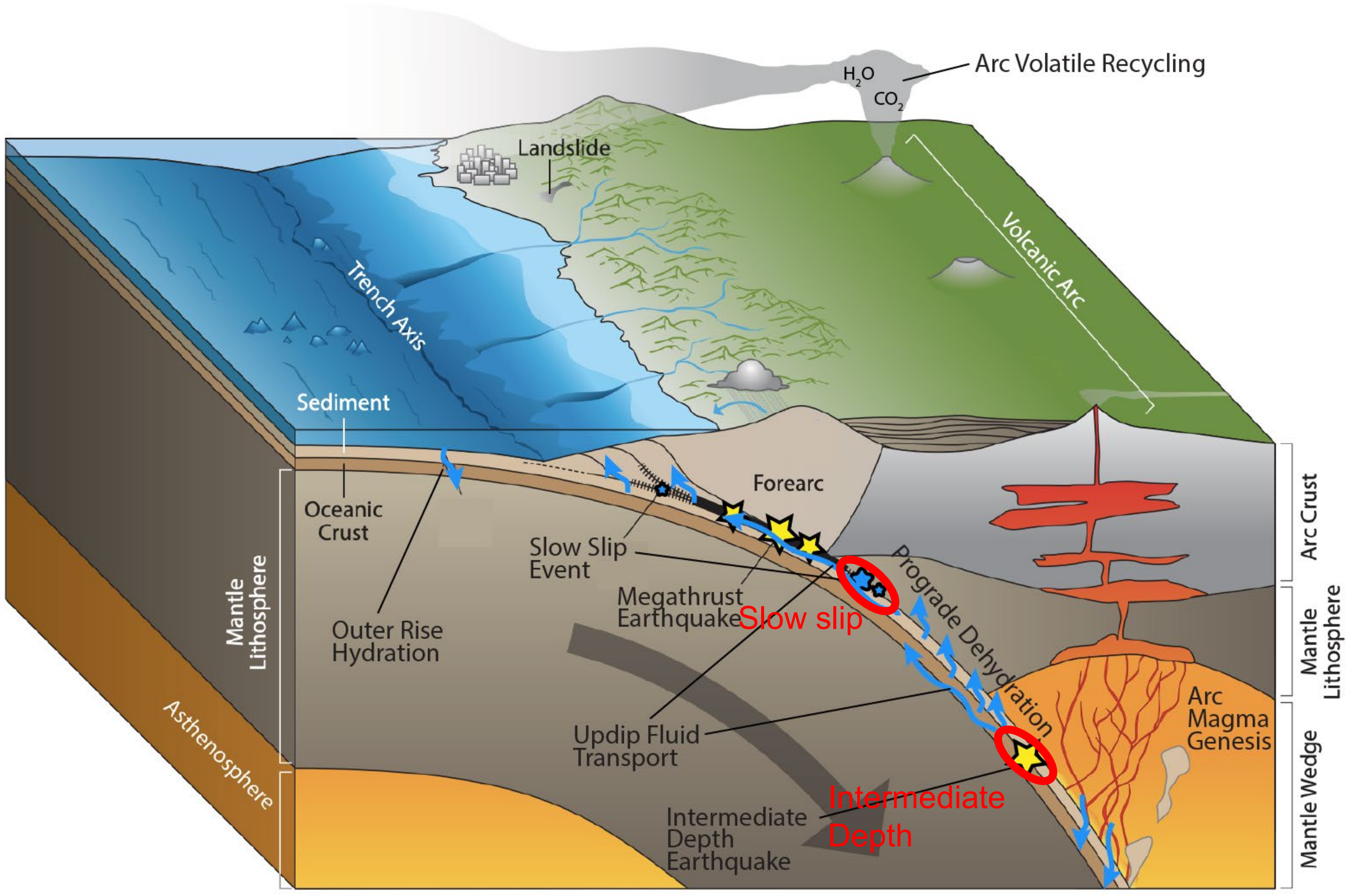
Why is subduction fluid flow important?

- Fluid transport within subduction zones is important for mass transfer and geochemical cycling.

- Fluids are implicated in the generation of arc volcanoes.

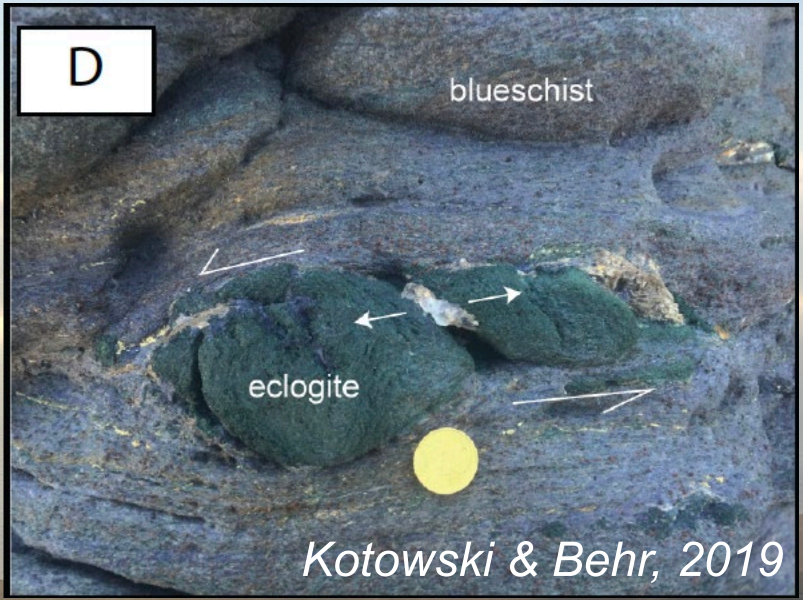
- Fluids are associated with slow slip processes and also deeper seismic events

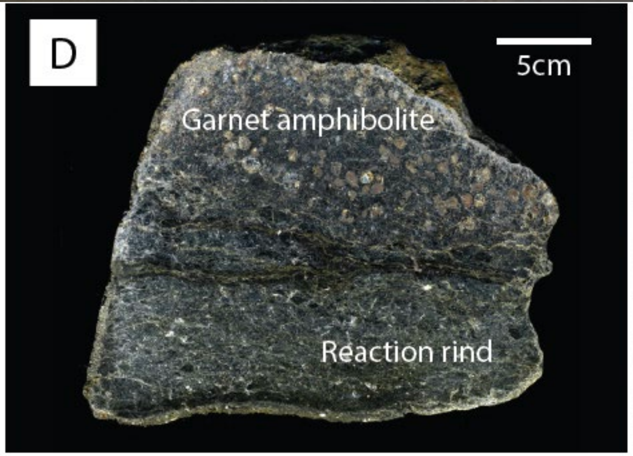
- Exhumed metamorphic rocks are only source of material directly from deep subduction interface

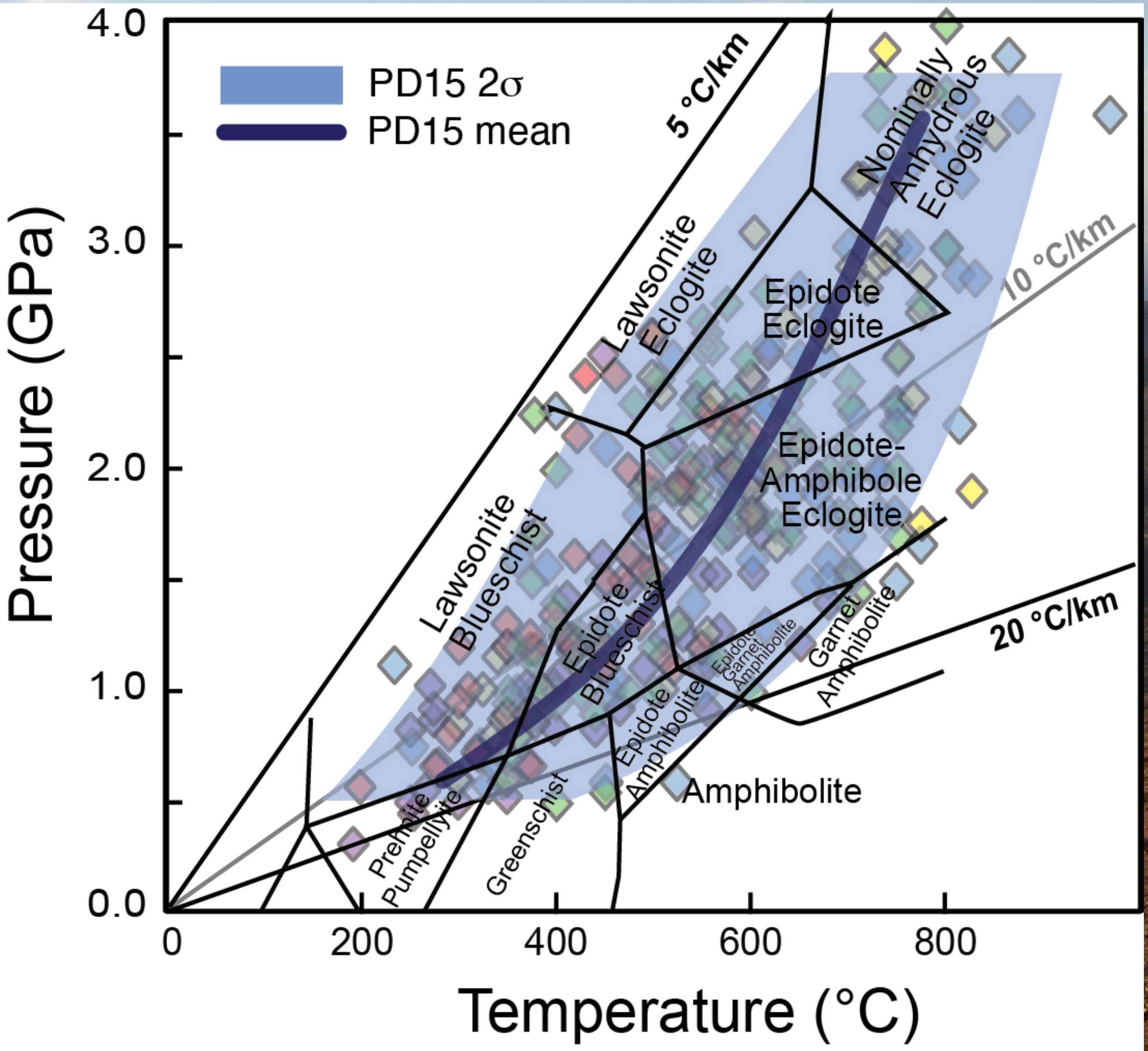


after McGuire et al., 2017

Fluid flow in subduction systems



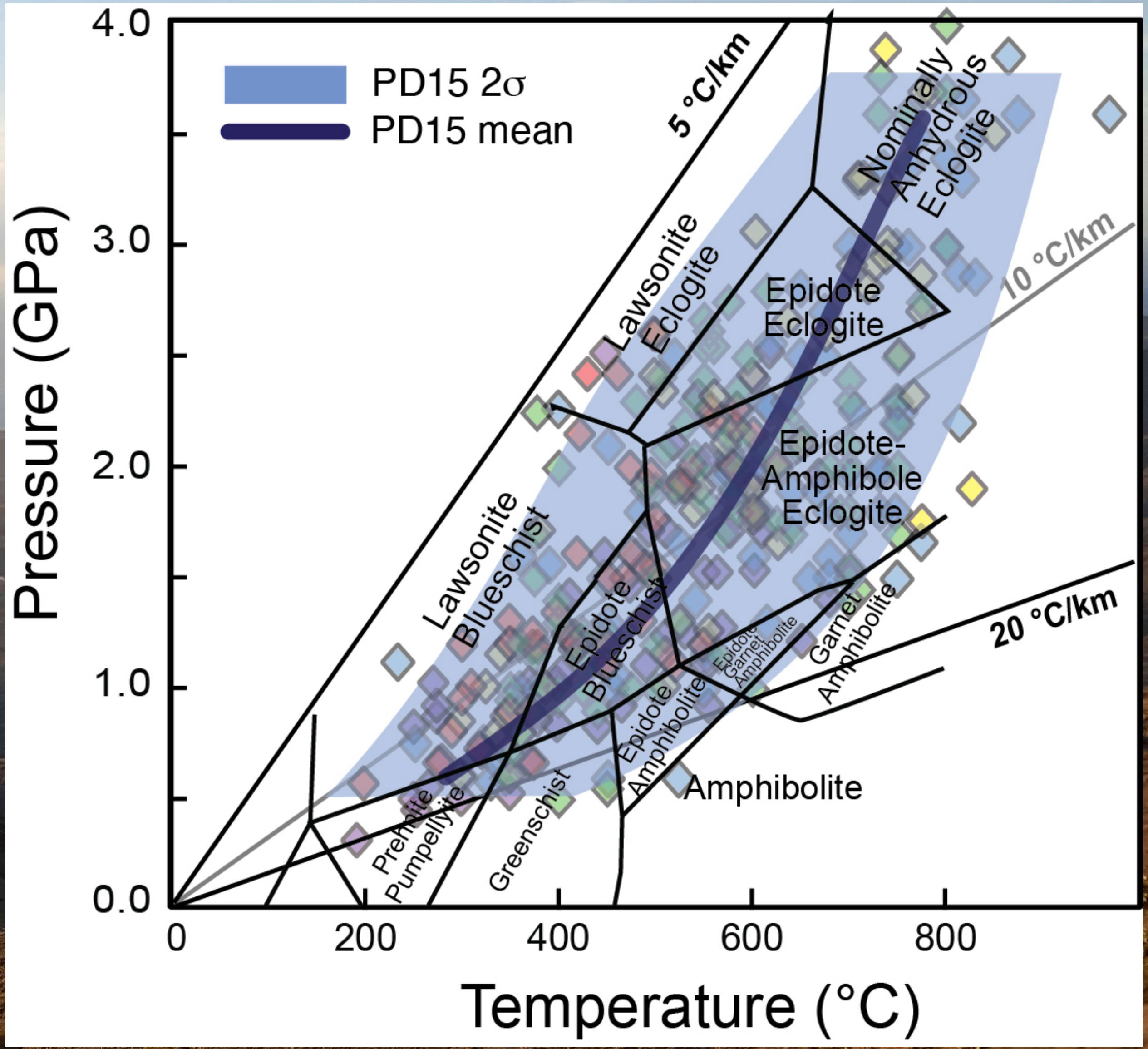




Penniston-Dorland et al., 2015

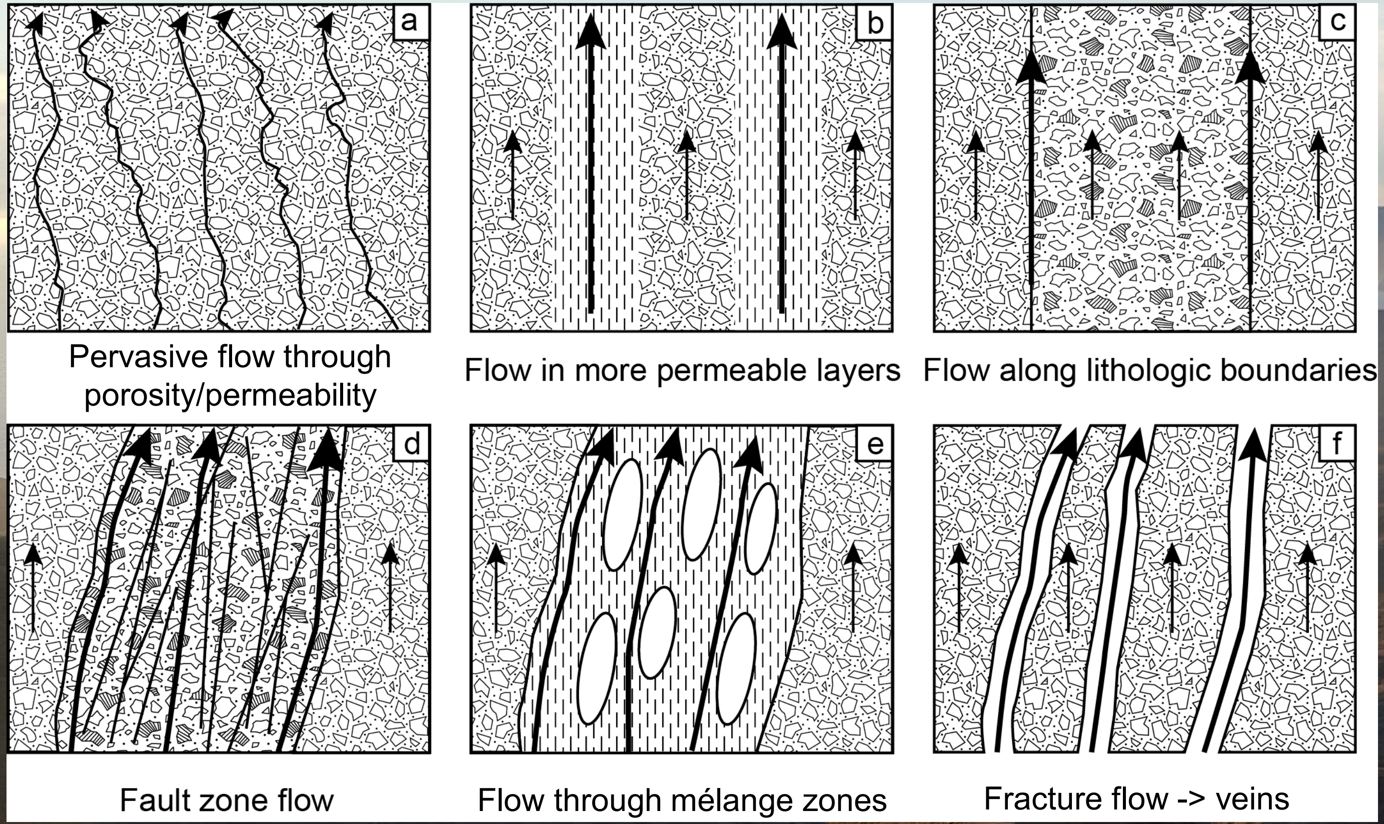
Fluid flow in subduction systems

- Mechanisms of fluid flow
- Elemental transport in fluids
- Fluid fluxes
- Fluid flow timescales



Fluid flow in subduction systems

- Mechanisms of fluid flow



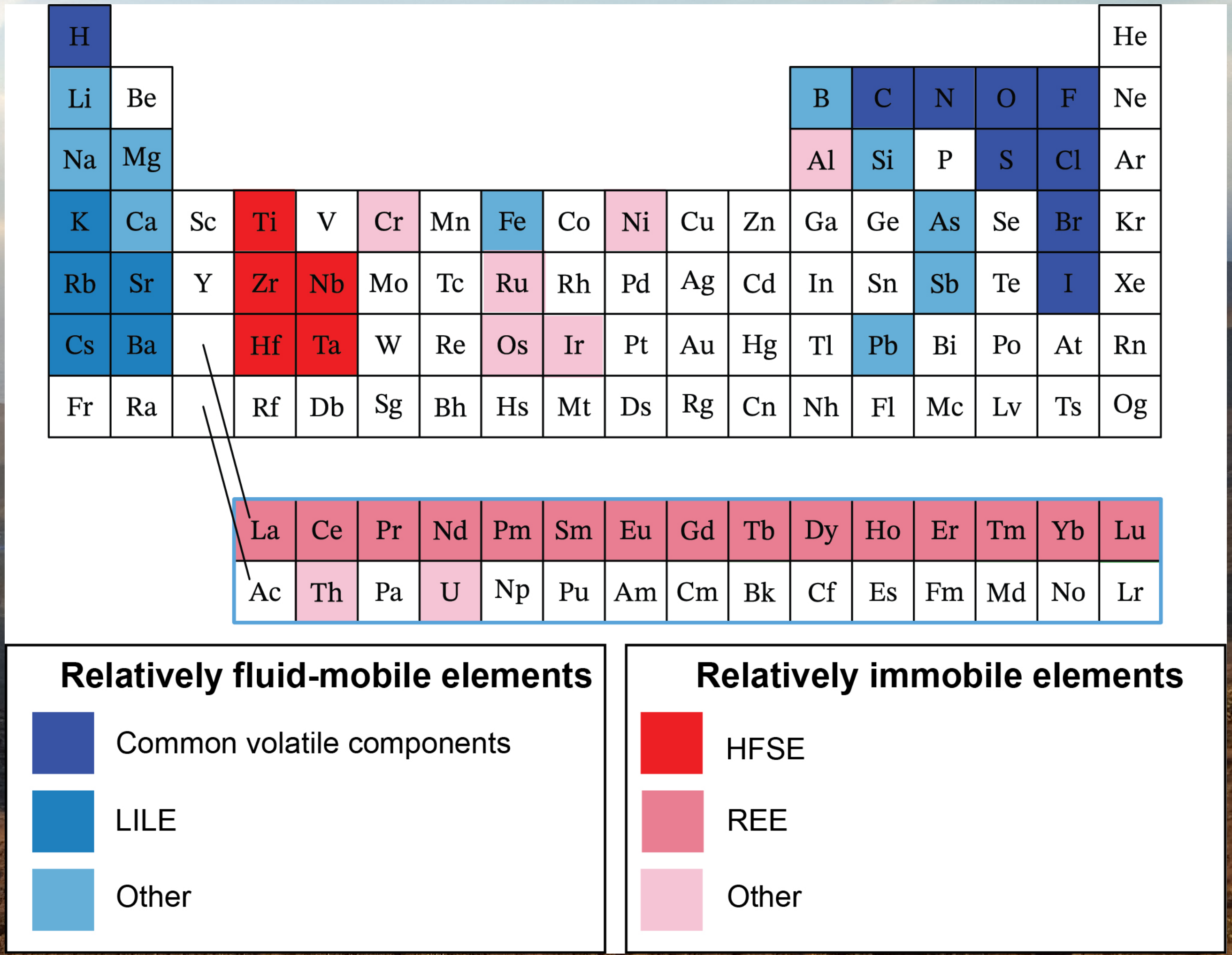
Penniston-Dorland, Treatise on Geochemistry, 2025

Fluid channelization *controls reaction rates and element redistributions during metamorphism of the subducting plate (Zack and John, 2007)*

Fluid flow in subduction systems

- Elemental transport in fluids

Determined by evaluating changes in metamorphic rocks compared to protoliths or lower-grade equivalents.

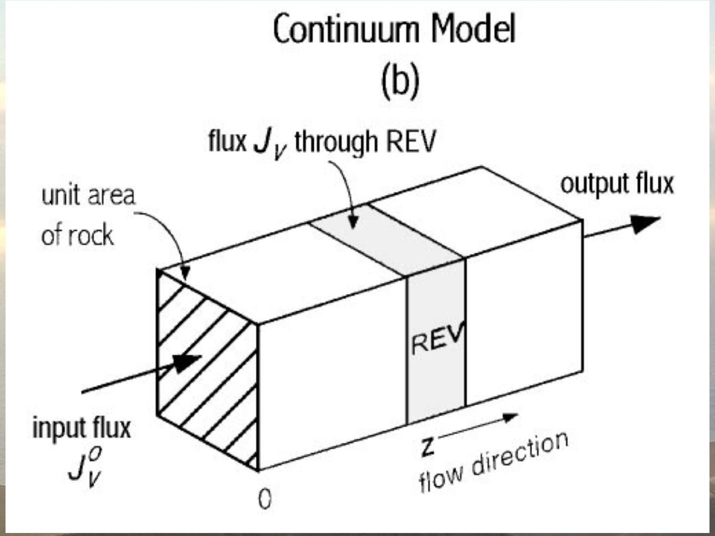


There are exceptions to these generalizations for almost every element - some field settings contain evidence for mobility of even the most recalcitrant immobile elements

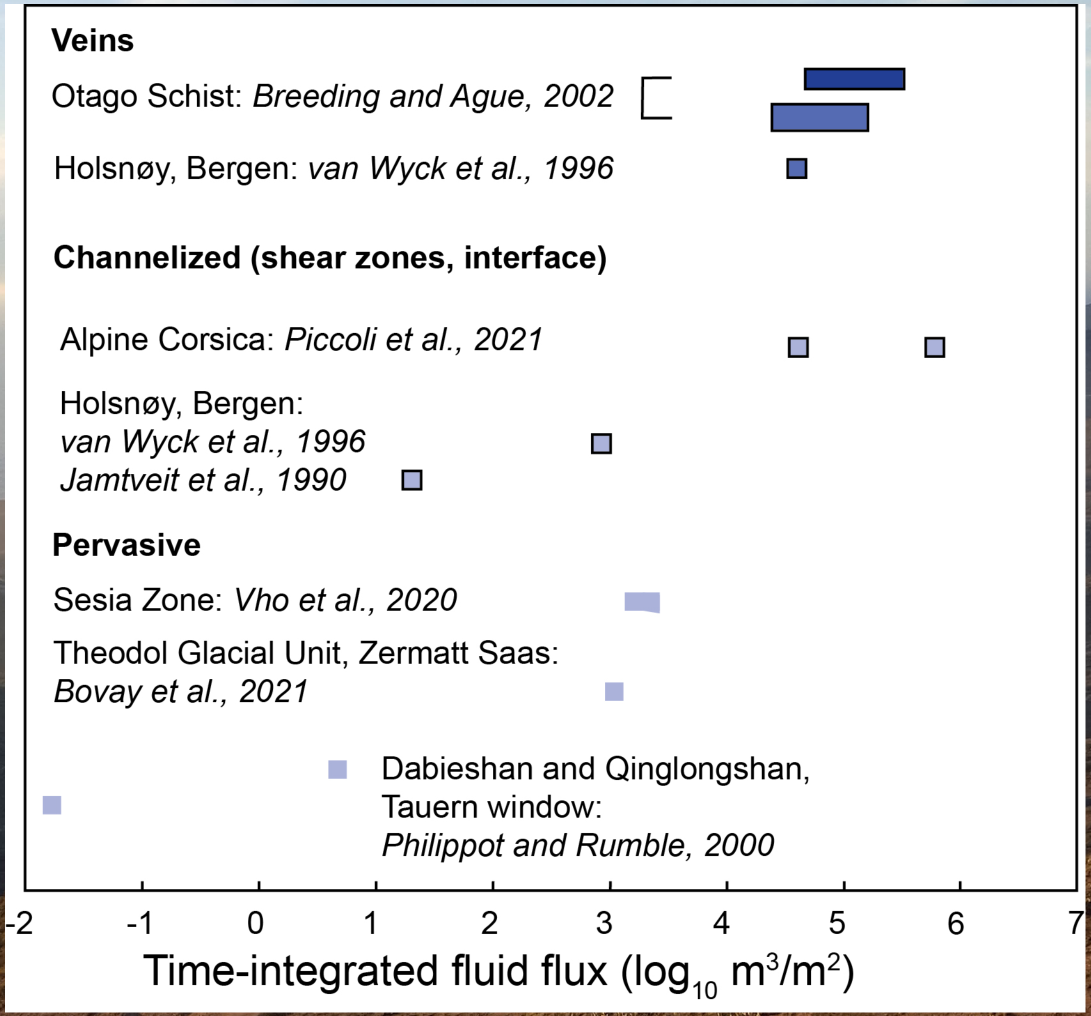
Penniston-Dorland, Treatise on Geochemistry, 2025

Fluid flow in subduction systems

- Fluid fluxes



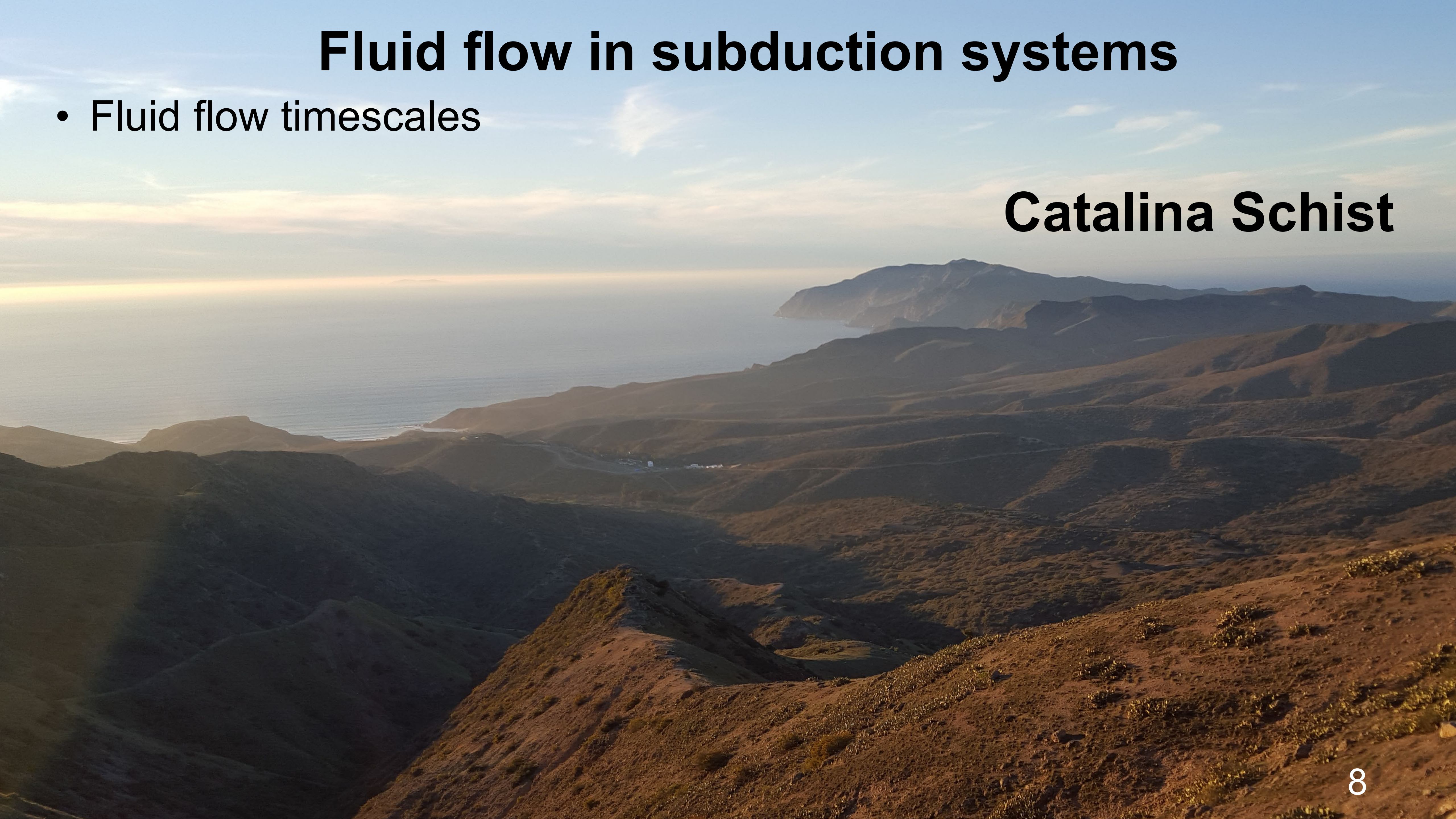
Ferry and Gerdes, 1998



Penniston-Dorland, Treatise on Geochemistry, 2025

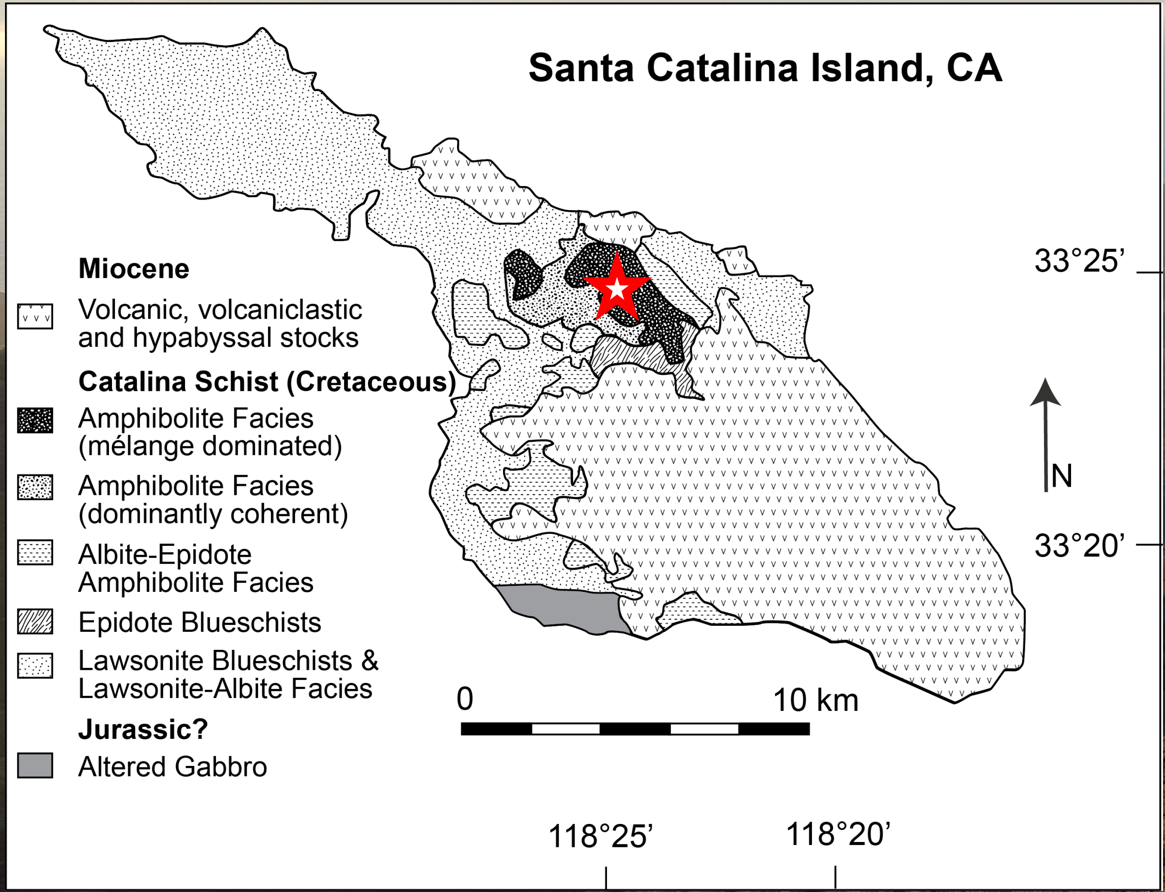
Fluid flow in subduction systems

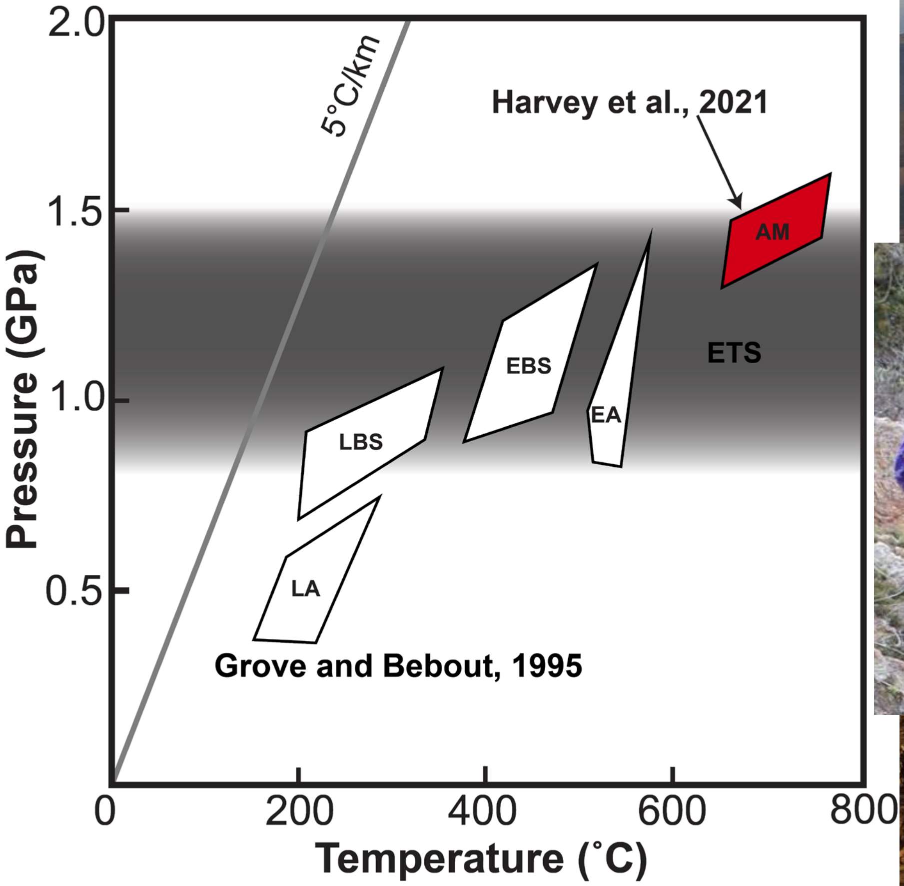
- Fluid flow timescales

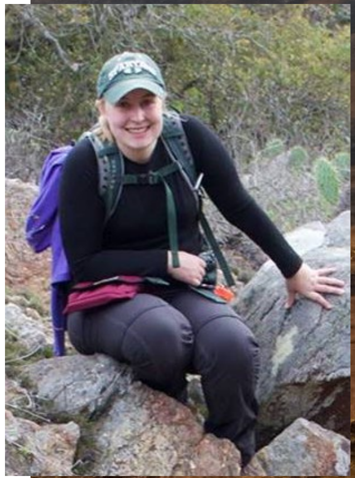


Catalina Schist

- Subduction-related metamorphic rocks span range of *P-T* conditions
- Depths of metamorphism are equivalent to ETS (episodic tremor and slip) depths

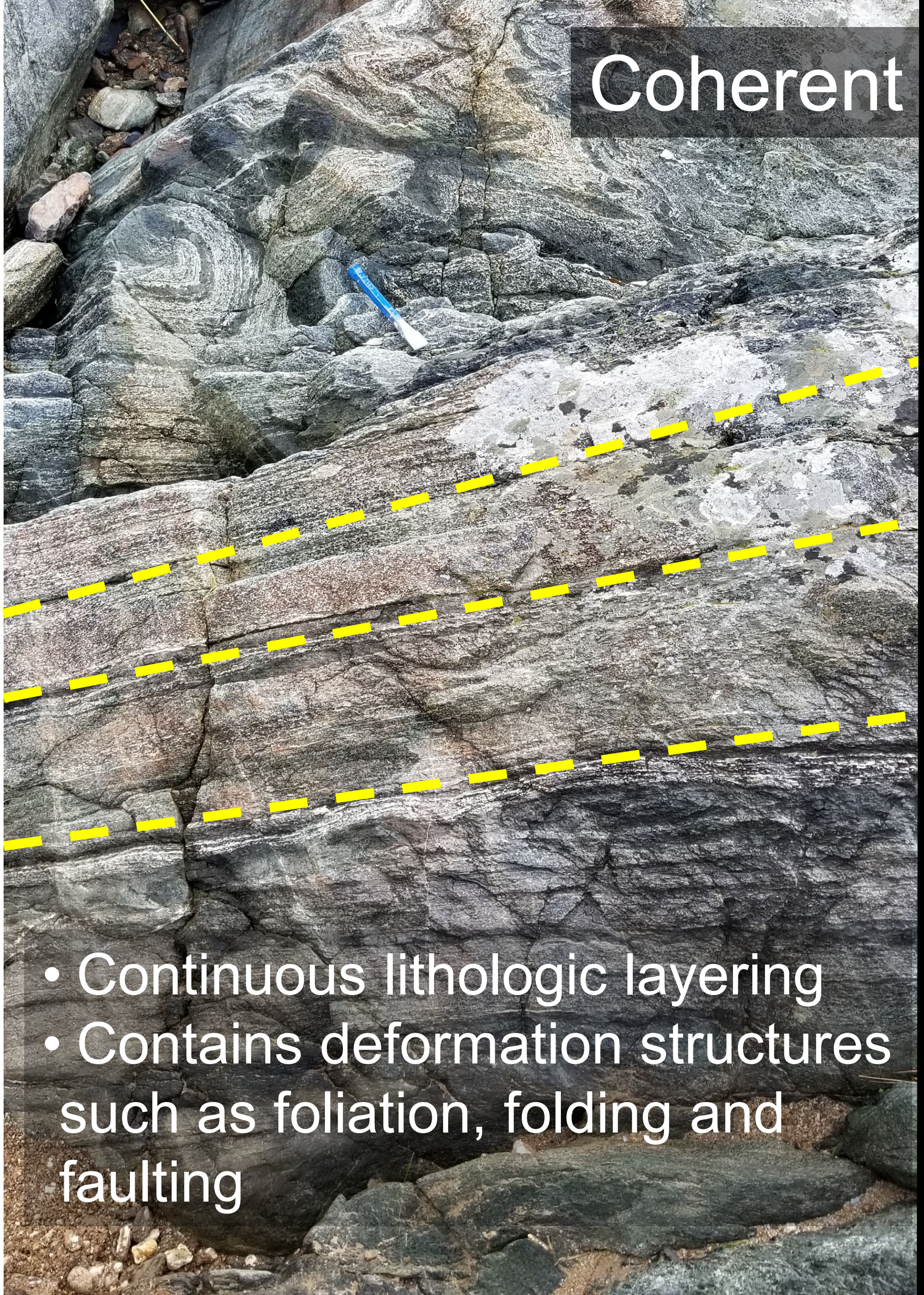






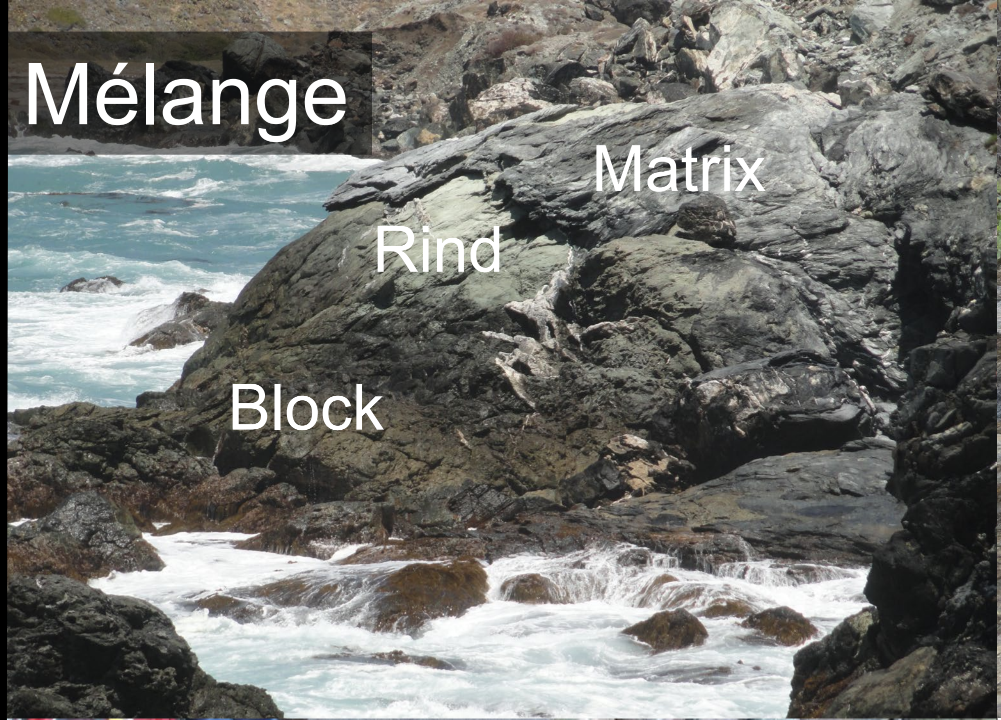
After Platt, 1975, 1976; Grove and Bebout, 1995

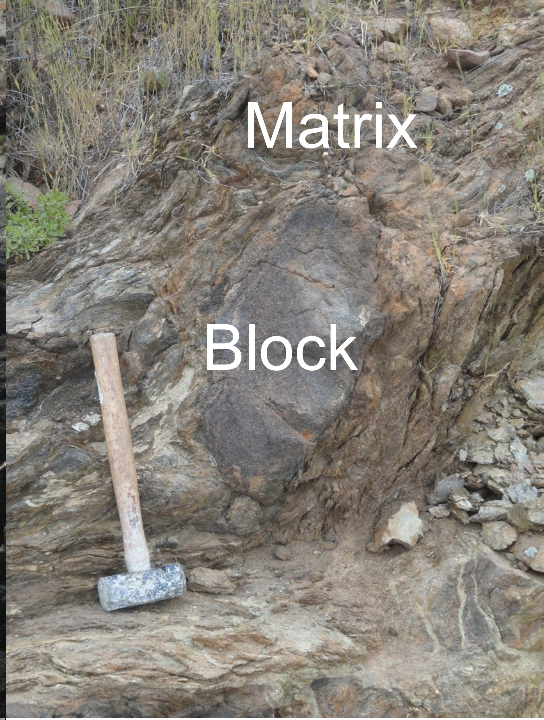
Coherent

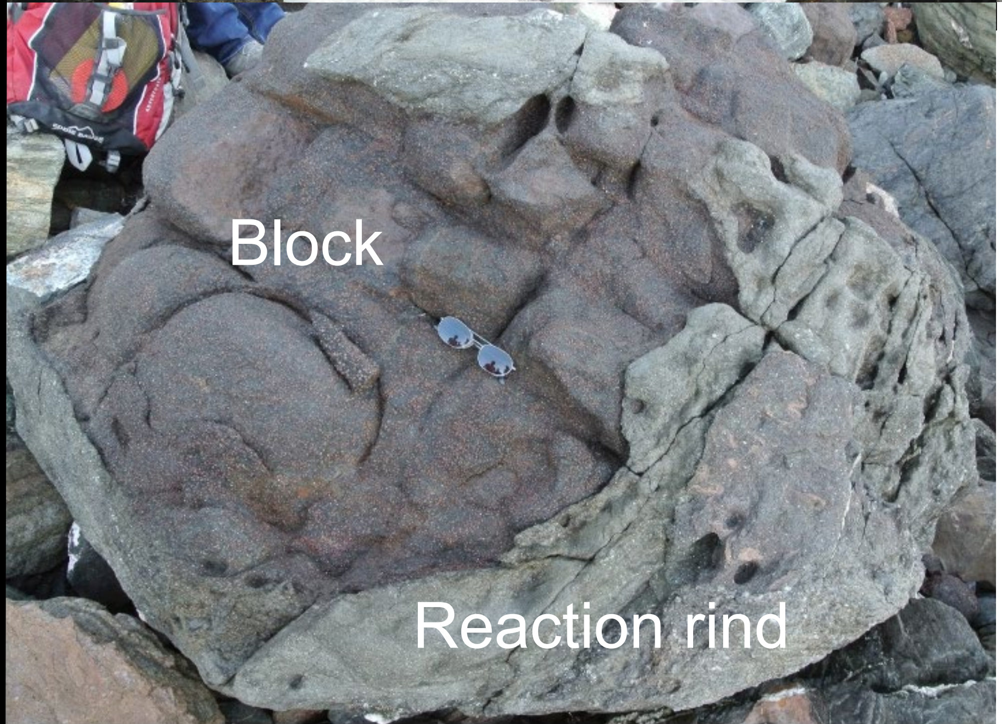


- Continuous lithologic layering
- Contains deformation structures such as foliation, folding and faulting

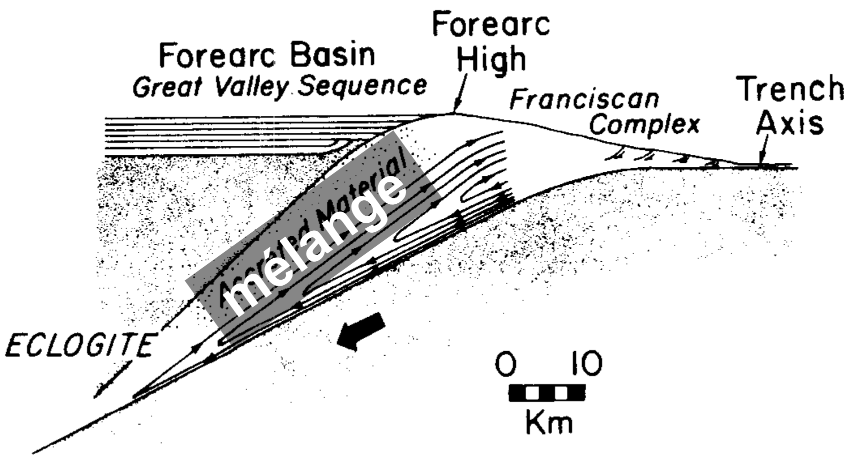
Mélange





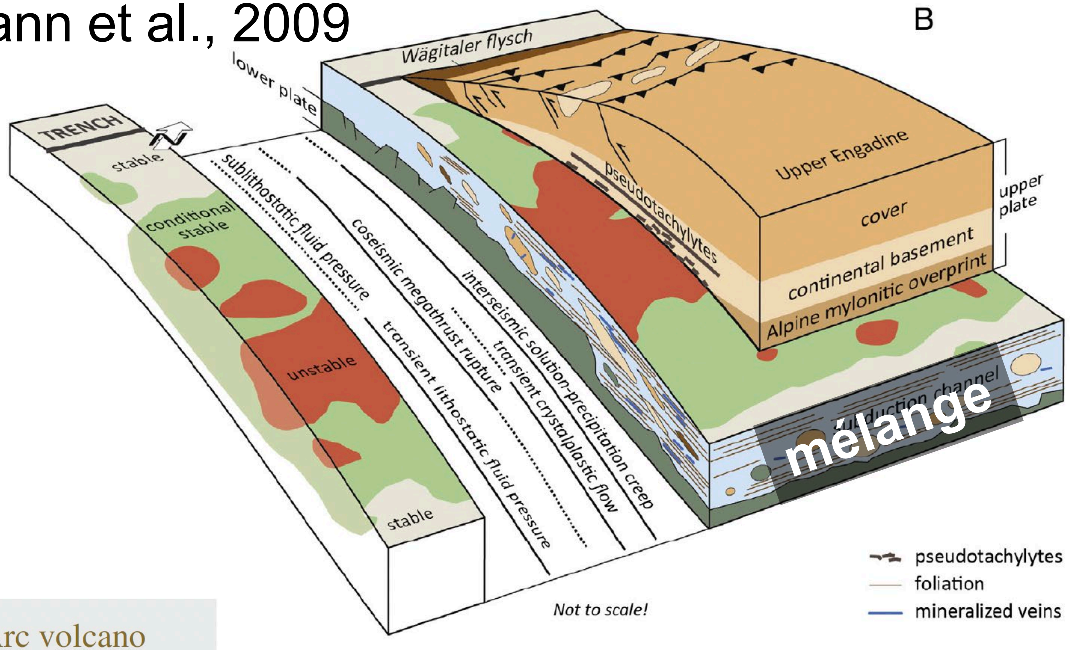


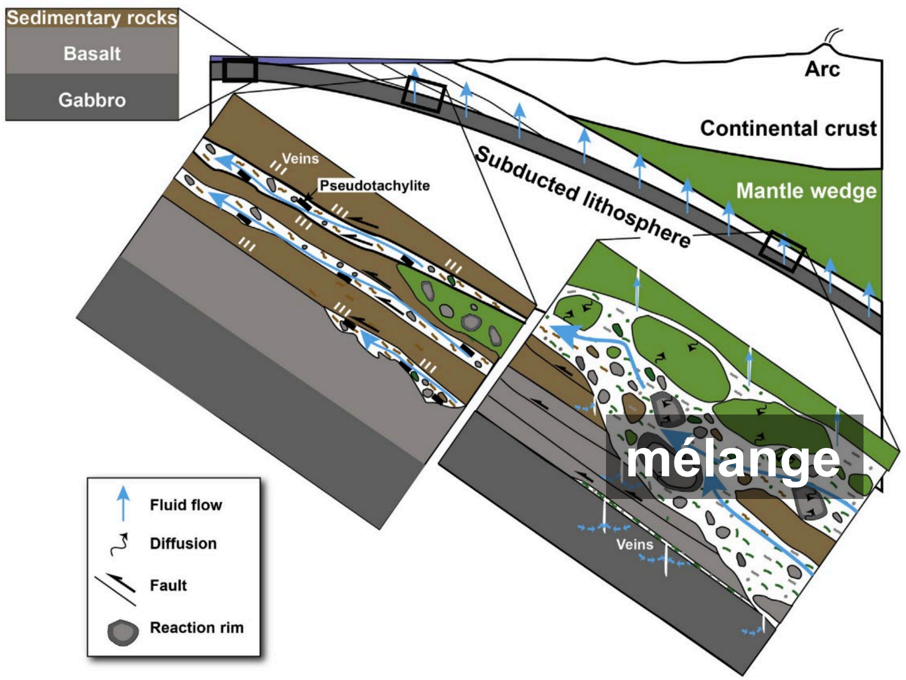
- Block-in-matrix structure
- Foliated matrix; wraps around blocks
- Blocks have reaction rinds



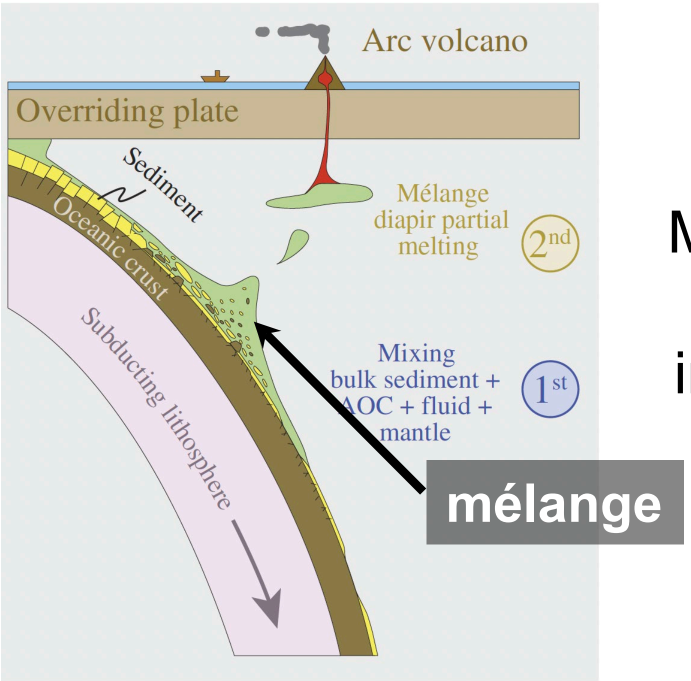
Cloos, 1982

Bachmann et al., 2009





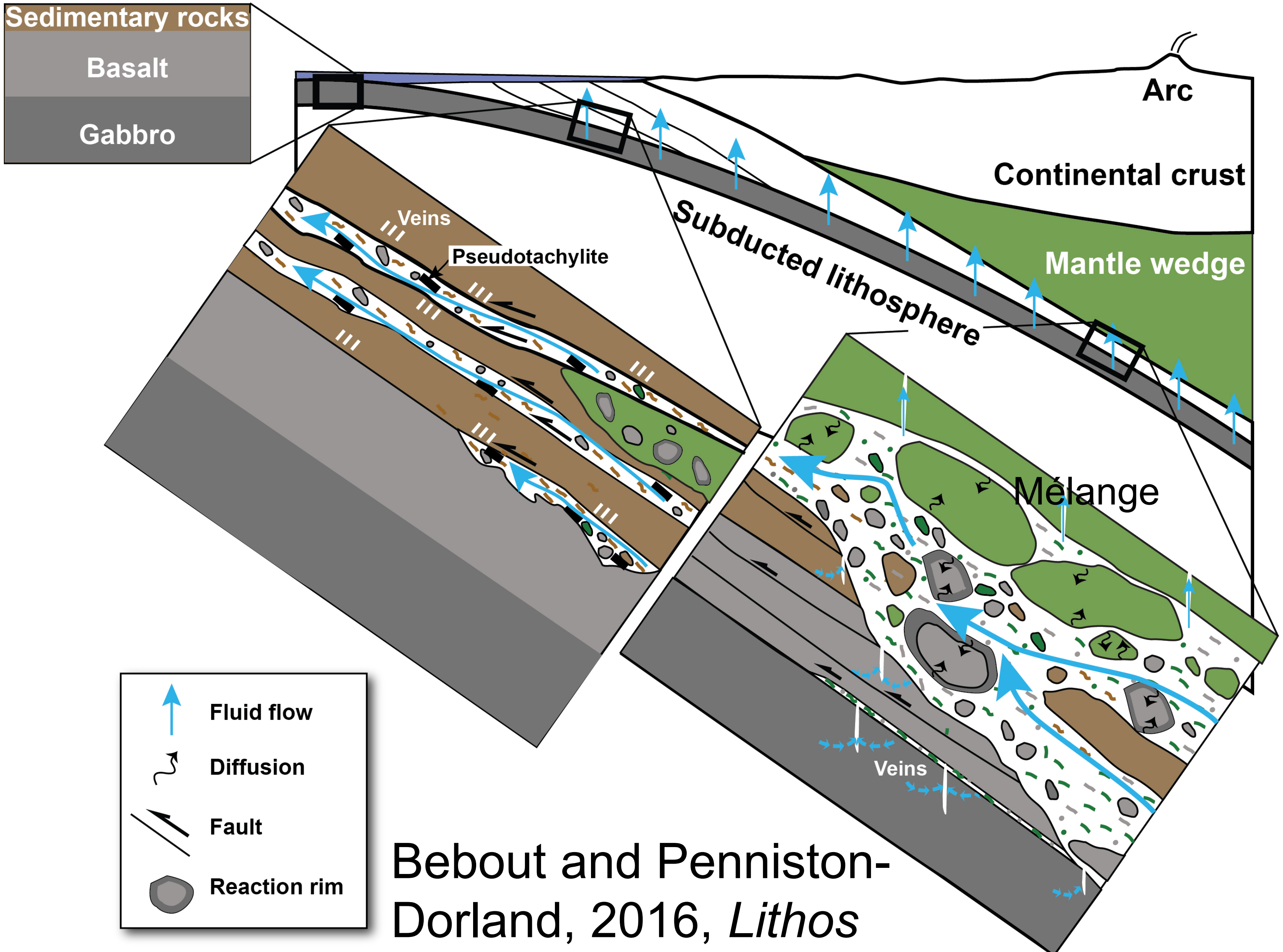
Bebout and Penniston-Dorland, 2016



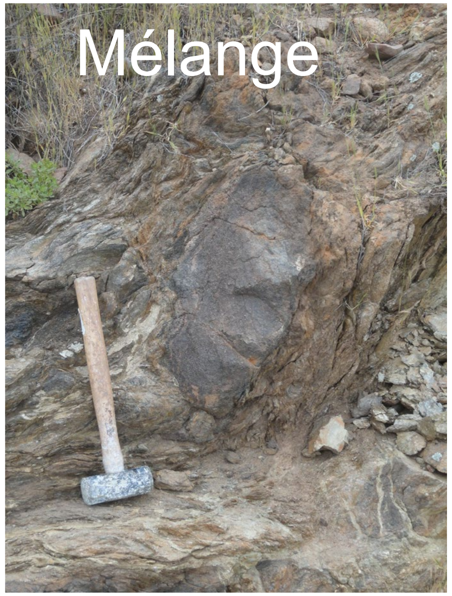
Nielsen and Marschall, 2017

Mélange zones are thought to represent material at the interface between subducting slab and overlying plate.

What does mélange tell us about fluid flow at the subduction interface?

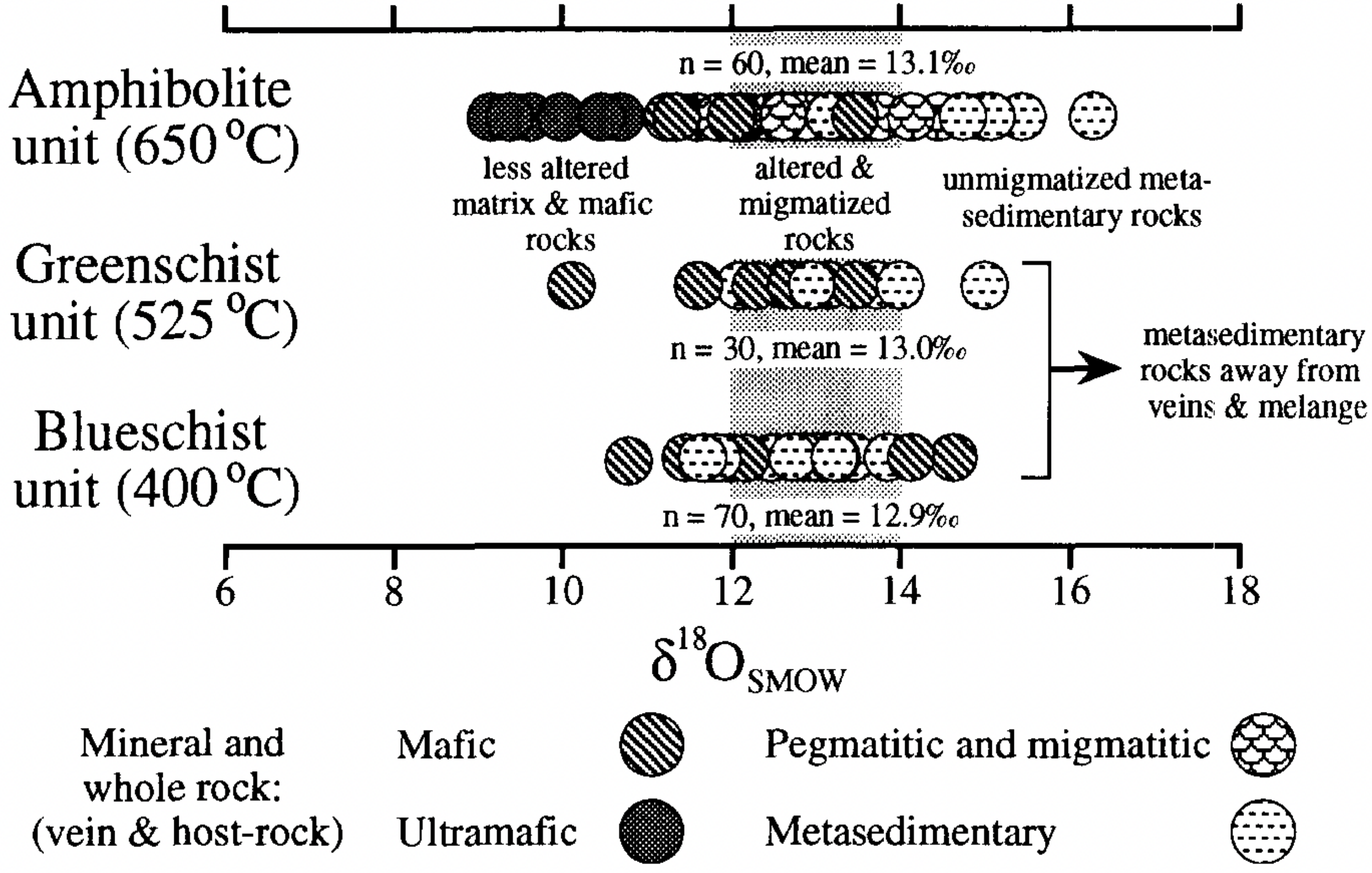


Bebout and Penniston-Dorland, 2016, *Lithos*



Catalina Schist fluids:
Evidence for large-scale fluid infiltration through mélange

Sedimentary-derived fluid ($\delta^{18}O$=13‰)



Amphibolite facies blocks are mostly mafic and ultramafic

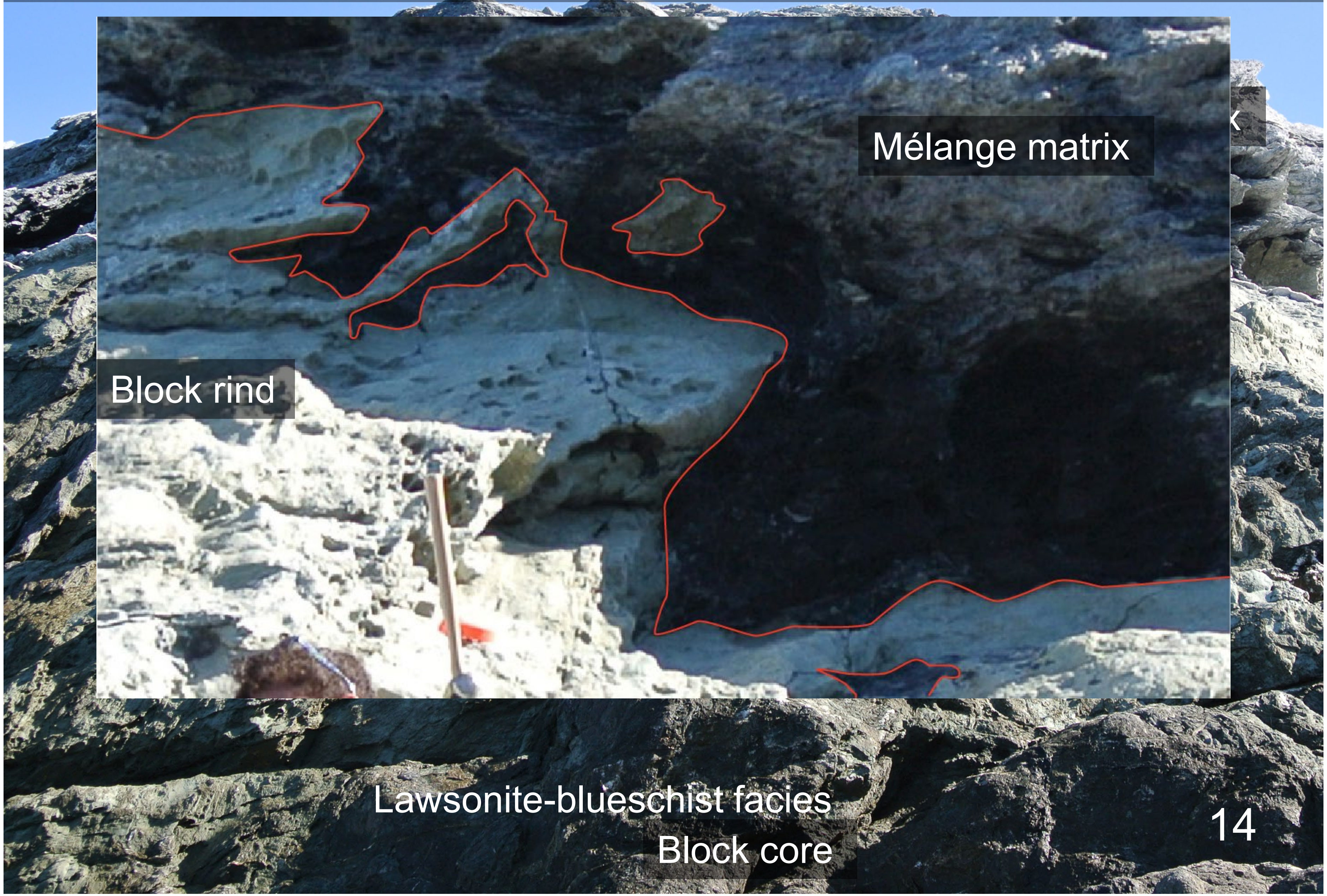
Reaction rinds have interacted with fluids!

Bebout and Barton, 1989; 1993; Bebout 1991

Mechanical mixing

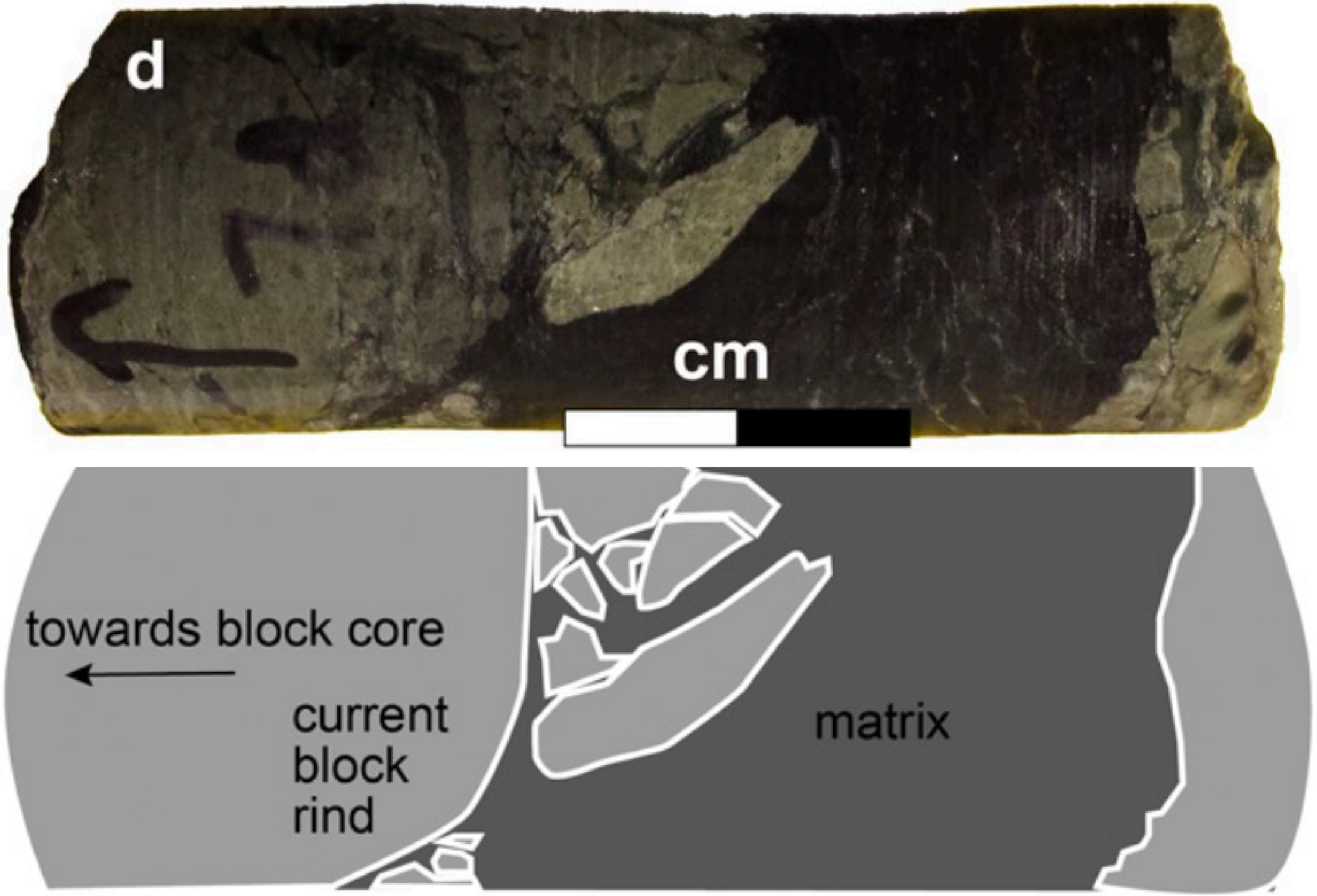
Evidence for mechanical mixing of materials at block-matrix interface

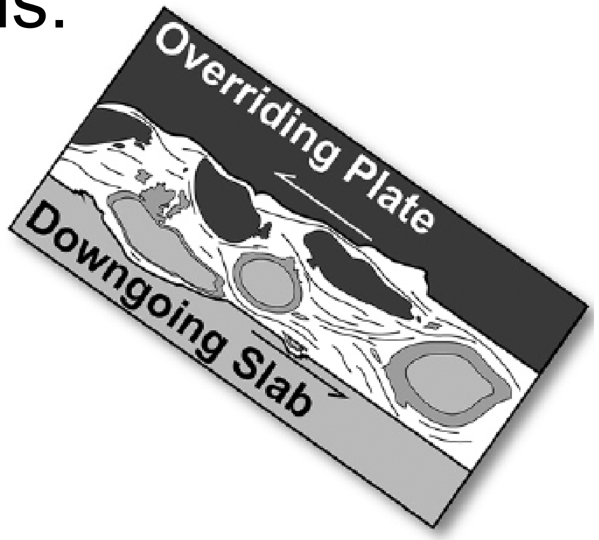
Reaction rind and matrix formation



Reaction rind and matrix formation

- Blocks form reaction rinds due to fluid flow and mechanical disaggregation followed by recrystallization.
- Over time, mélange matrix forms from mixing of materials disaggregated from reaction rinds.

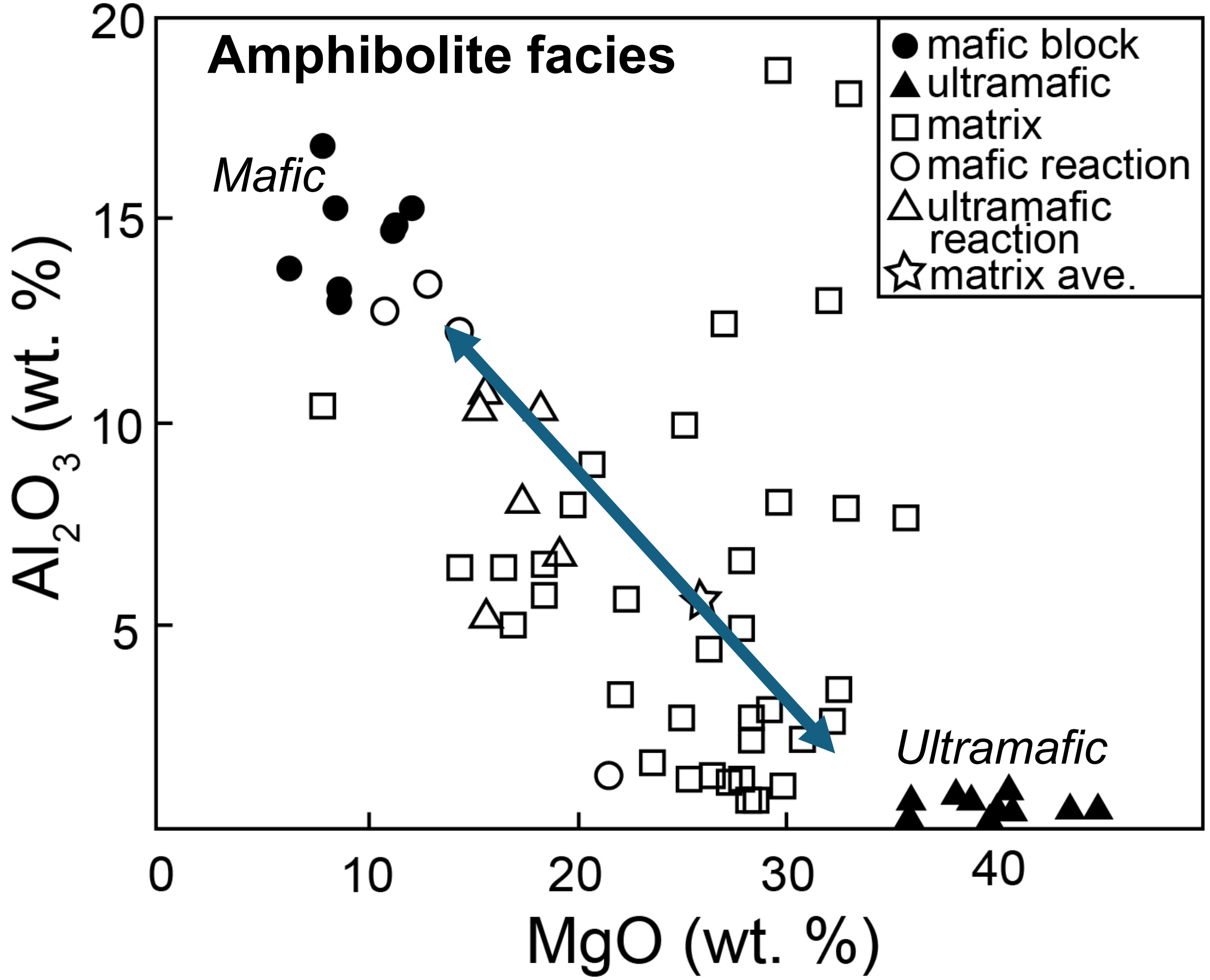




Lawsonite albite facies

Penniston-Dorland et al., 2014

Mechanical mixing changes chemistry



Amphibolite facies mélange is mostly mafic and ultramafic blocks surrounded by matrix.

Immobile element concentrations of *mélange matrix* and *reaction rinds* document mechanical mixing of materials derived from mafic and ultramafic blocks.

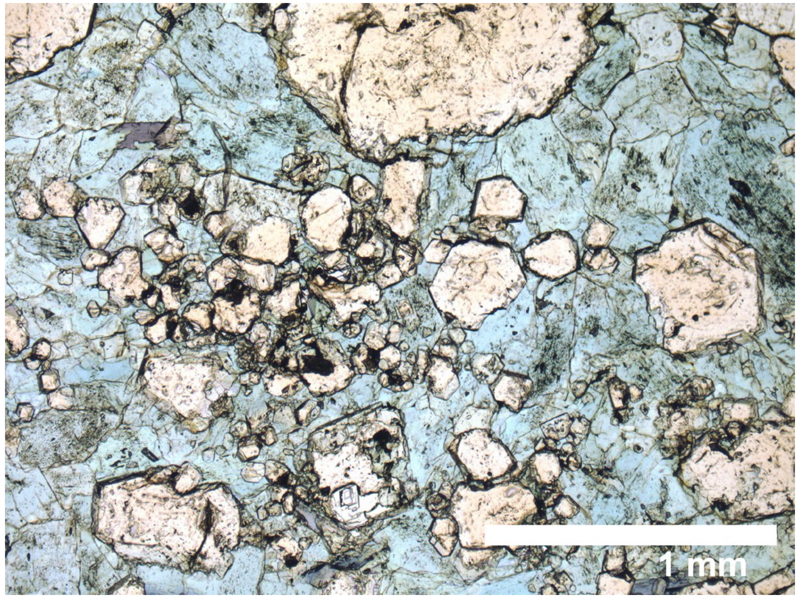
Both matrix and reaction rinds fall in between mafic and ultramafic blocks in concentrations of fluid-immobile elements: MgO, Cr, Ni, HSE, Al_2O_3, TiO_2, and Zr.

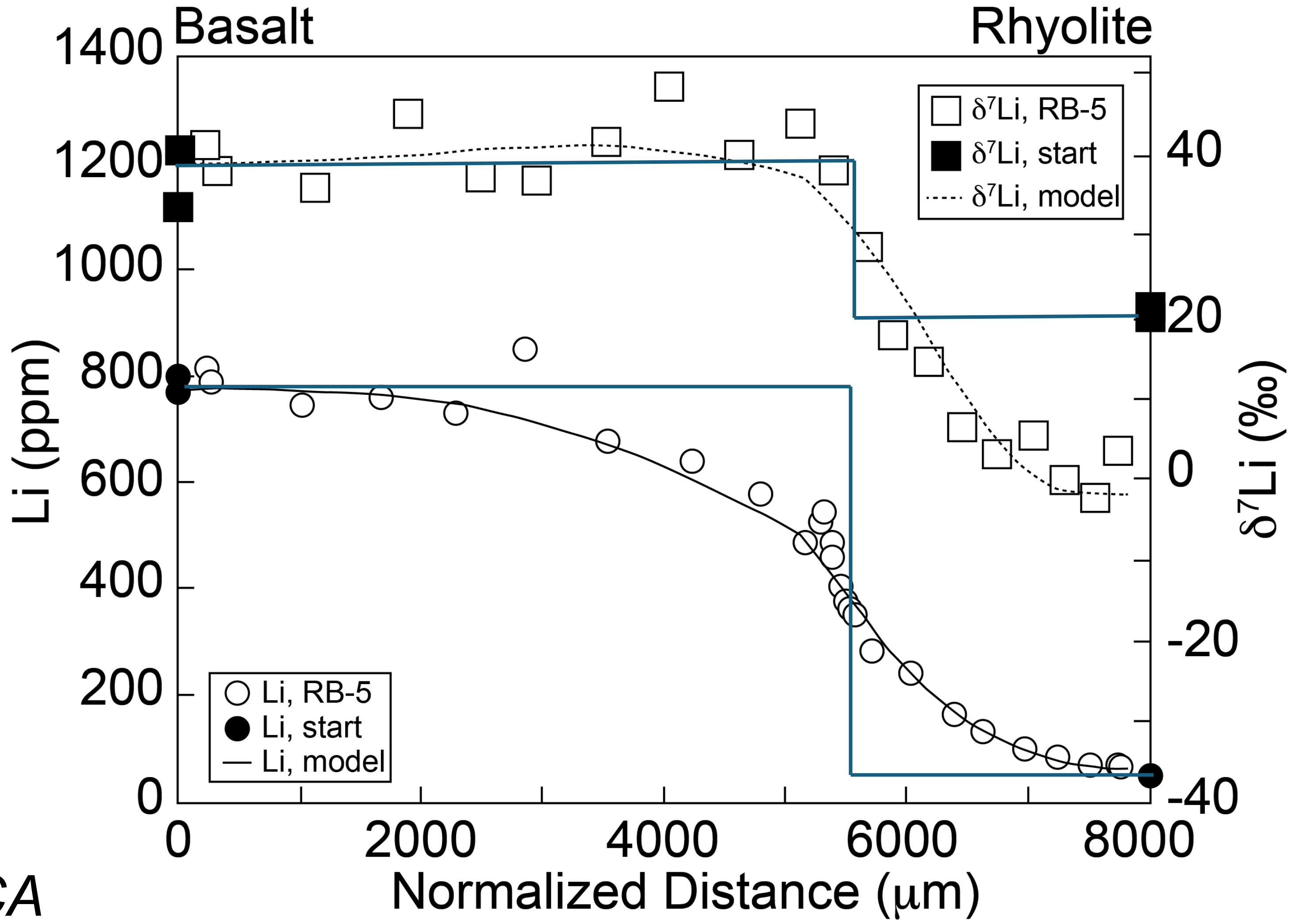
Bebout and Barton, 2002

^{7}Li Lithium ^{6}Li

$$\delta^7 Li = \left(\frac{{}^7Li/{}^6Li_{sample} - {}^7Li/{}^6Li_{L-SVEC}}{{}^7Li/{}^6Li_{L-SVEC}} \right) \times 1000$$

- Li is a fluid mobile element
- Lithium diffuses rapidly and its isotopes can fractionate during diffusion





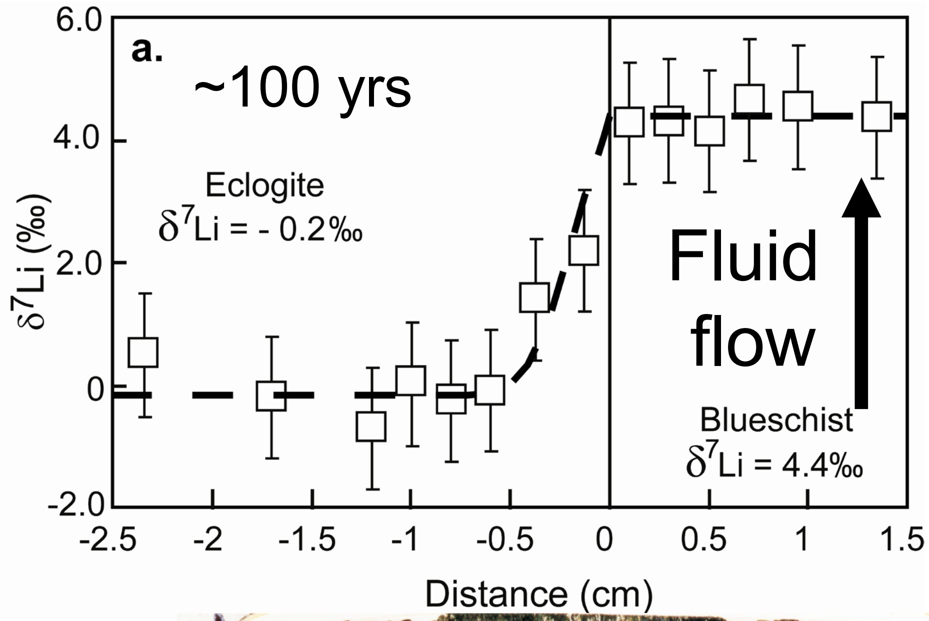
Richter et al., 2003, *GCA*

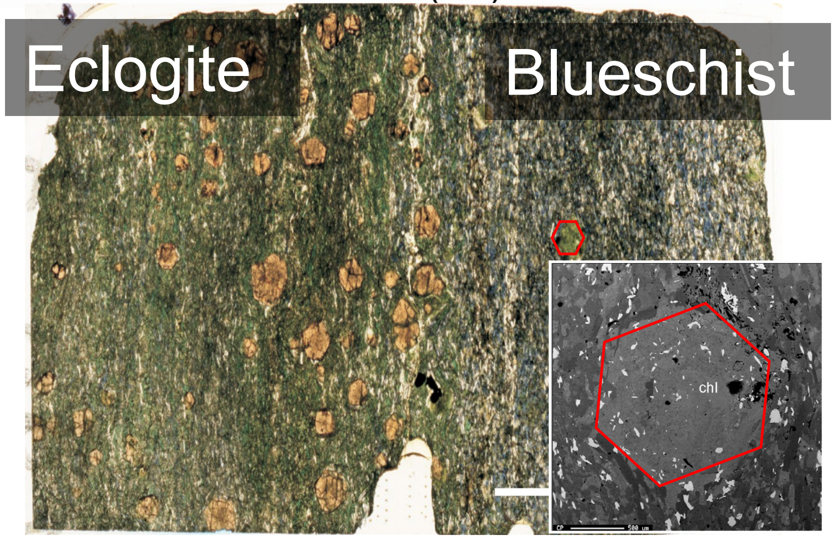
Bulk-rock Li and ™7Li

- Fluid travels through rock in fractures (veins) or within rock porosity

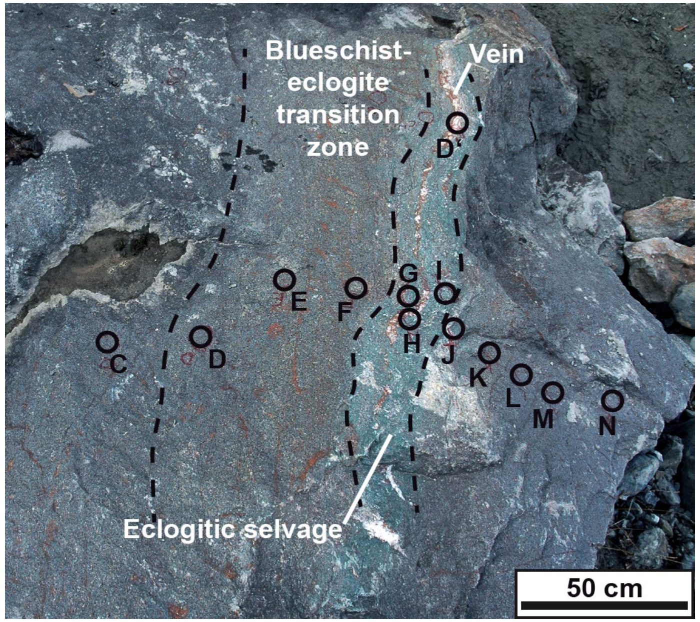
- Li diffuses through intergranular fluid

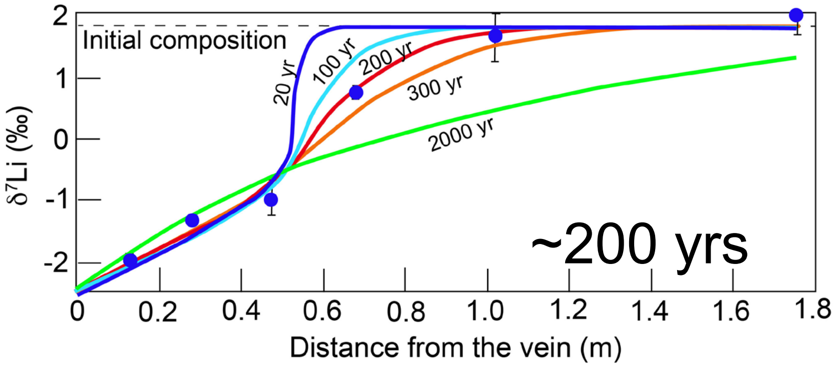
- Duration of fluid pulses (weeks to hundreds of years!)





Penniston-Dorland et al., 2010, *EPSL*



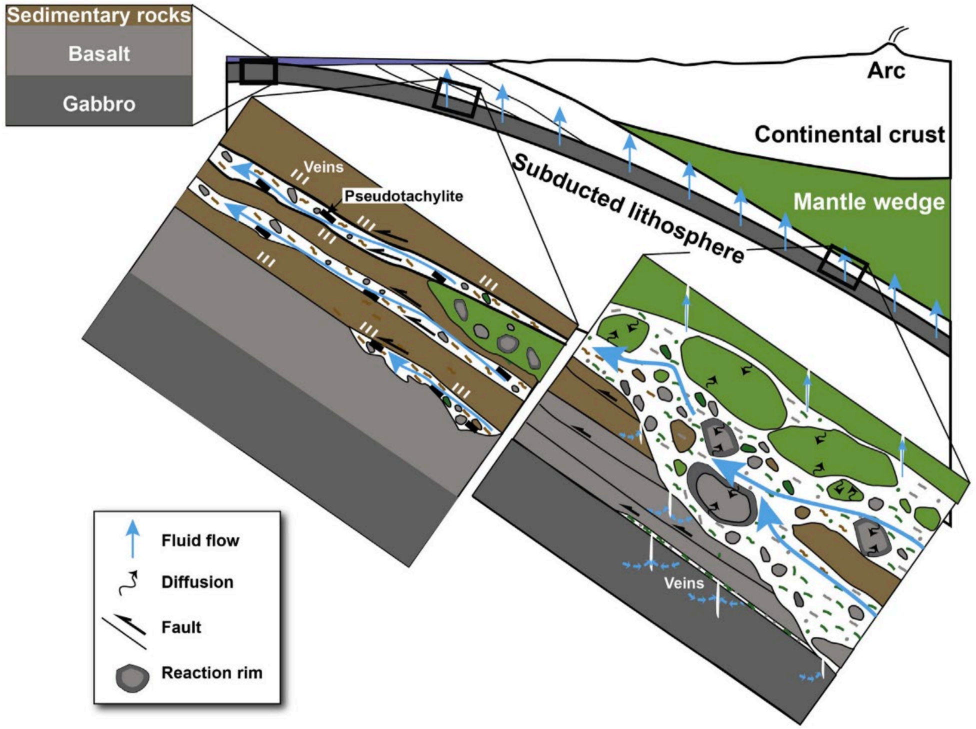


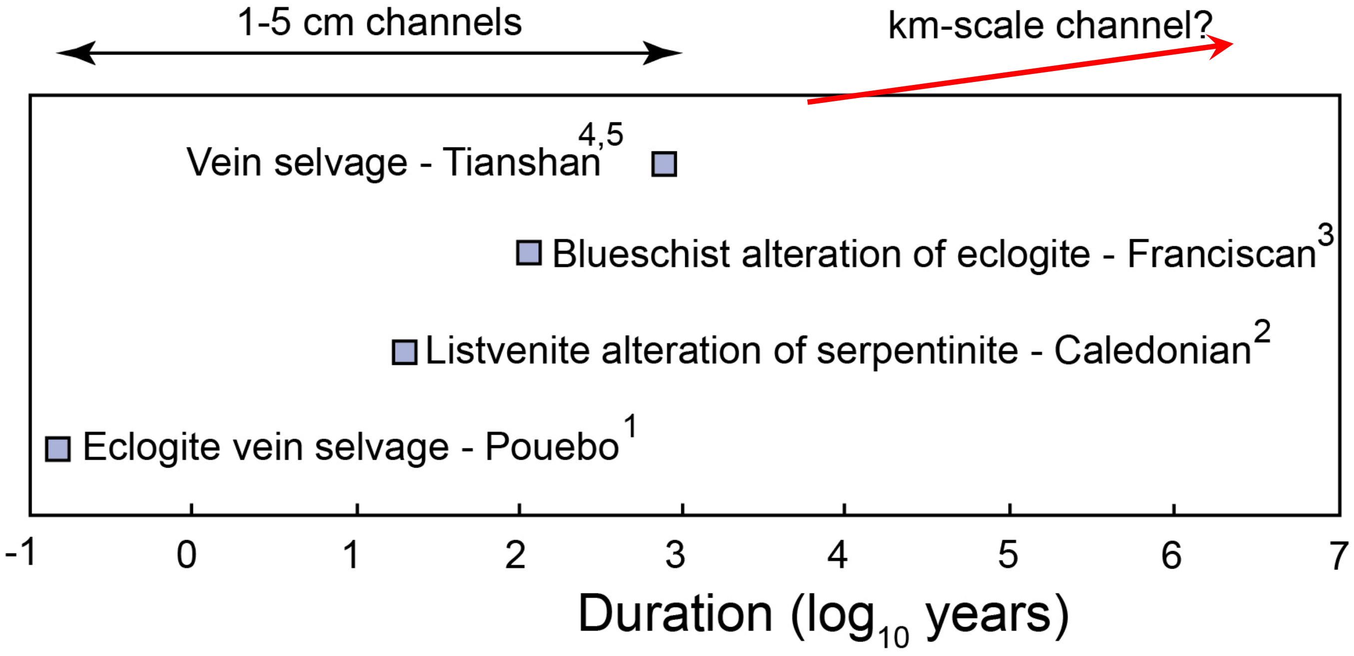
John et al., 2012, *Nat. Geoscience*

Timescales of fluid movement

- 10 days to hundreds of years for cm-scale features
  - Short timescales = seismicity?
  - Single events or multiple?
  - Would larger-scale flow exhibit longer durations?

What is the duration of fluid transport at the subduction interface?





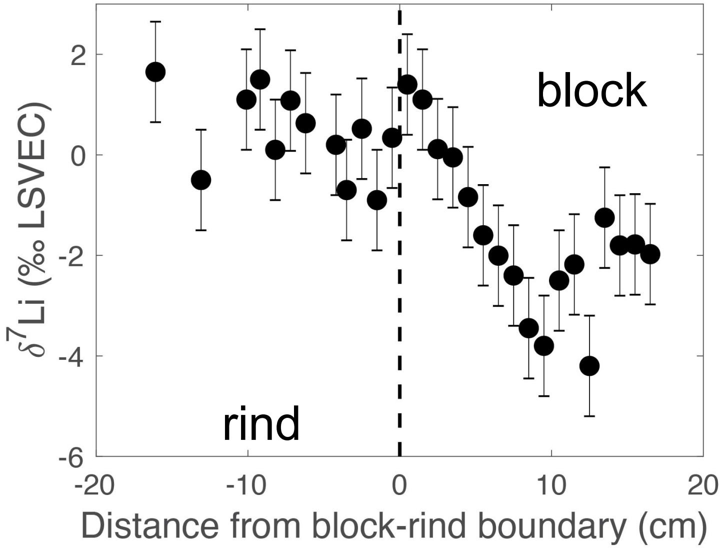
[1,5]Taetz et al., 2018, [2]Smit and Pogge von Strandmann, 2020; [3]Penniston-Dorland et al., 2010; [4]John et al., 2012

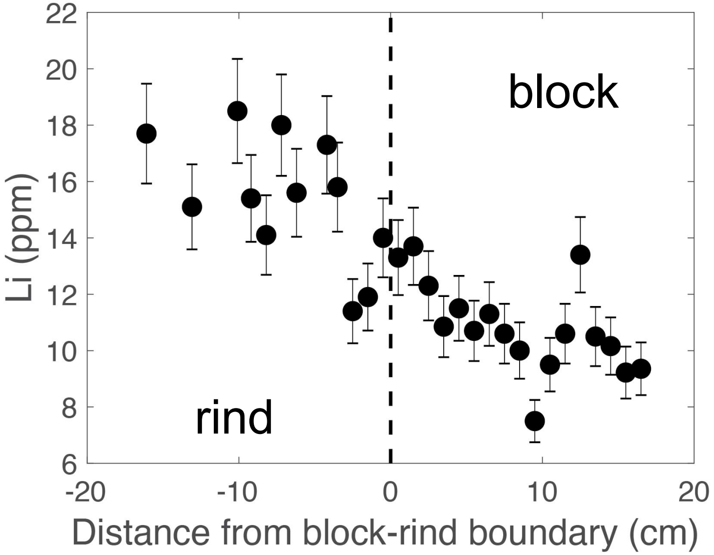
Li concentration and δ^7Li

- Li isotope transects of 2 block-rind pairs

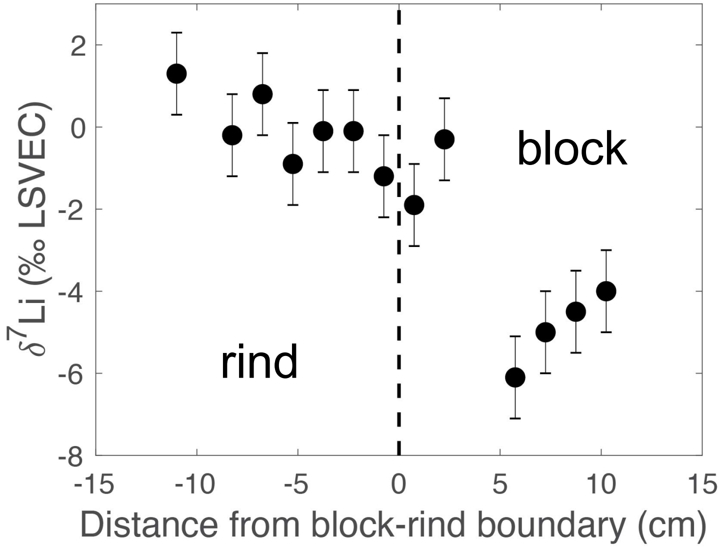
Hoover et al., *in prep*

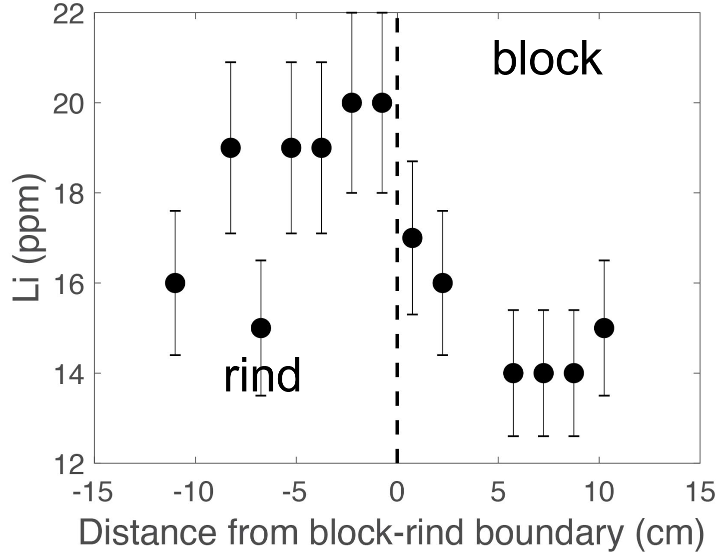
A10-3





A12-4

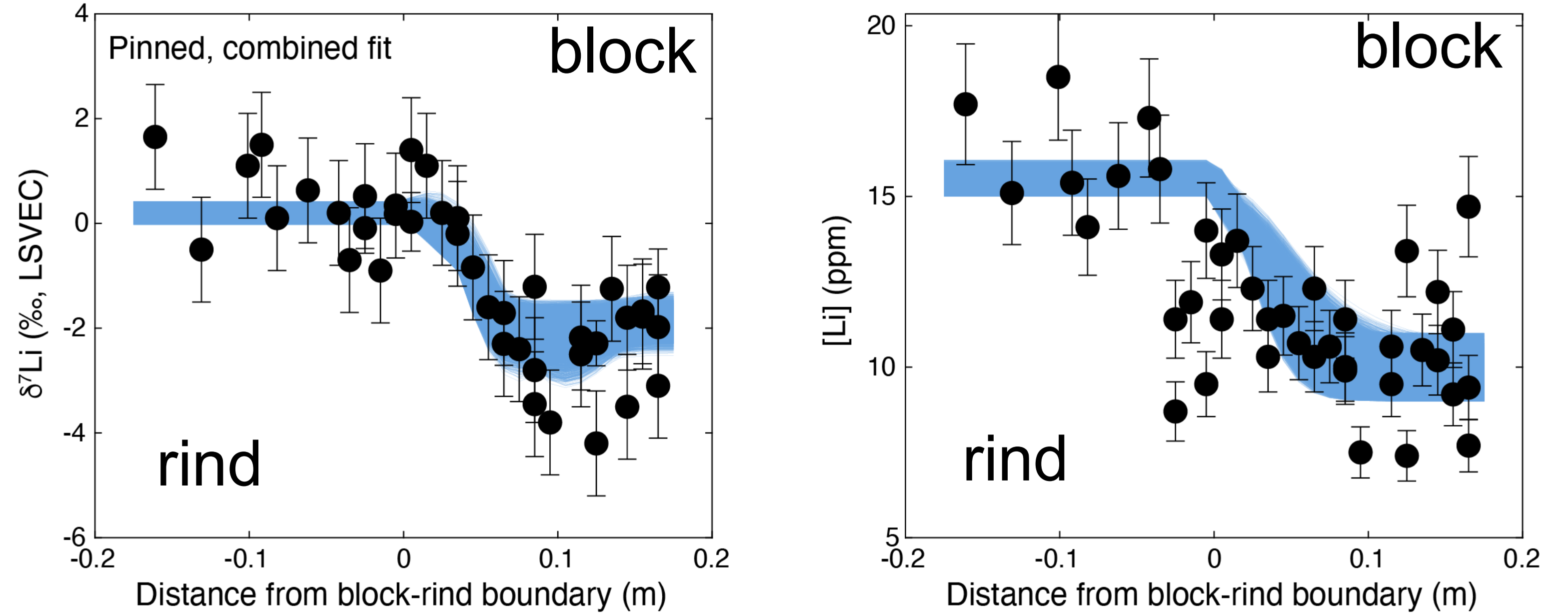




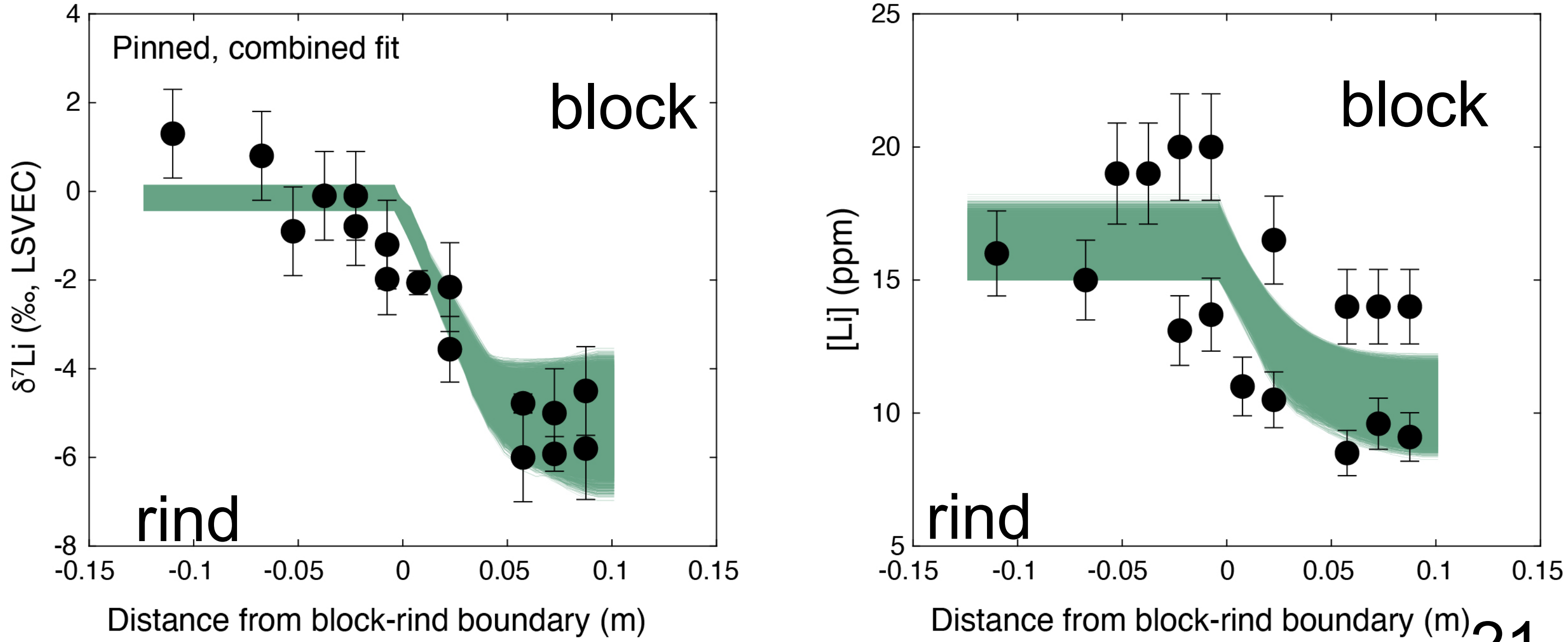
Diffusion model

- Bulk Li advection-diffusion model
- Monte Carlo estimate of uncertainty

A10-3



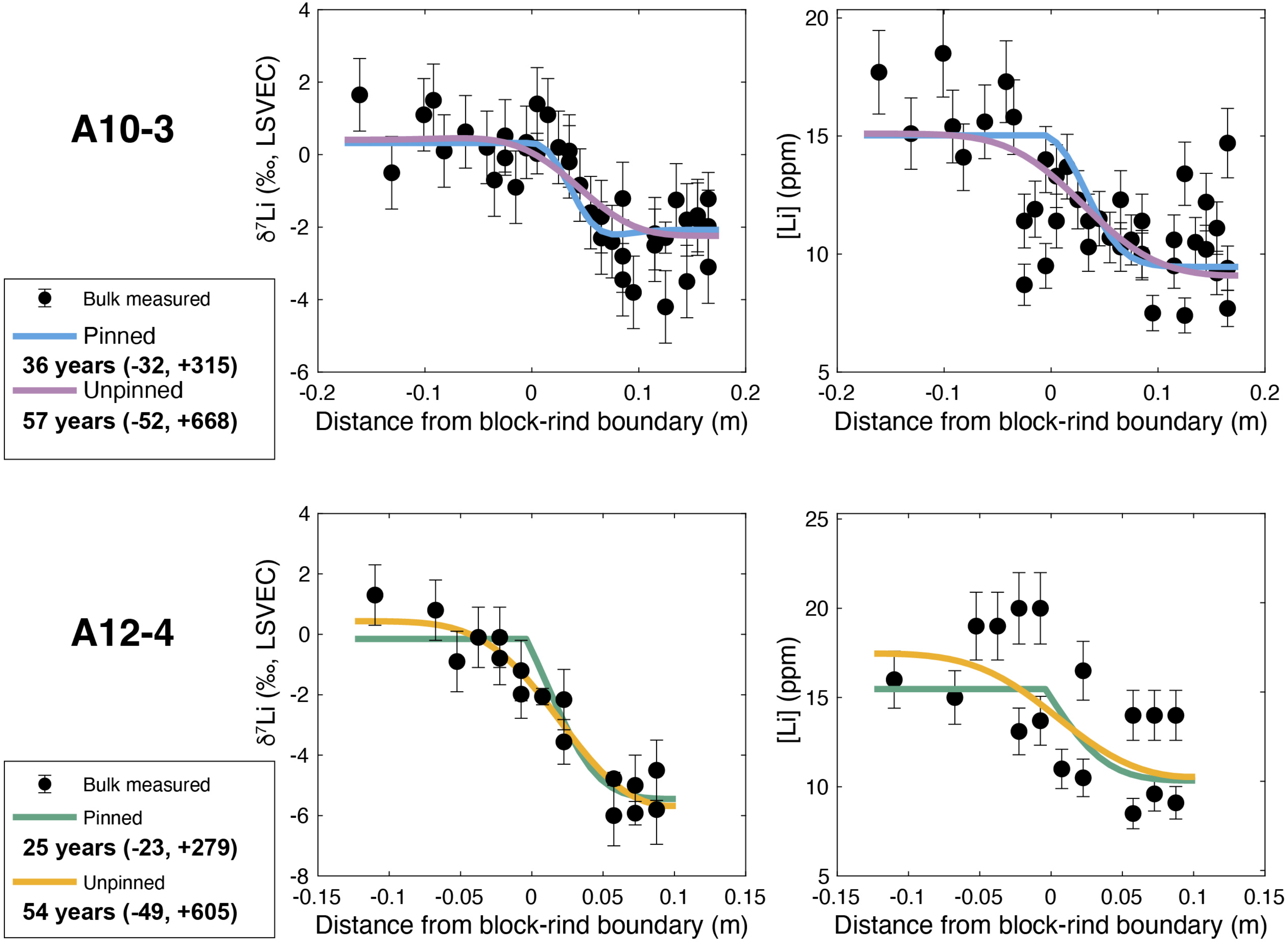
A12-4



Hoover et al., *in prep*

Fluid transport duration

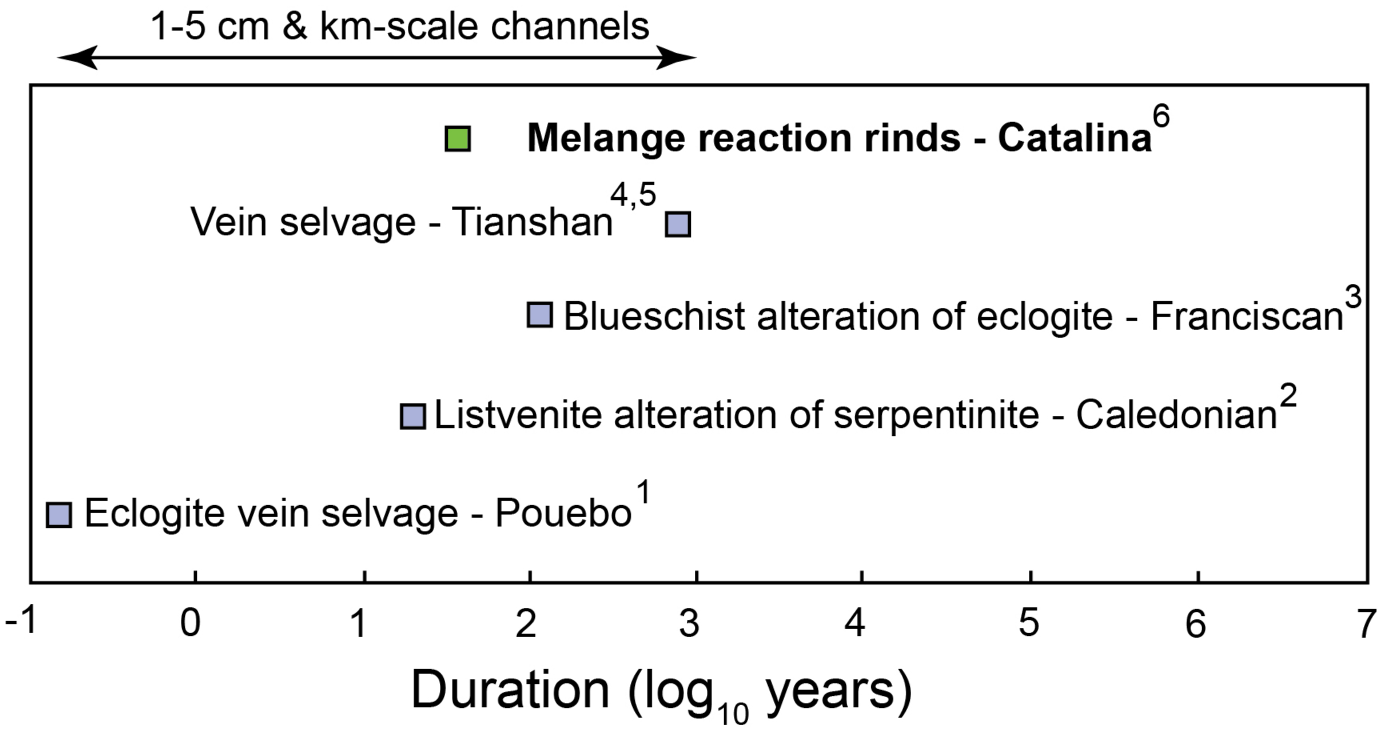
- ~40 years of fluid transport within the mélange matrix
  - 2 to 725 years (±2 SD)
- Overlapping timescales between blocks
  - Regionally-pervasive fluid transport

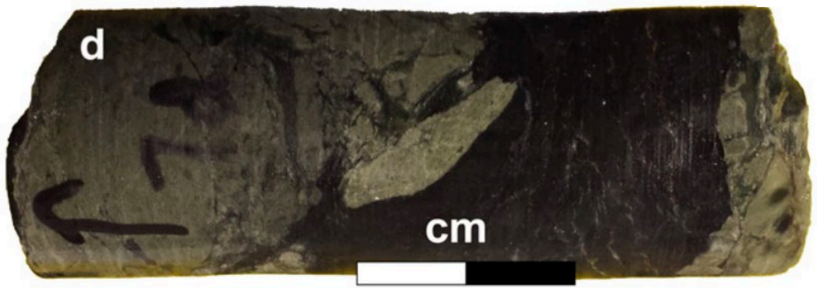


Hoover et al., *in prep*

Conceptual model

- Duration at subduction interface not any longer than cm-scale veins
- 40 years << subduction to 50km depth
- Diffusion profiles develop → Mechanical aspect of rind formation destroys profiles



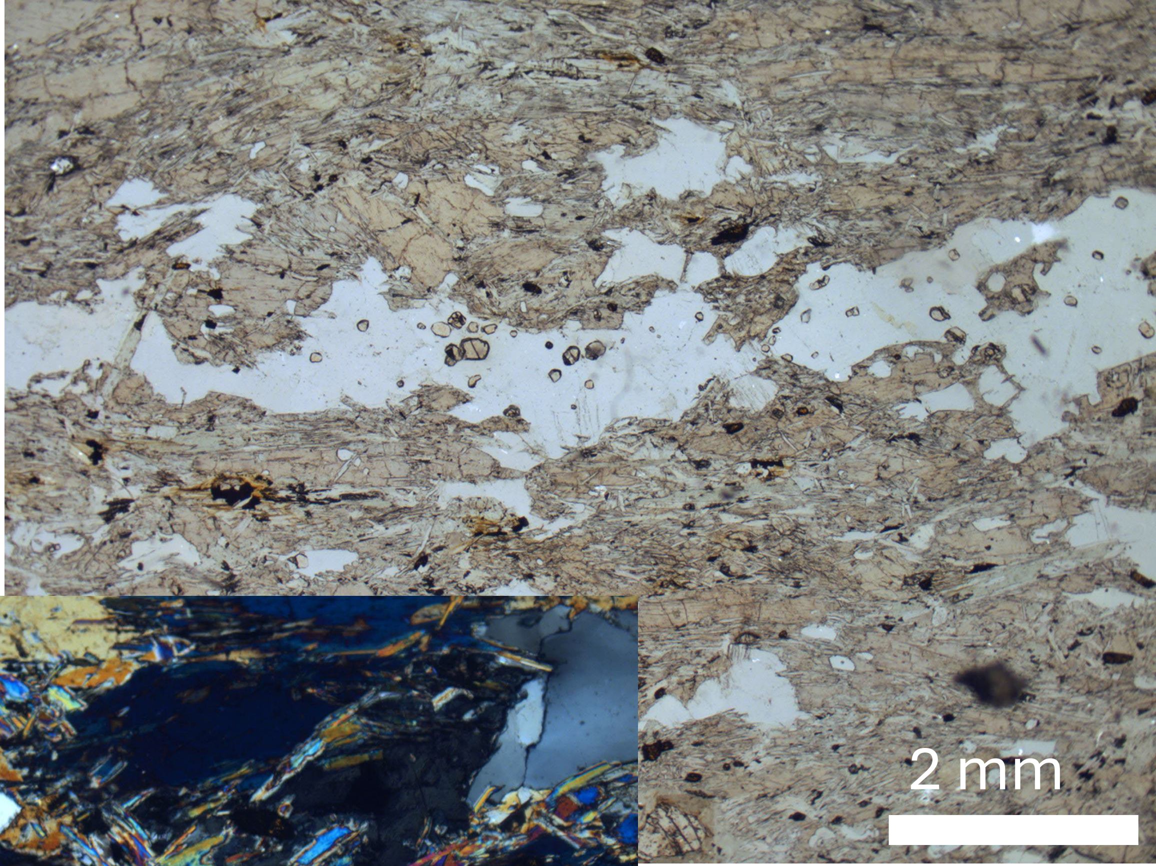


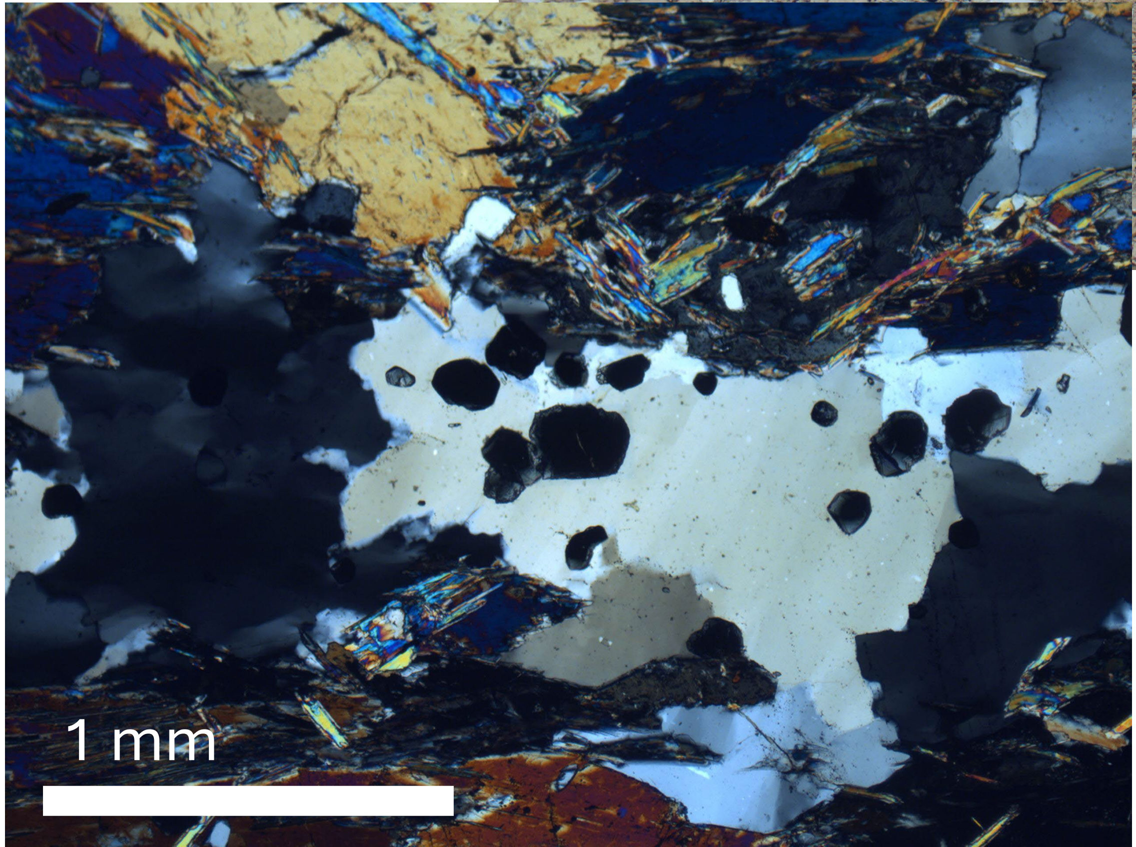
[1,5]Taetz et al., 2018, [2]Smit and Pogge von Strandmann, 2020; [3]Penniston-Dorland et al., 2010; [4]John et al., 2012; [6]This study, Hoover et al., *in prep*

Rind veining

- Quartz + garnet veins
  - Peak metamorphic conditions

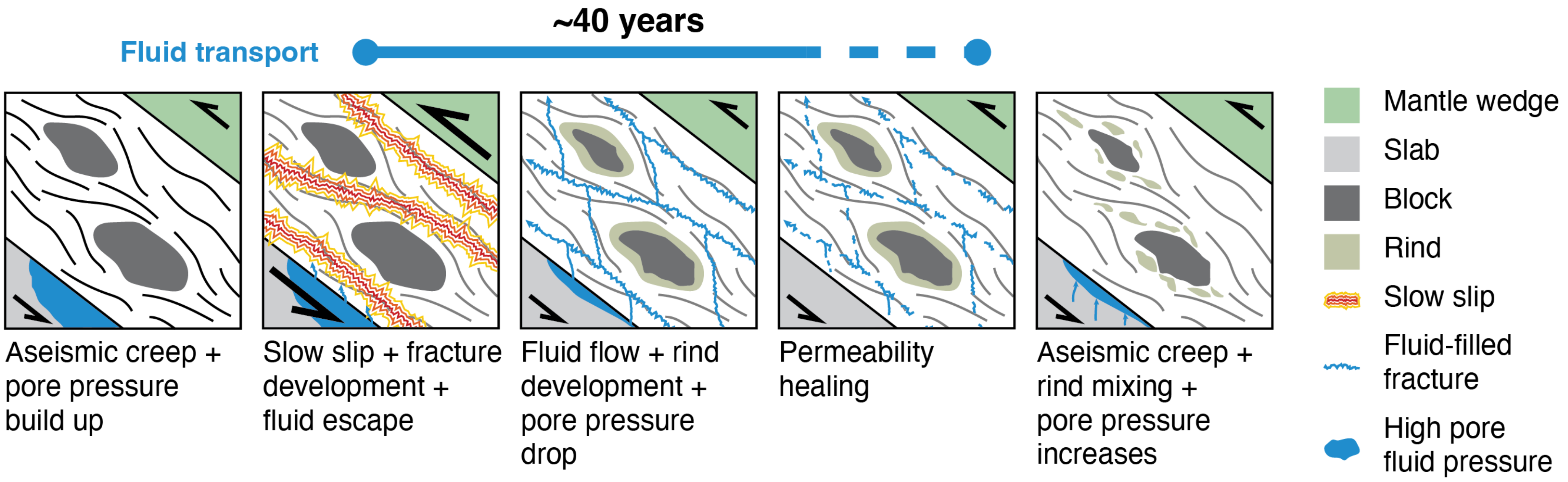
- Fracturing





Single or multiple events?

- Fault-valve/fluid pressure cycling model e.g., Sibson, 1992

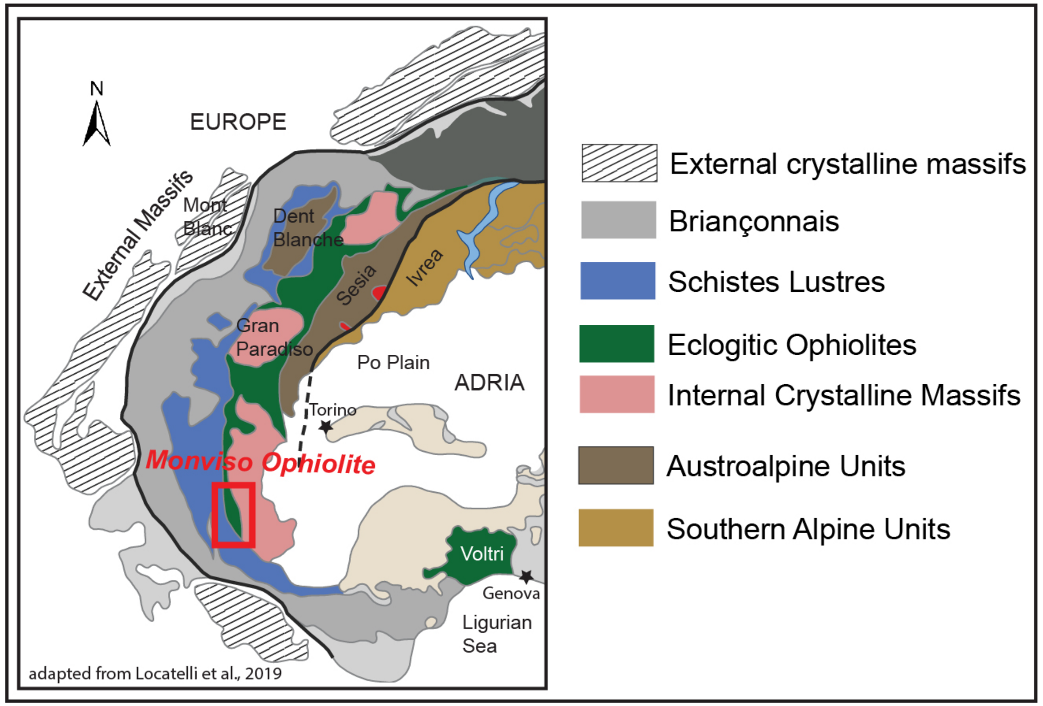


- 40 years =
  - the permeability lifetime of one cycle?
  - the integration of many cycles of seismicity and healing?

How episodic is fluid flow?

Episodic fluid flow

In situ Li isotopes in garnet → episodic fluid transport

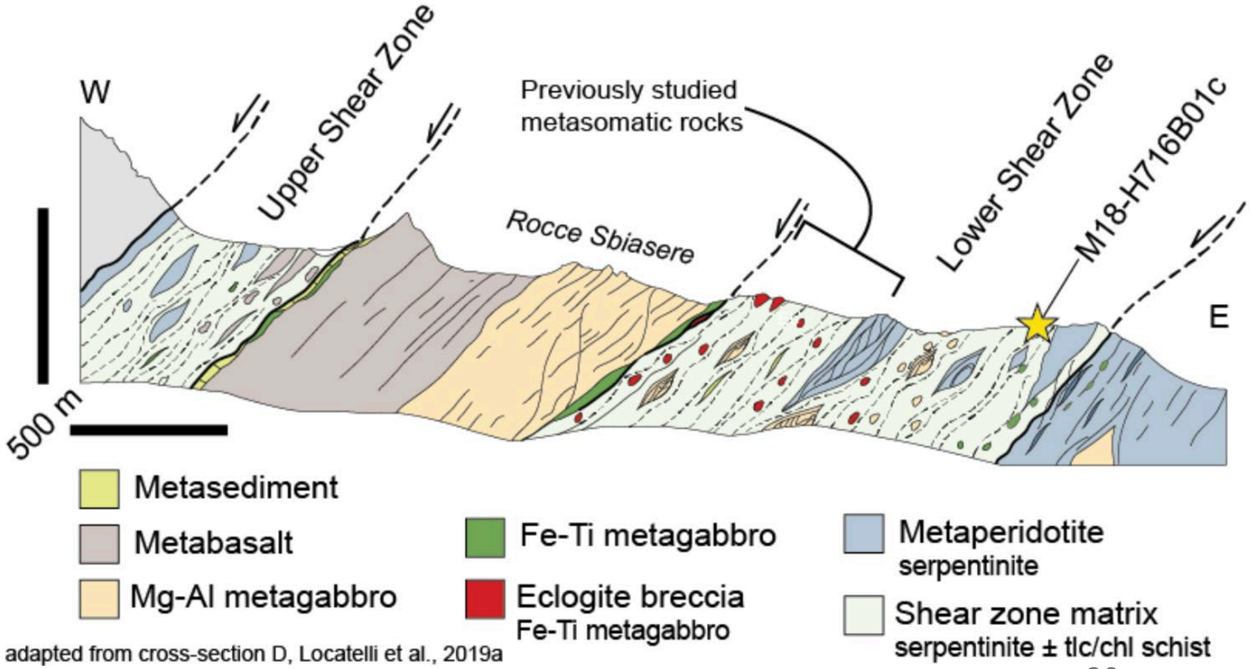


Monviso Ophiolite

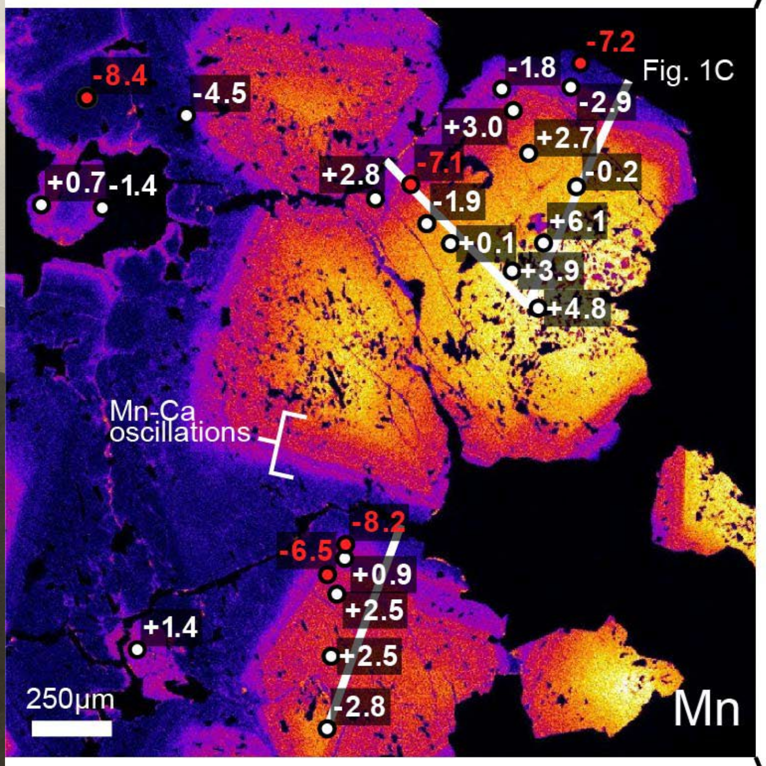
Western Alps

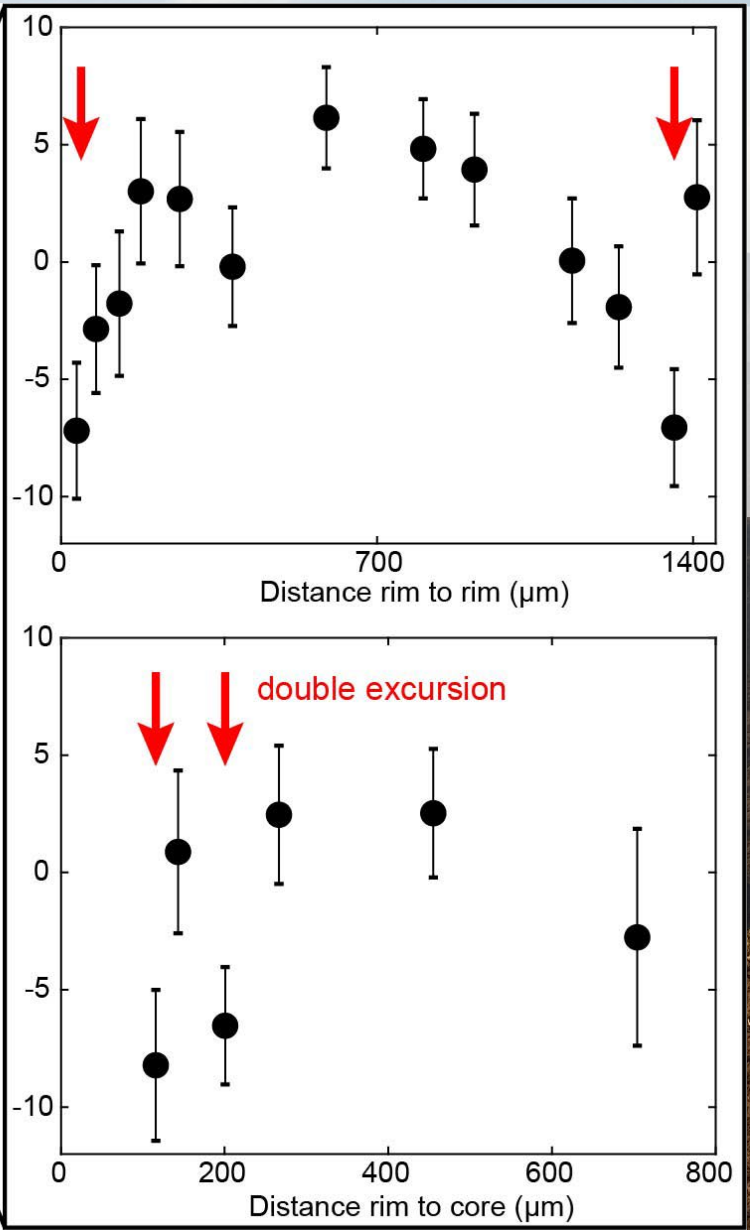
High-grade block in shear zone

550ºC, 2.6–2.7 GPa



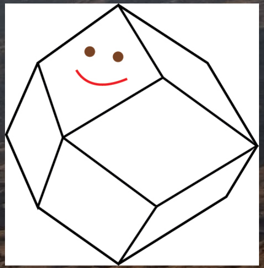
Hoover et al., 2022





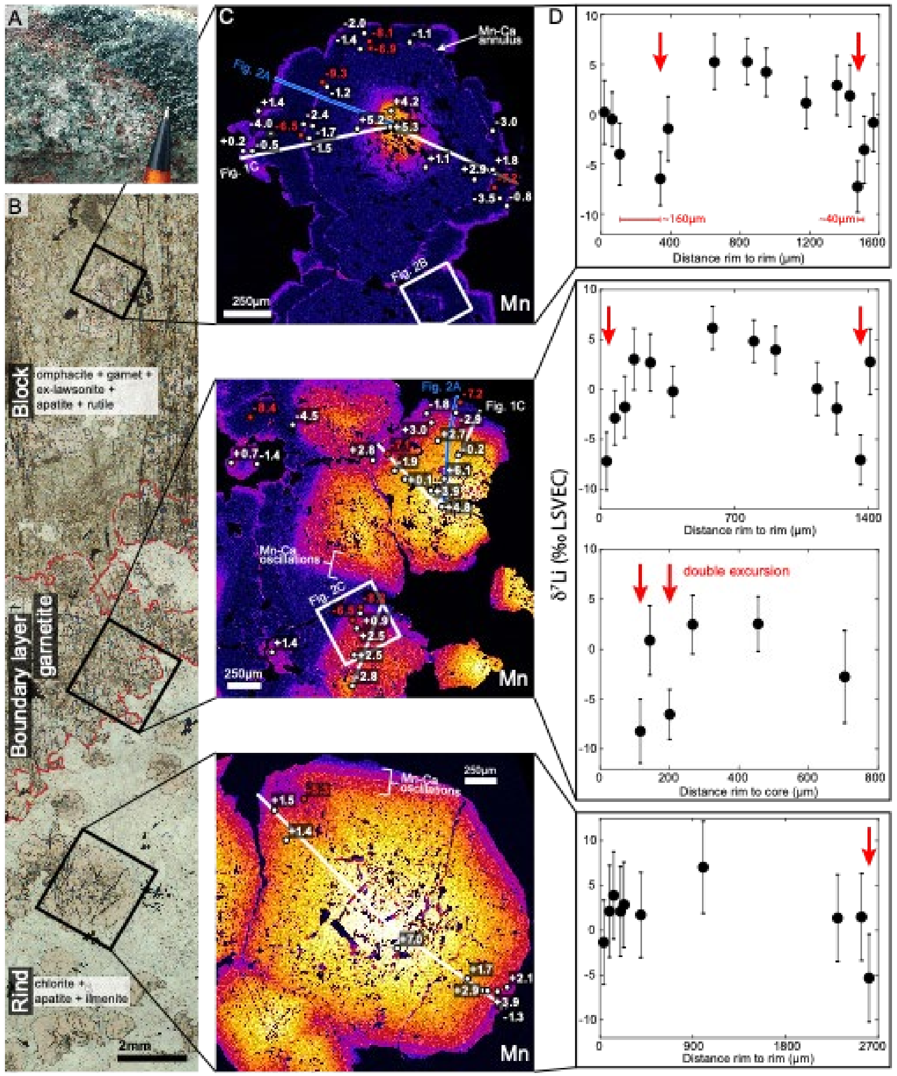
Episodic fluid flow

In situ Li isotopes in garnet → episodic fluid transport



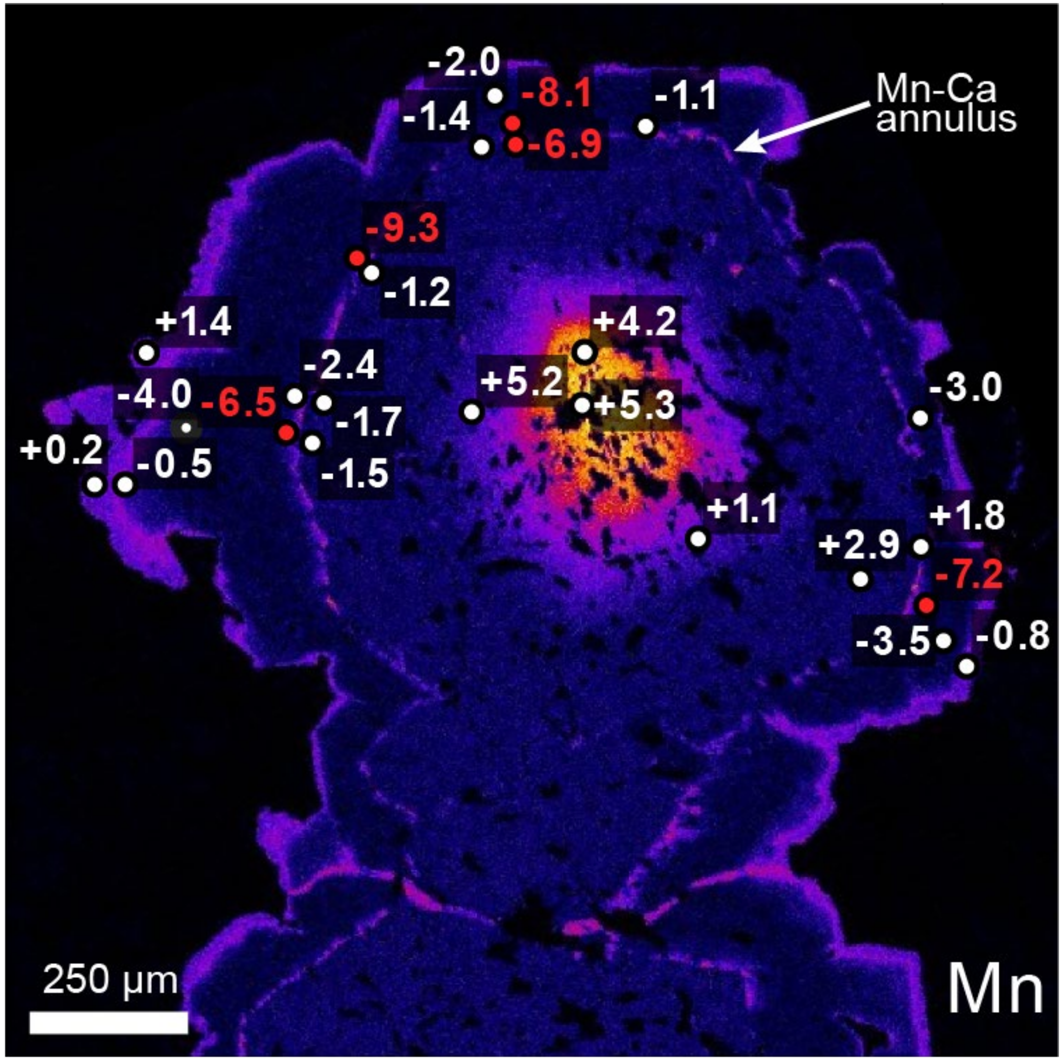
Monviso Ophiolite

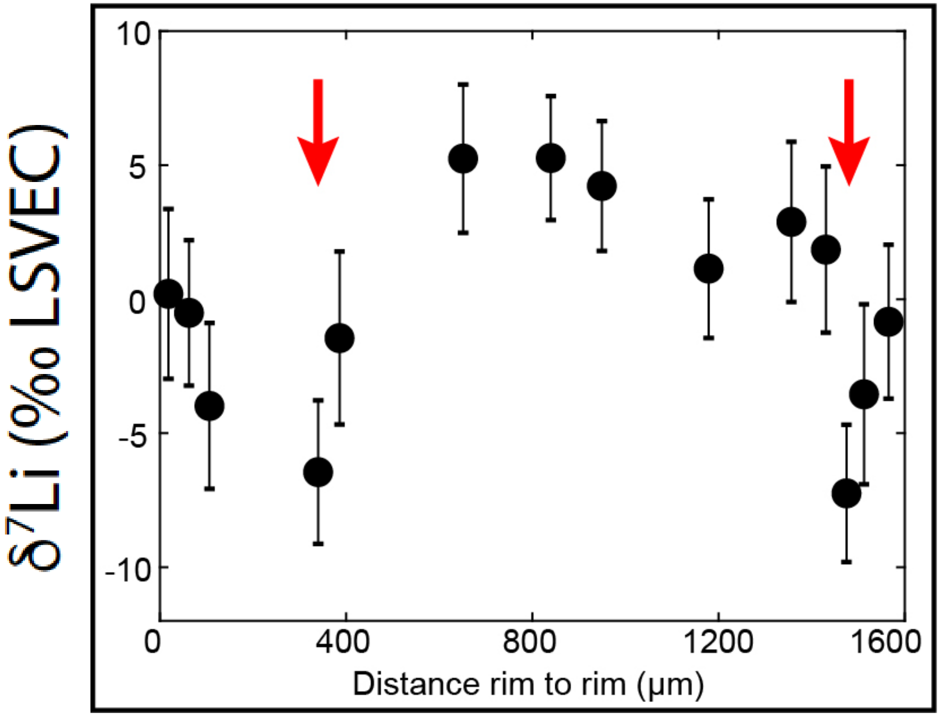
Reaction rind wrapping around eclogite block in a high-pressure ultramafic shear zone



Monviso Ophiolite

High-grade blocks in shear zone
Garnet from block interior



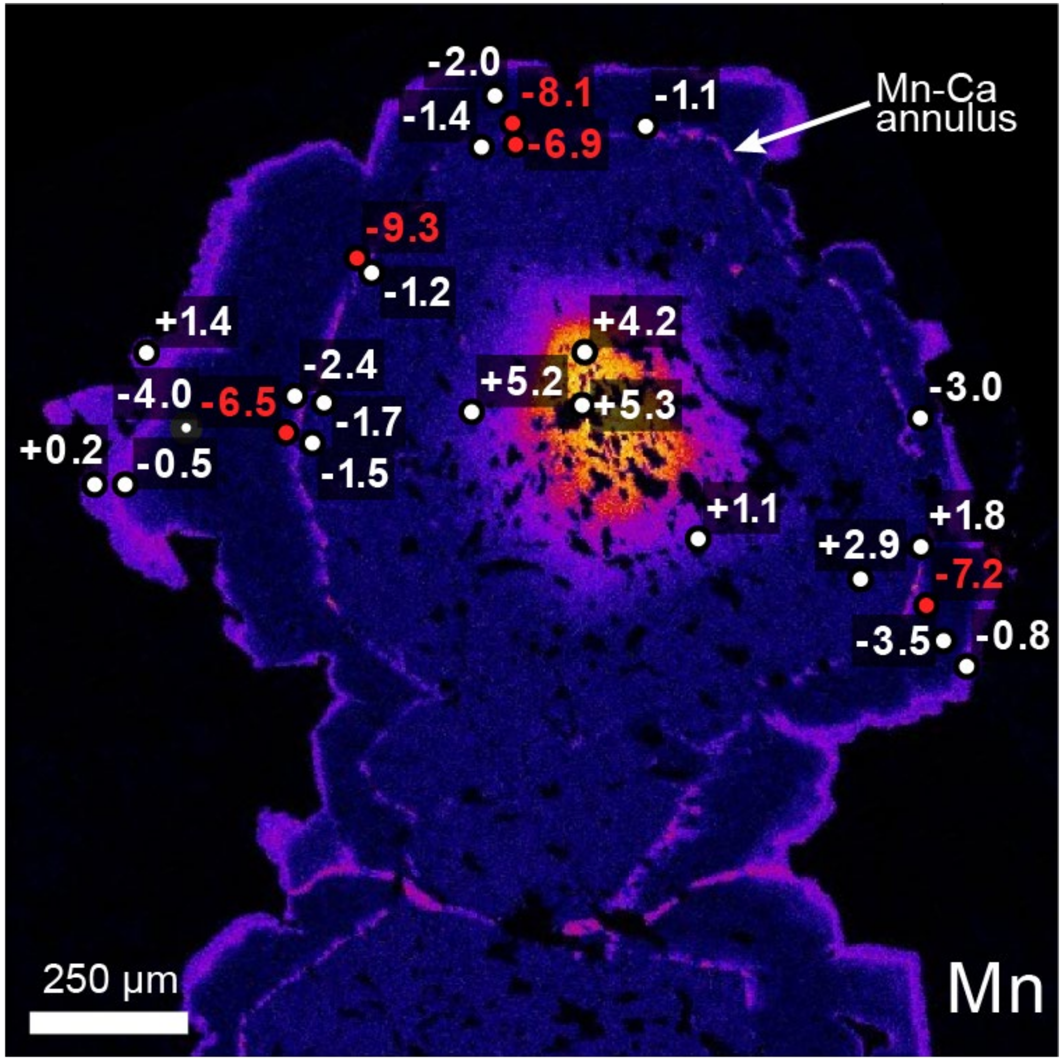


Negative δ^7Li troughs observed outside Mn-Ca growth annulus

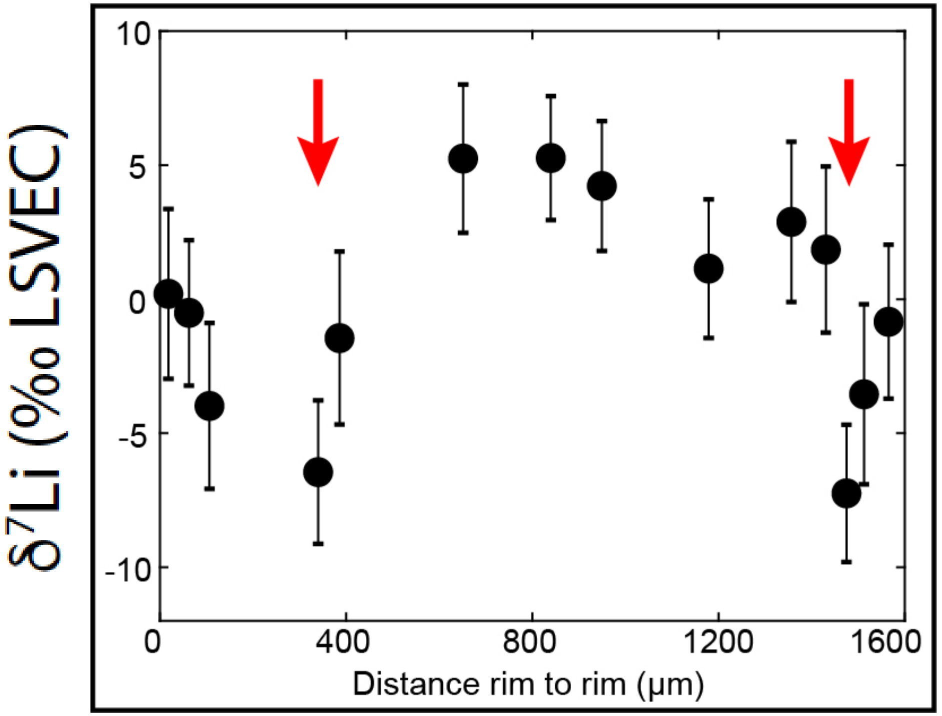
Hoover et al., 2022, Geology

Monviso Ophiolite

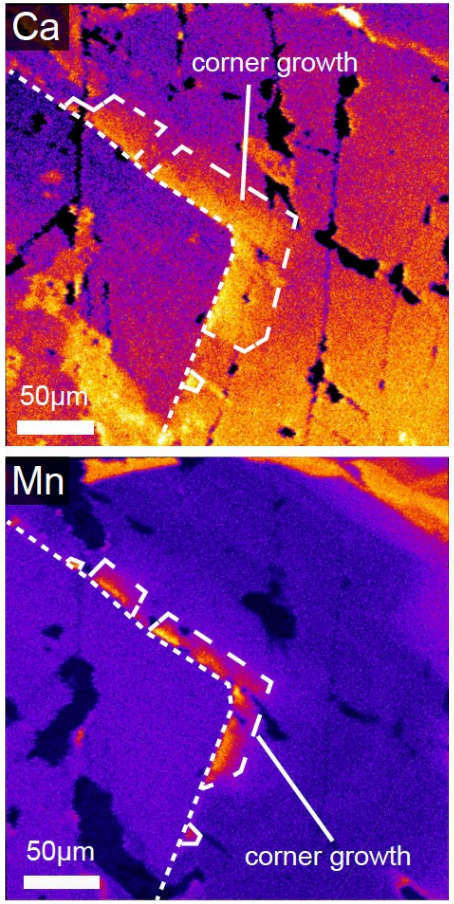
High-grade blocks in shear zone
Garnet from block interior



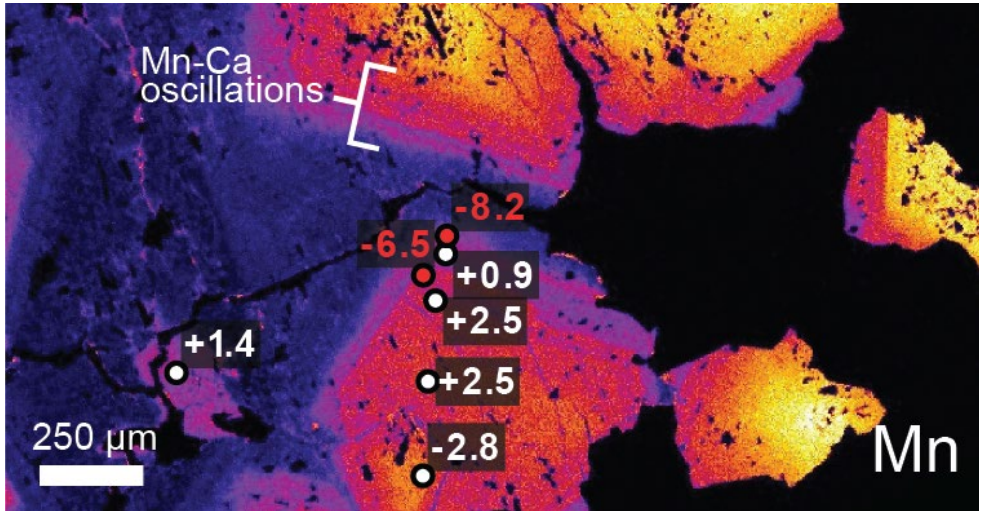
- Negative δ^7Li troughs observed outside Mn-Ca growth annulus
- Annuli thicker at growth zone corners
- Characteristic of rapid disequilibrium growth

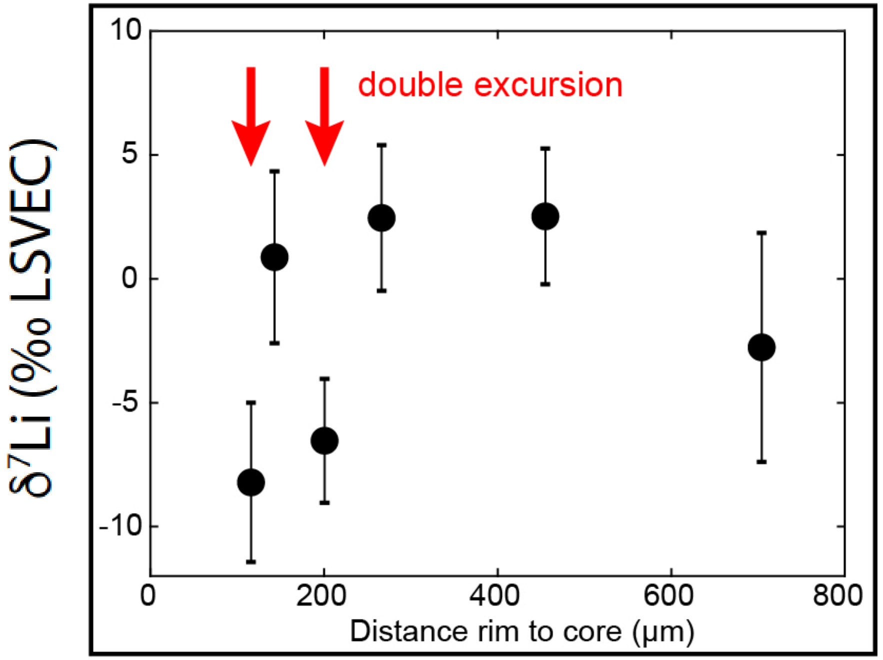


Hoover et al., 2022, Geology



Monviso Ophiolite

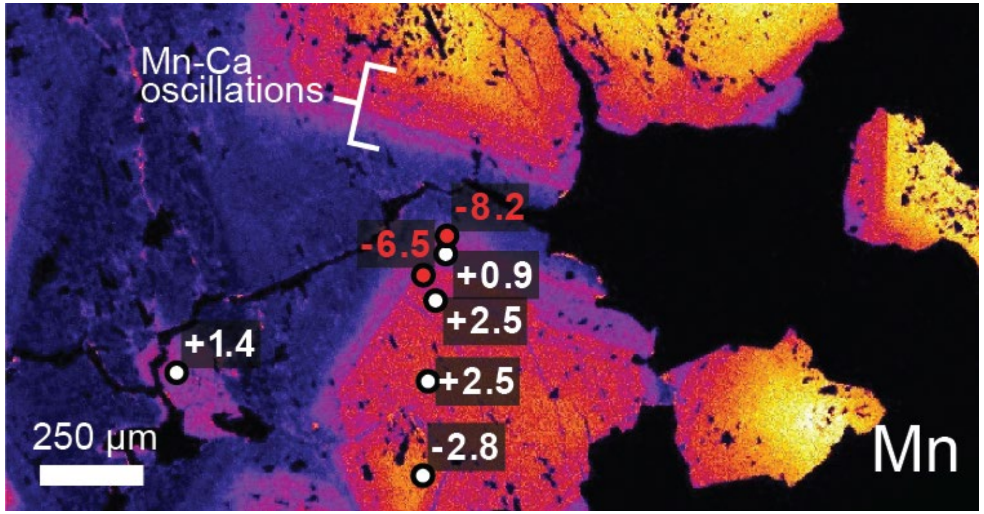


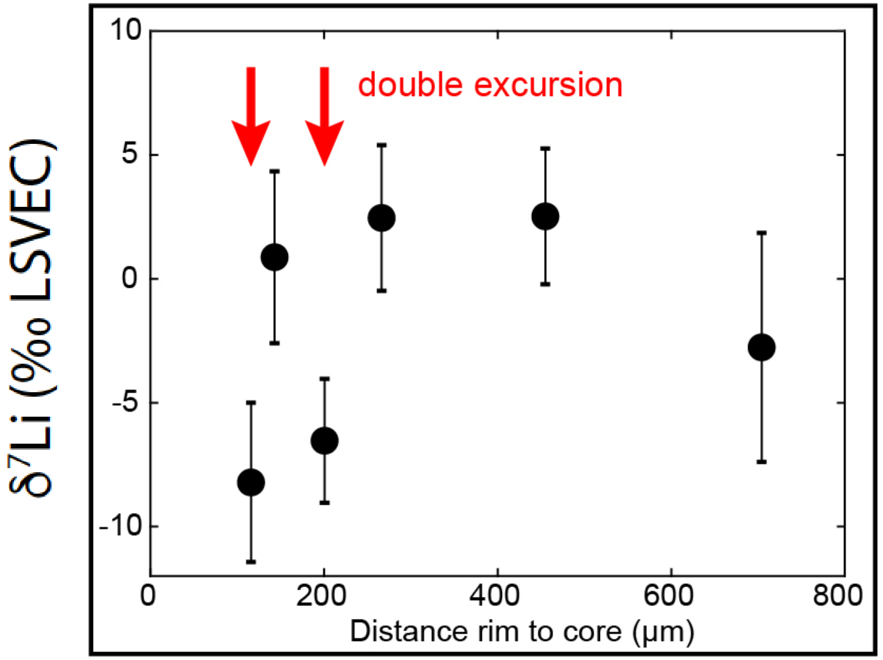


Garnet adjacent to outer reaction zone

- Multiple low δ^7Li troughs observed (at least 4)

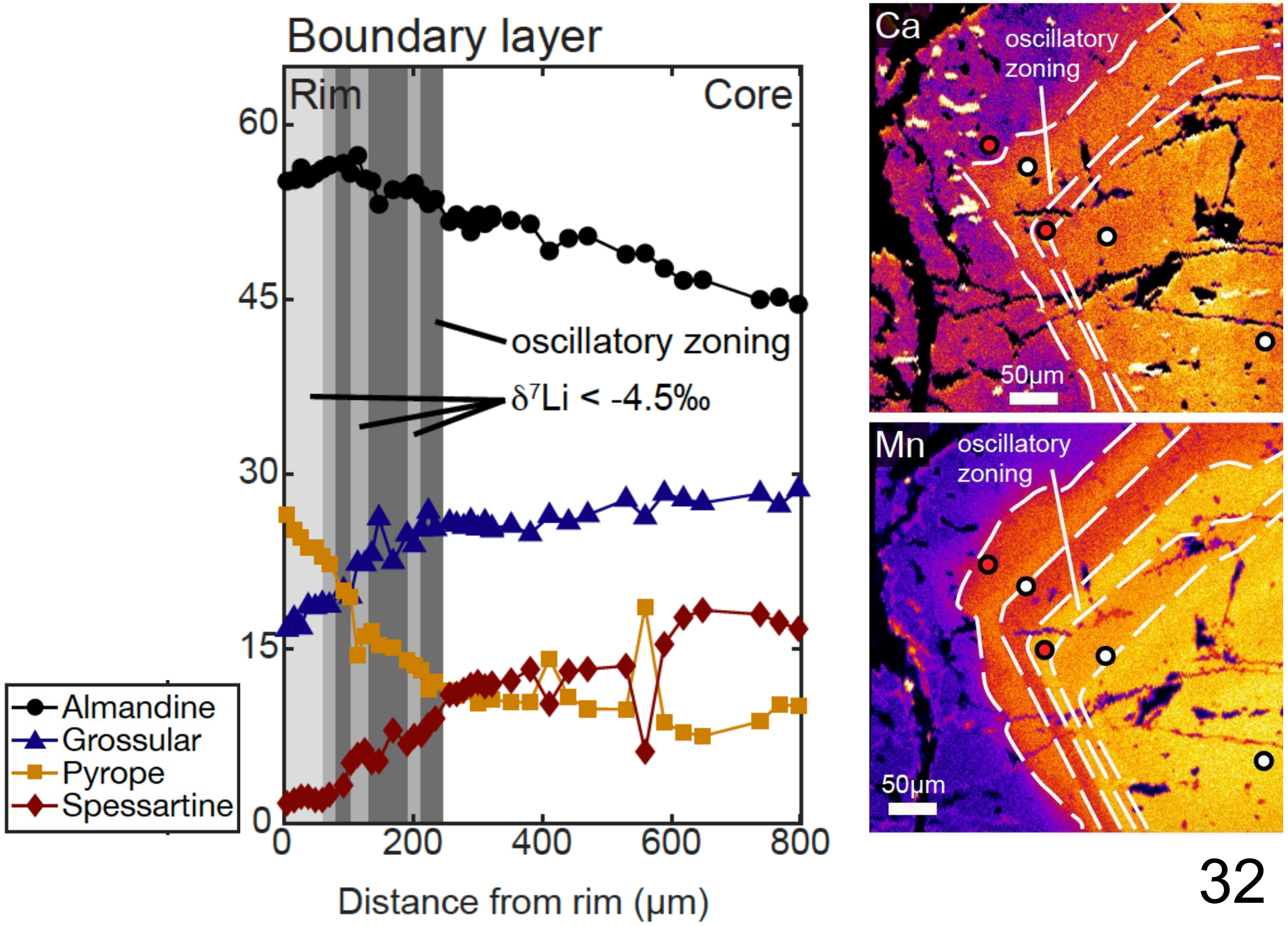
Monviso Ophiolite





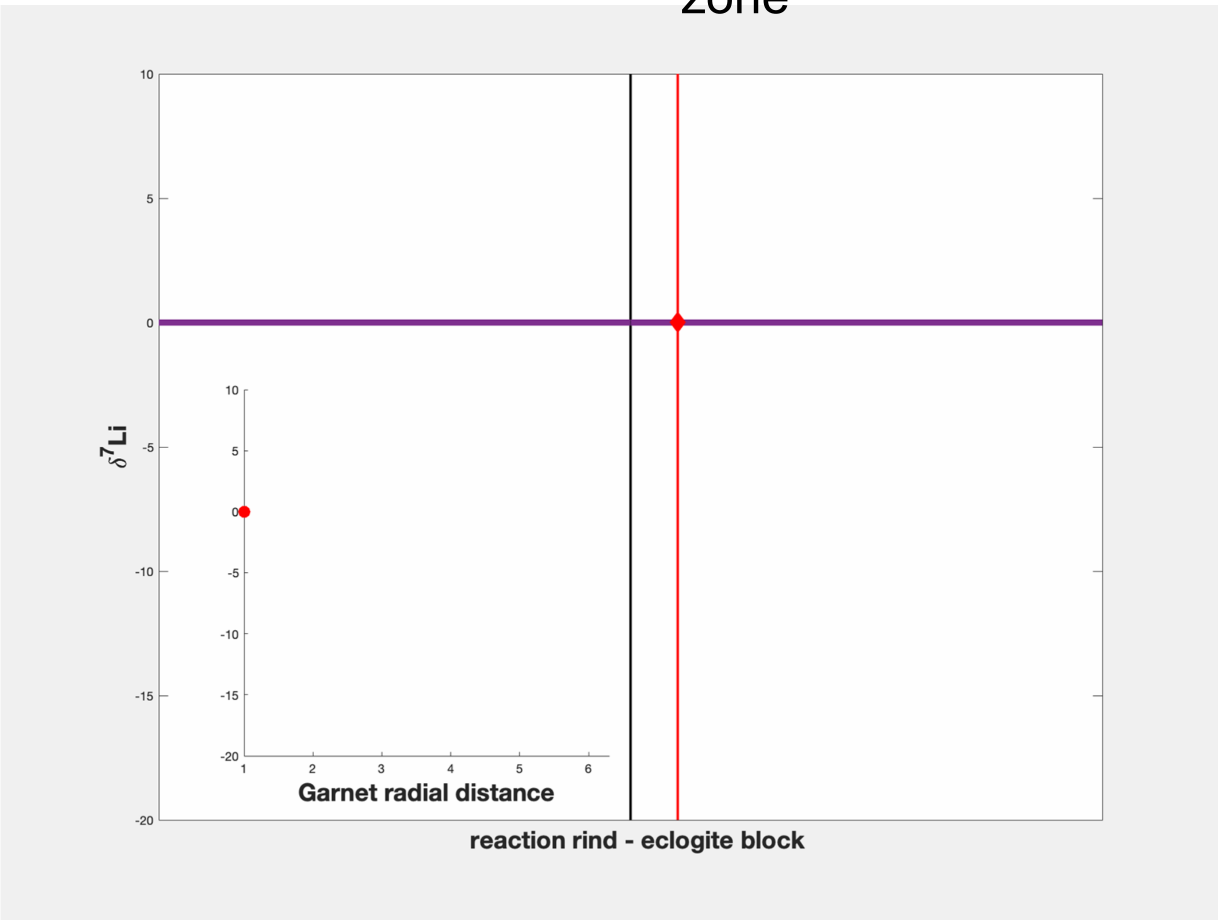
Garnet adjacent to outer reaction zone

- Multiple low δ^7Li troughs observed (at least 4)
- Low δ^7Li values found in regions of oscillatory zoning, also commonly associated with disequilibrium



Bulk-diffusion + garnet growth

Shear zone Reaction zone Block



Diffusion direction

Useful for determining fluid flow episodicity!

Li diffusion through an intergranular fluid occurs into the block from the shear zone.

Garnet acts as passive marker while diffusion front passes by

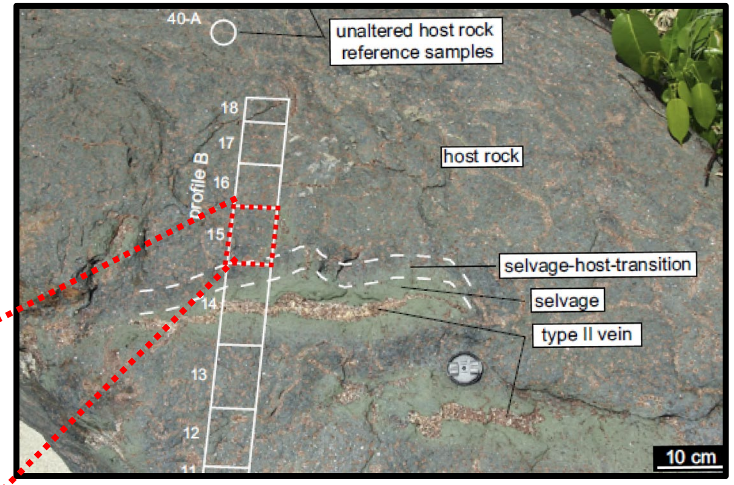
Multiple troughs imply multiple instances of diffusion (at least four!) and therefore **episodic** fluid flow events

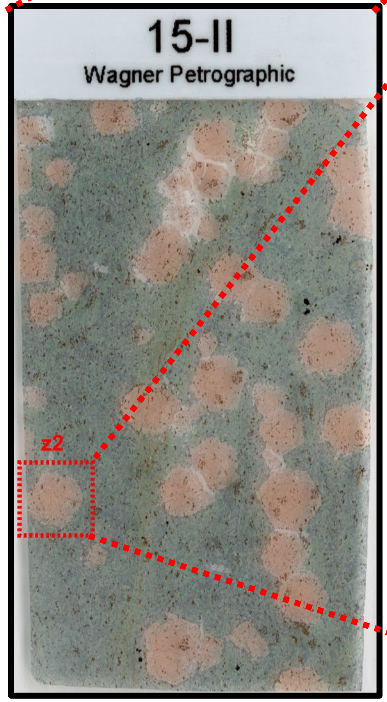
Future goal is to combine bulk rock and *in situ* measurements

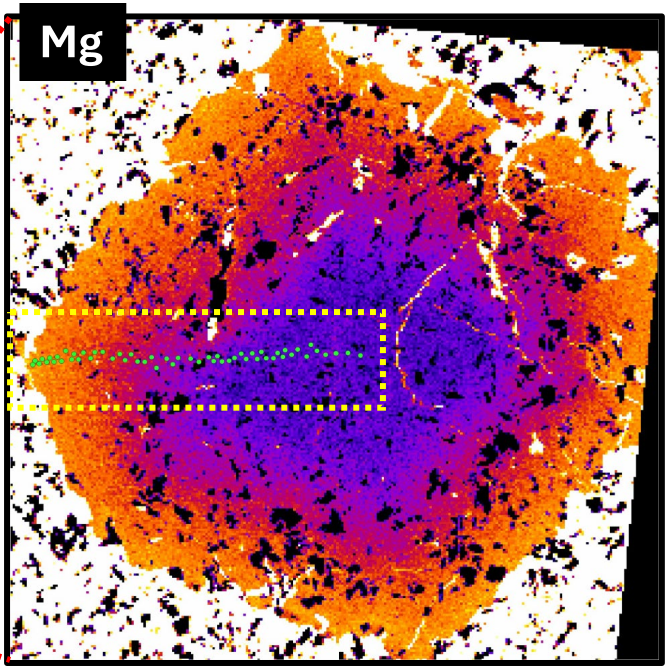
Ongoing work: Investigate samples from a variety of localities

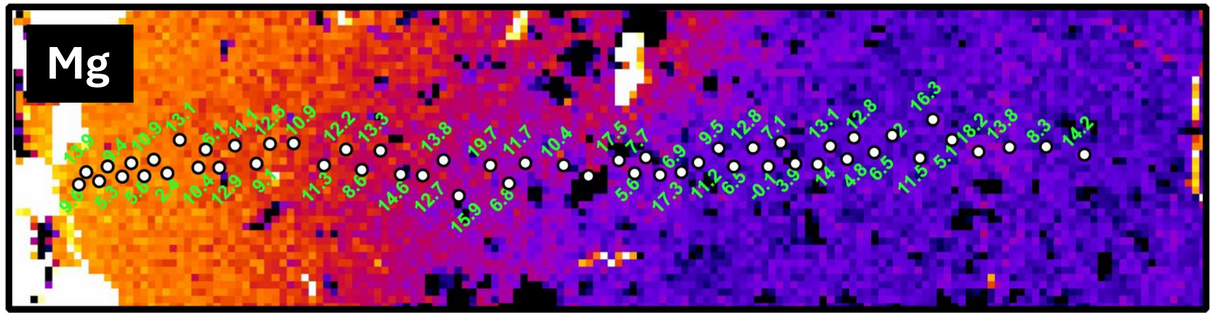
Alex Cisneros

New Caledonia eclogite

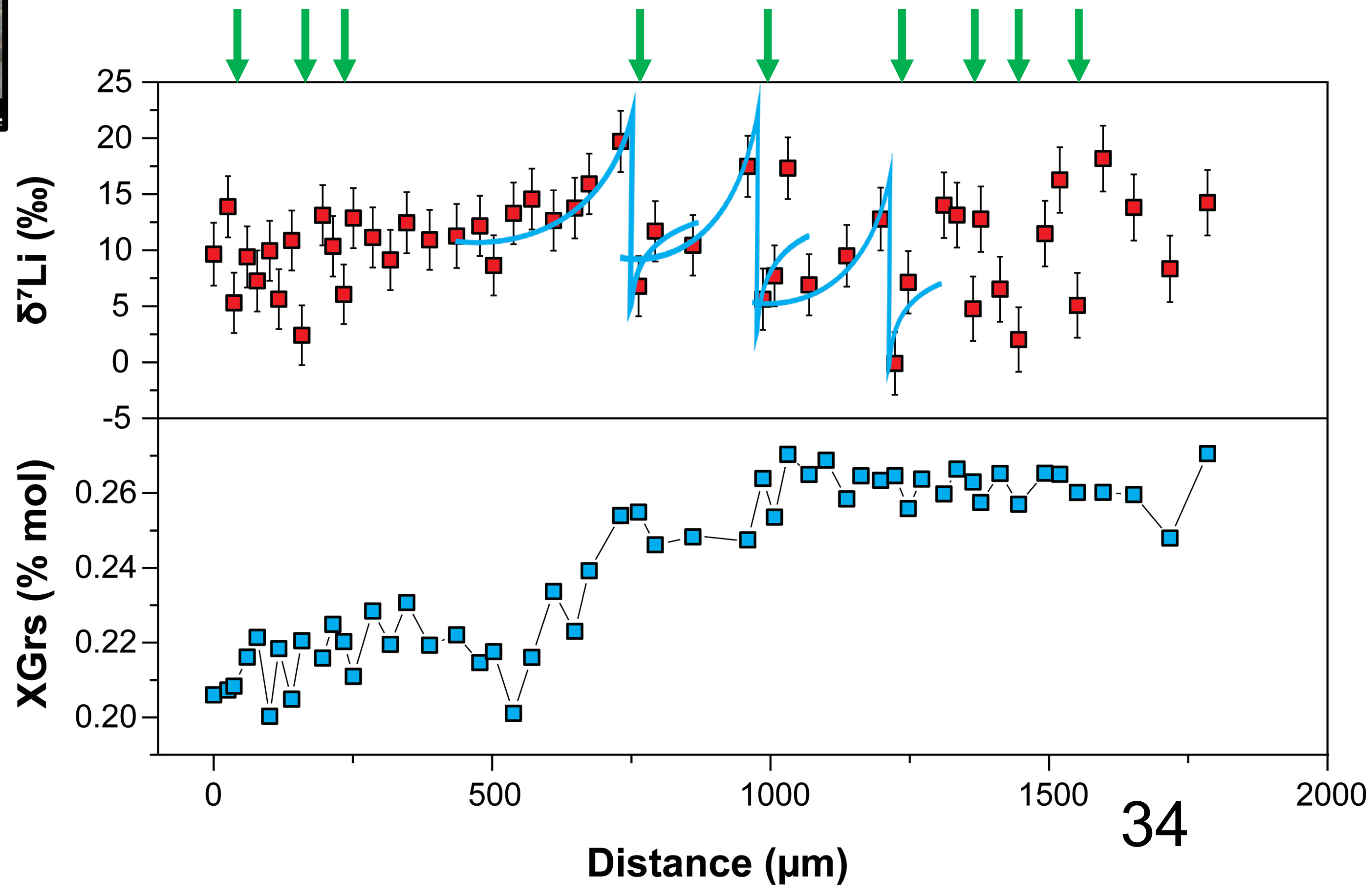








Multiple isotopic excursions along garnet growth

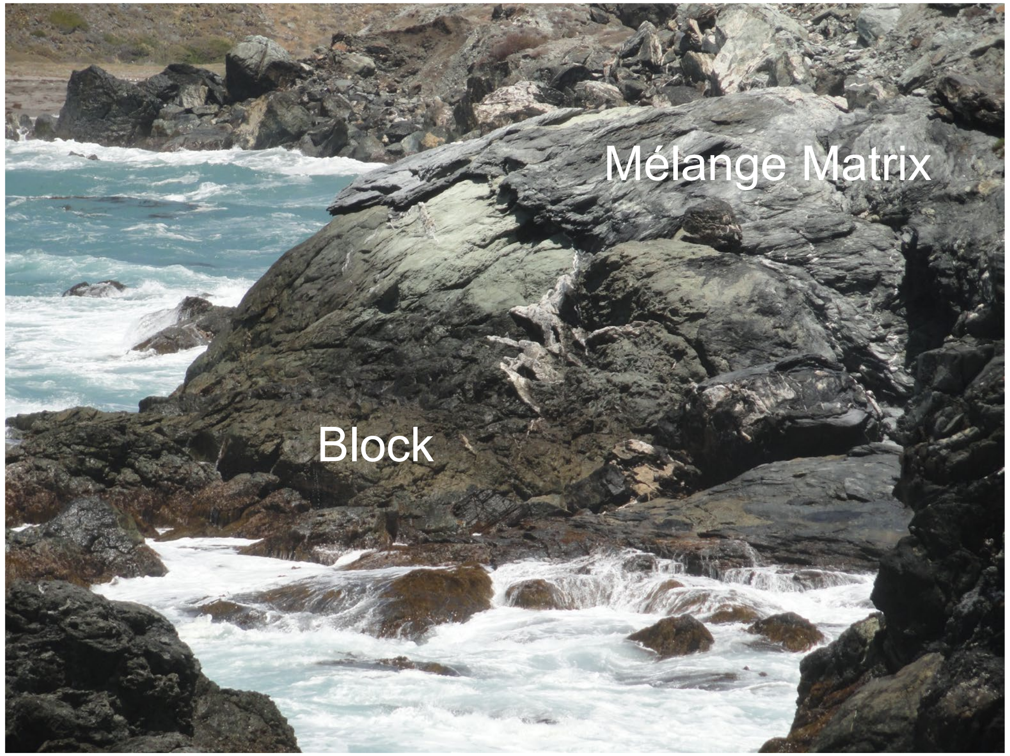


Conclusions

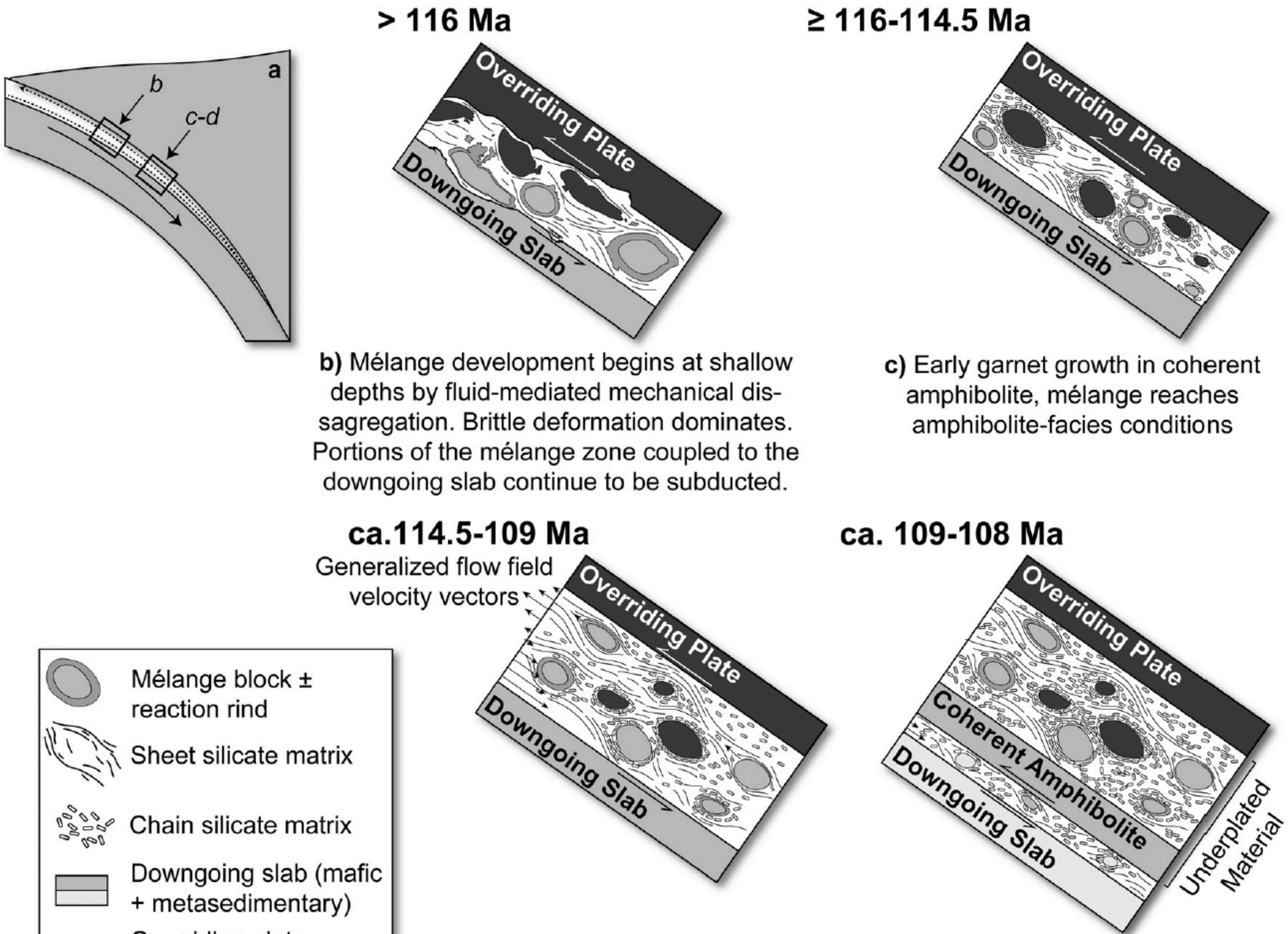
- **Duration**: Li diffusion profiles in mélange reaction rinds from the subduction interface record ~40 years of flow; shorter than expected for large-scale flow but the same order of magnitude as ETS (days to tens of years)
- **Episodicity***: In situ* Li isotope measurements in garnet record multiple (at least 4) episodes of fluid flow
- **Moving forward**: We need to combine bulk rock Li measurements (total duration) with *in situ* Li in garnet measurements (number of episodes) at the same locality

Questions?


Block
Mélange Matrix


Mélange Matrix
Block


Block
Mélange Matrix



b) Mélange development begins at shallow depths by fluid-mediated mechanical dis-sagregation. Brittle deformation dominates. Portions of the mélange zone coupled to the downgoing slab continue to be subducted.

c) Early garnet growth in coherent amphibolite, mélange reaches amphibolite-facies conditions

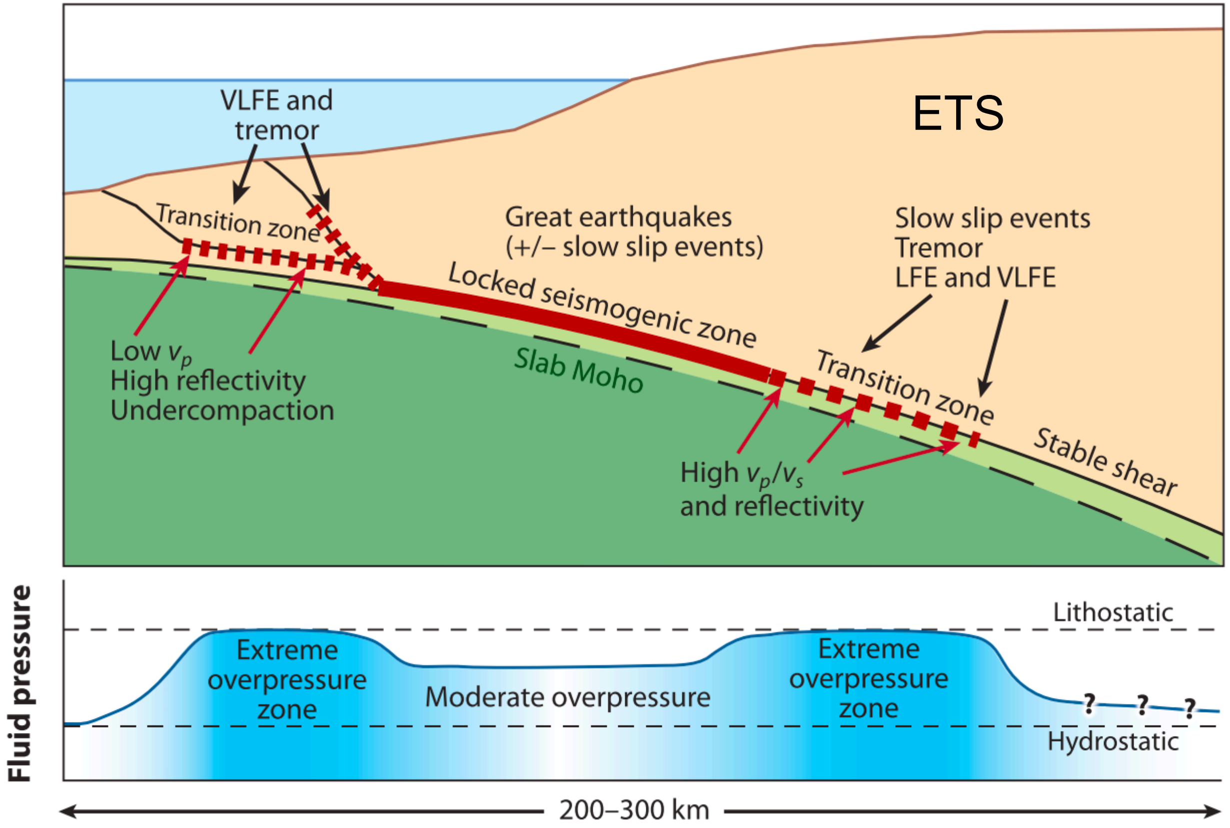
d) Garnet growth continues in coherent amphibolite, mélange continues to develop, shearing juxtaposes blocks recording

e) The subduction interface is underplated between 109 and 108 Ma.

Deformation stops in mélange zone either

Connecting to active subduction processes

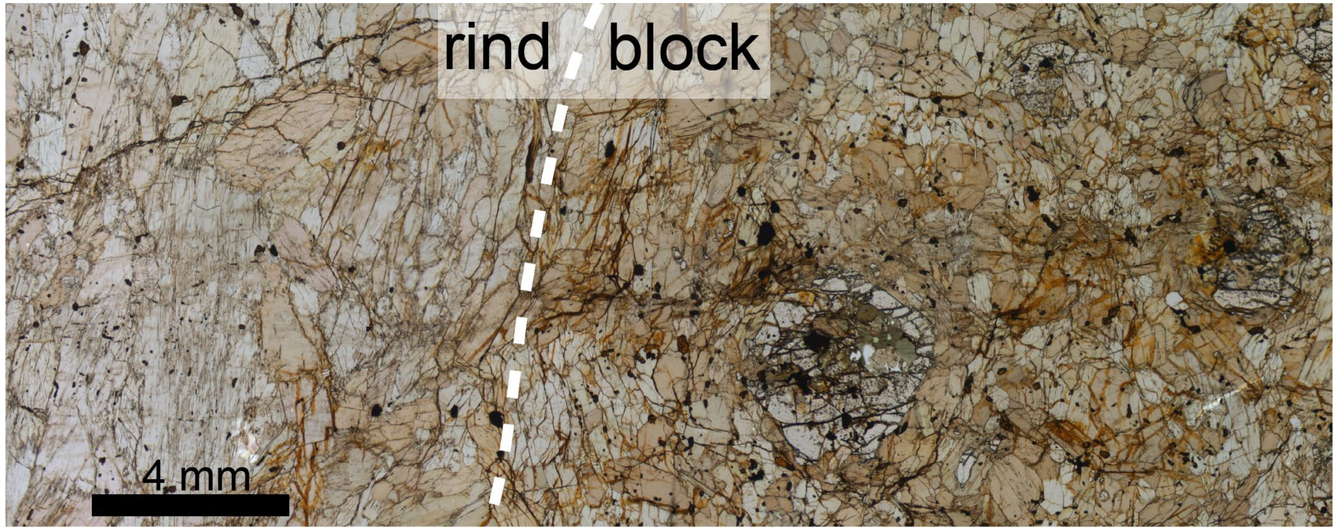
Fluid overpressure associated with seismicity in subduction zones

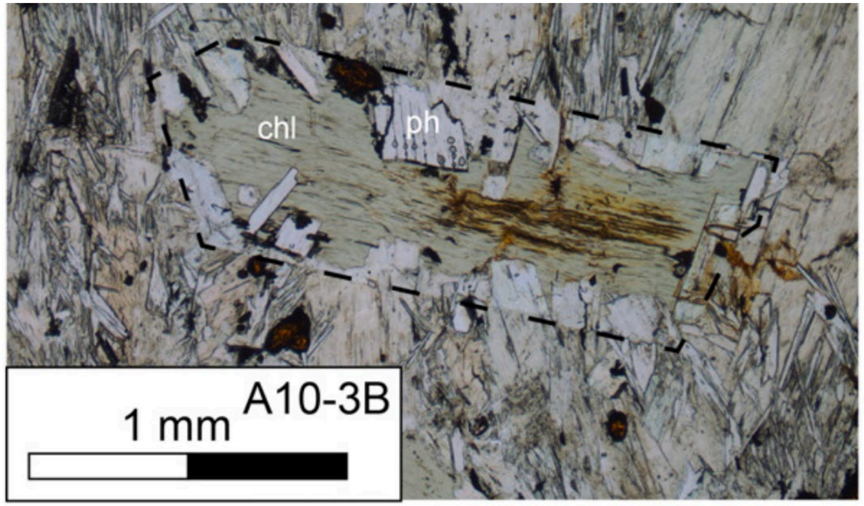


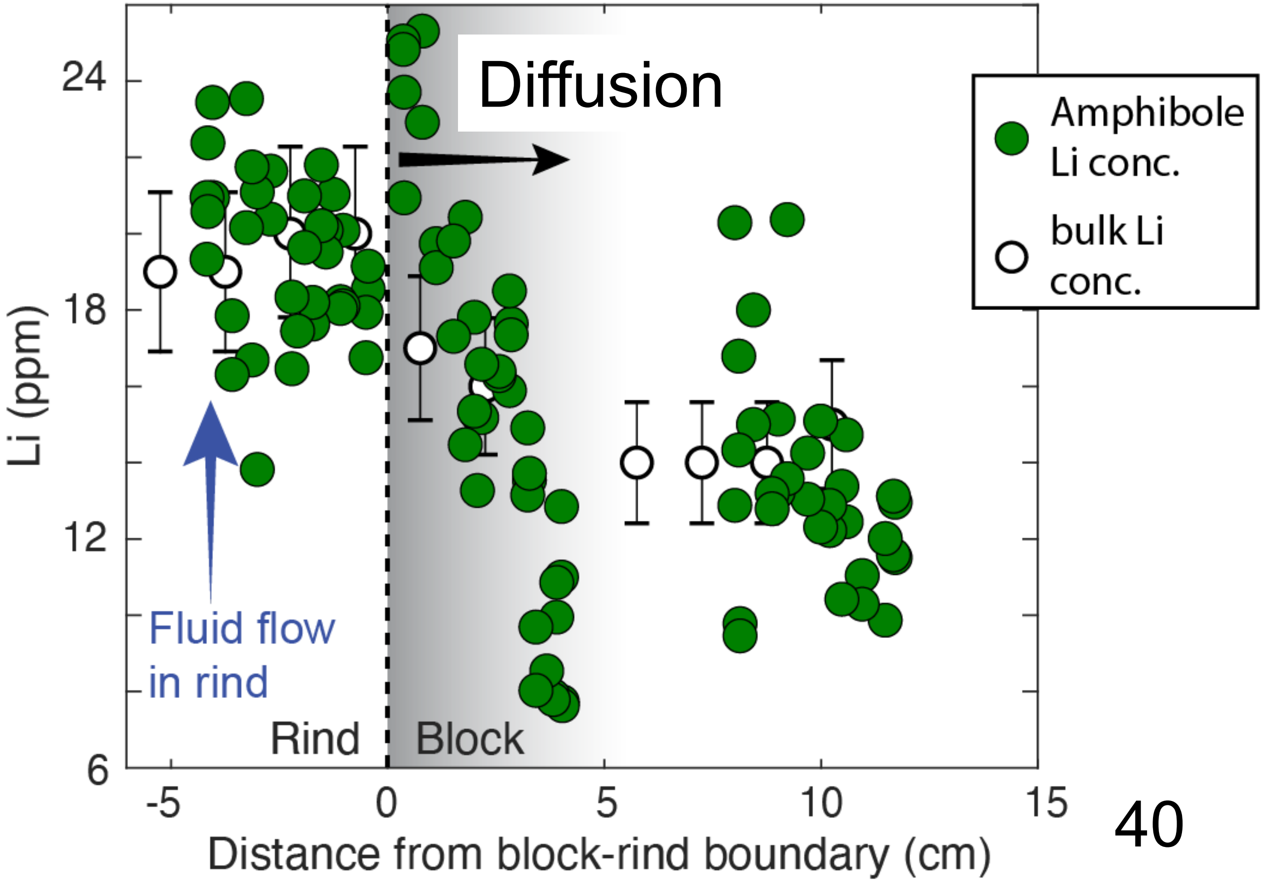
Saffer and Tobin, 2011

Timing of fluid influx

- Amphiboles formed during peak metamorphism record Li diffusion profile
- **~Peak metamorphic fluid transport**
- Retrograde fluids consumed amphibole

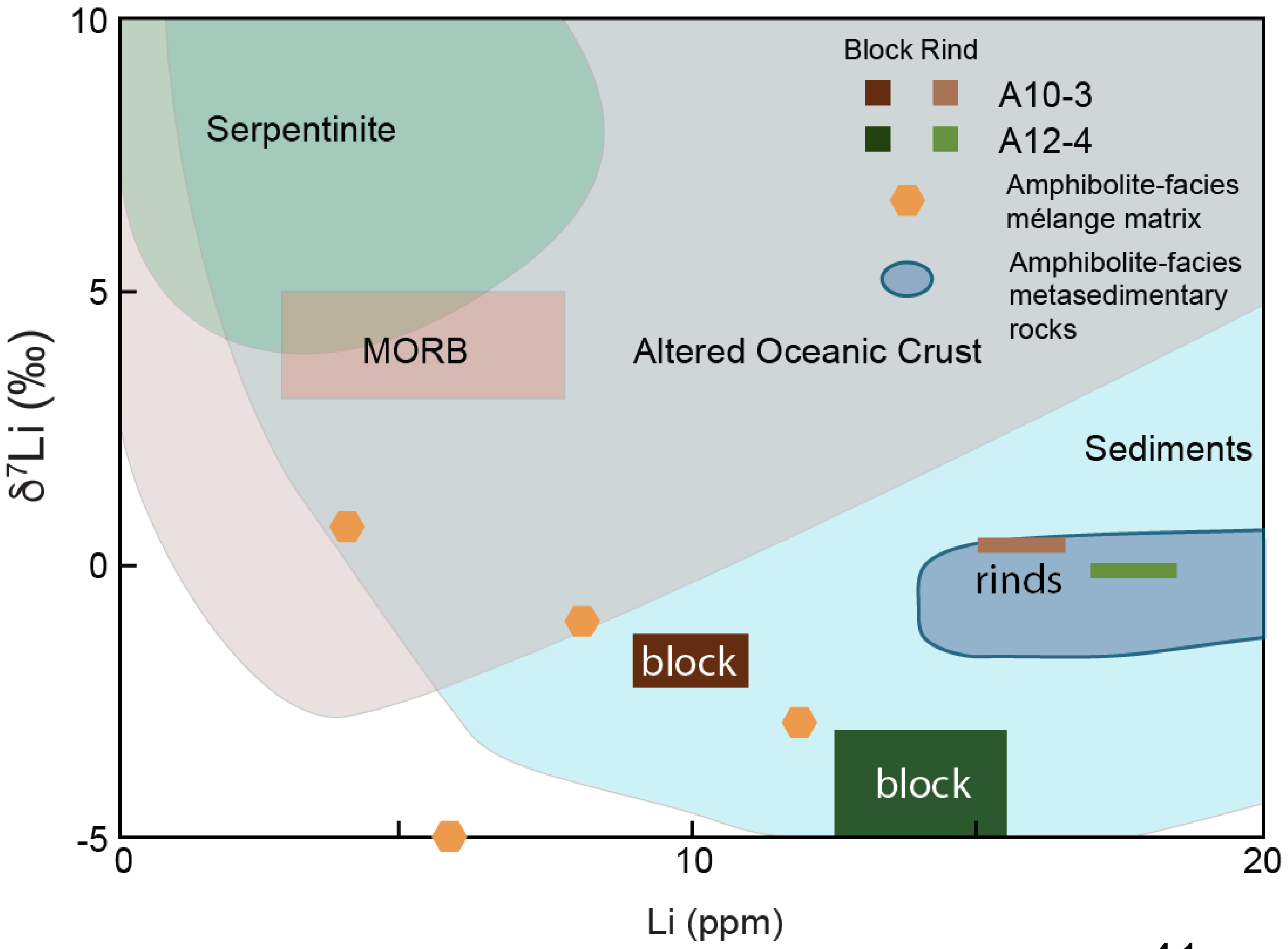






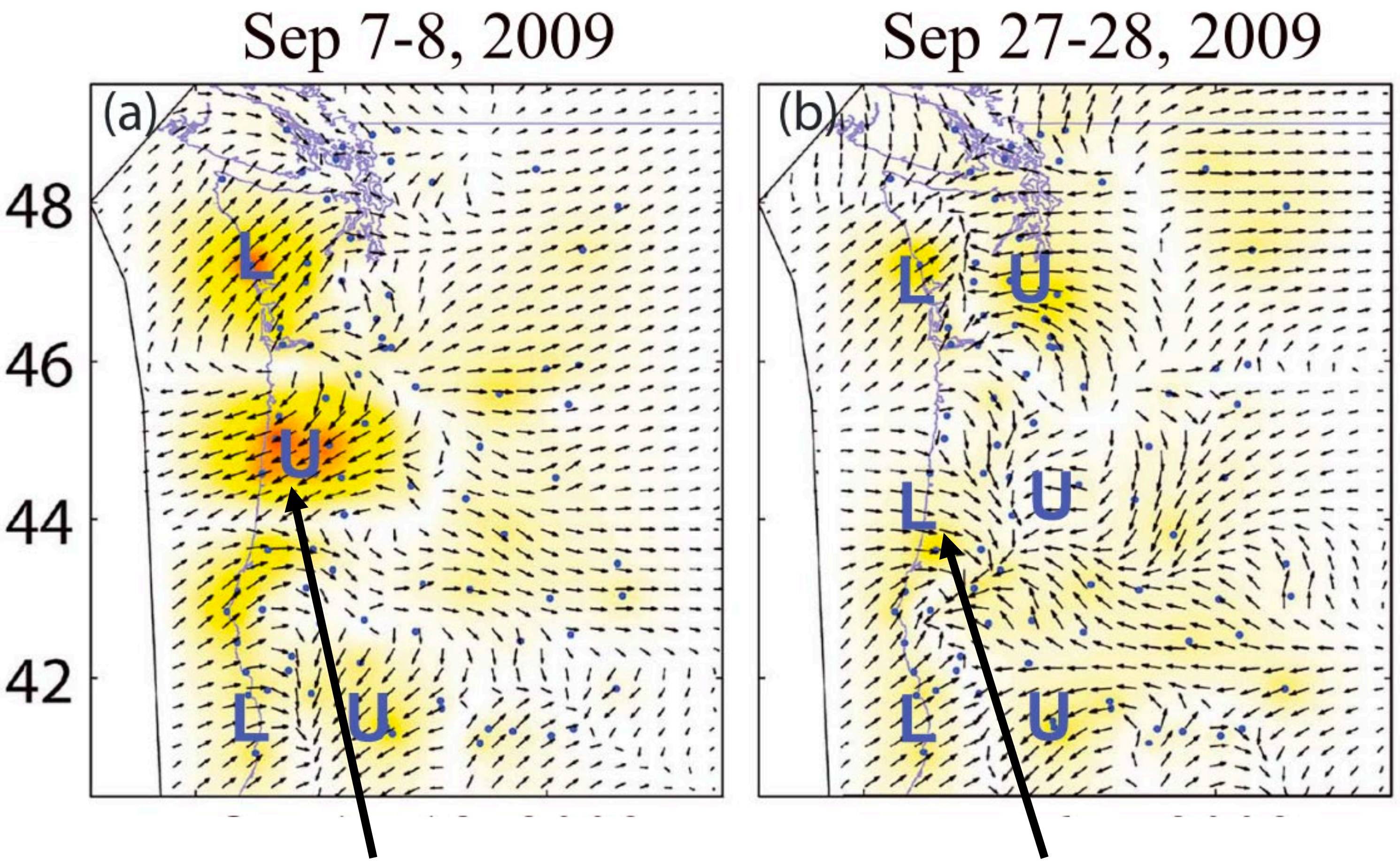
Fluid source

- Metasedimentary rock-derived fluids
- Consistent with O isotopes



Multiple events?

GPS surface deformation



Slow slipping region

Relocked

Haines et al., 2019

- Fluid-driven fault healing = days to weeks
- Only transient fluid transport @ interface
- 45 years = integration of many seismicity + healing cycles?

Table 5.1: Parameter ranges used in the Monte Carlo transport model.

Parameter	Units	Range		Source
Diffusivity	m^2/s	10^{-9}	10^{-6}	Oelkers and Helgeson (1988), Bourg and Sposito (2007), John et al. (2012), Bickle and McKenzie (1987), Penniston-Dorland et al. (2010)
Beta		0.015	0.215	Richter et al. (2003), Richter et al. (2006), Teng et al. (2006)
Porosity		10^{-6}	10^{-3}	Baumgartner and Valley (2001), Ague (2013), Taetz et al. (2018)
Tortuosity		0.3	0.6	Bear (1972), Fisher and Elliot (1973), Baumgartner and Valley (2001), Ague (2013)
Solid density	g/cm^3	3.1		Hacker et al. (2003), Gerya et al. (2002), Ji et al. (2013)
Fluid density	g/cm^3	0.95	1.21	Penniston-Dorland et al. (2010), John et al. (2012), Ague (2013)
Darcy velocity*	m/s	10^{-14}	10^{-9}	Baumgartner and Valley, 2001
Bulk partition coefficients	wr/fluid	A10-3: 0.489 A12-4: 0.512		Marschall et al. (2006, 2007), Caciagli et al. (2011), Gorman (2013), Penniston-Dorland et al. (2014), Roble (2014)

* Fluid velocity multiplied by porosity