Geology of the Subduction Megathrust Seismogenic Zone

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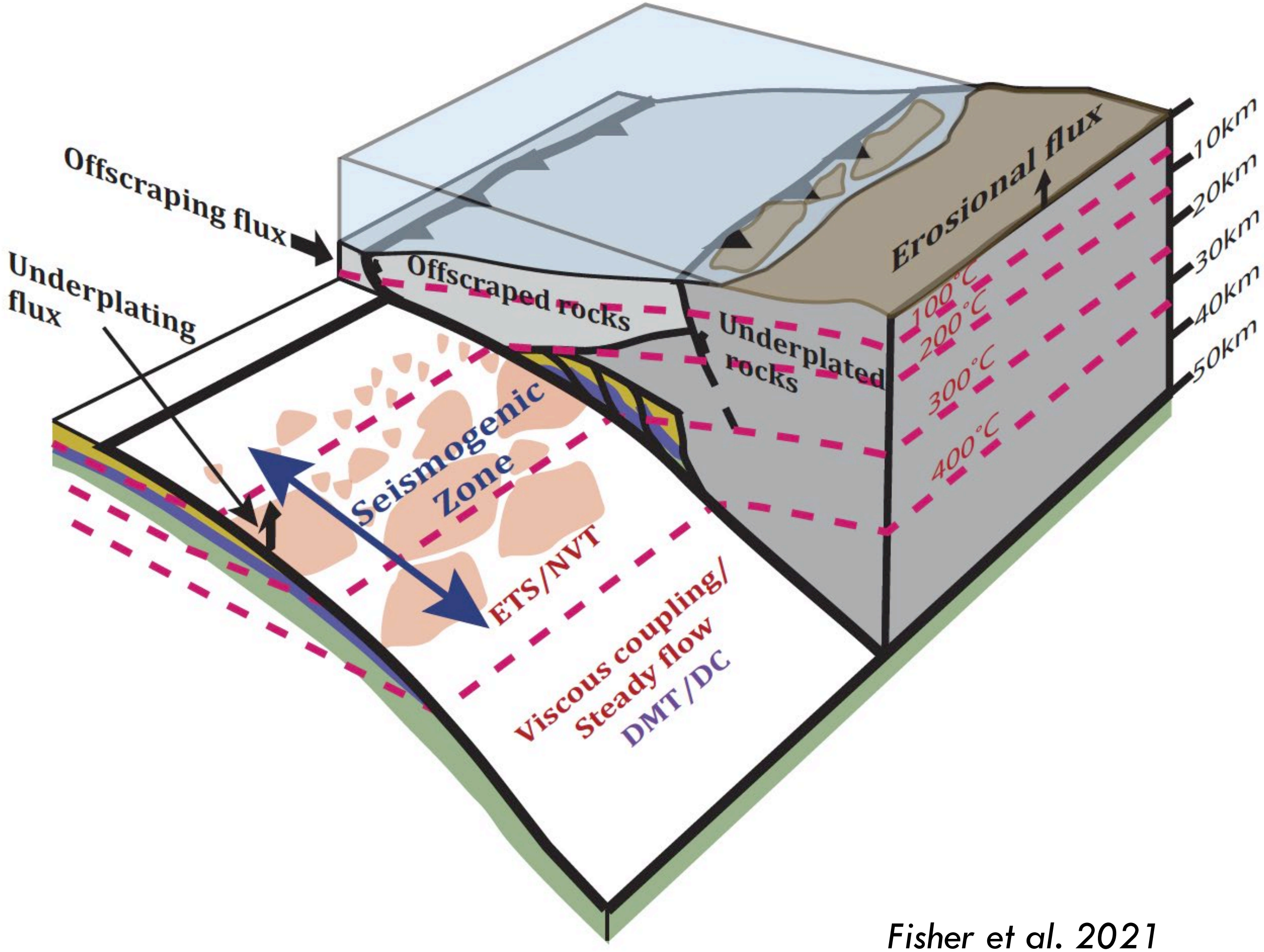
The habitat of megathrust earthquakes

What do we mean by the "seismogenic zone?"

Alternative definitions:

- Zone of rheological properties conducive to stick-slip behavior – often tied to temperature limits
- Area that slips in great subduction earthquakes
- Area of high interseismic slip deficit (a.k.a. "kinematic locking" or "coupling") as defined by geodesy
- Area defined by aftershocks and/or inter-event microseismicity



Fisher et al. 2021

Scholz's synoptic view of faulting in the crust

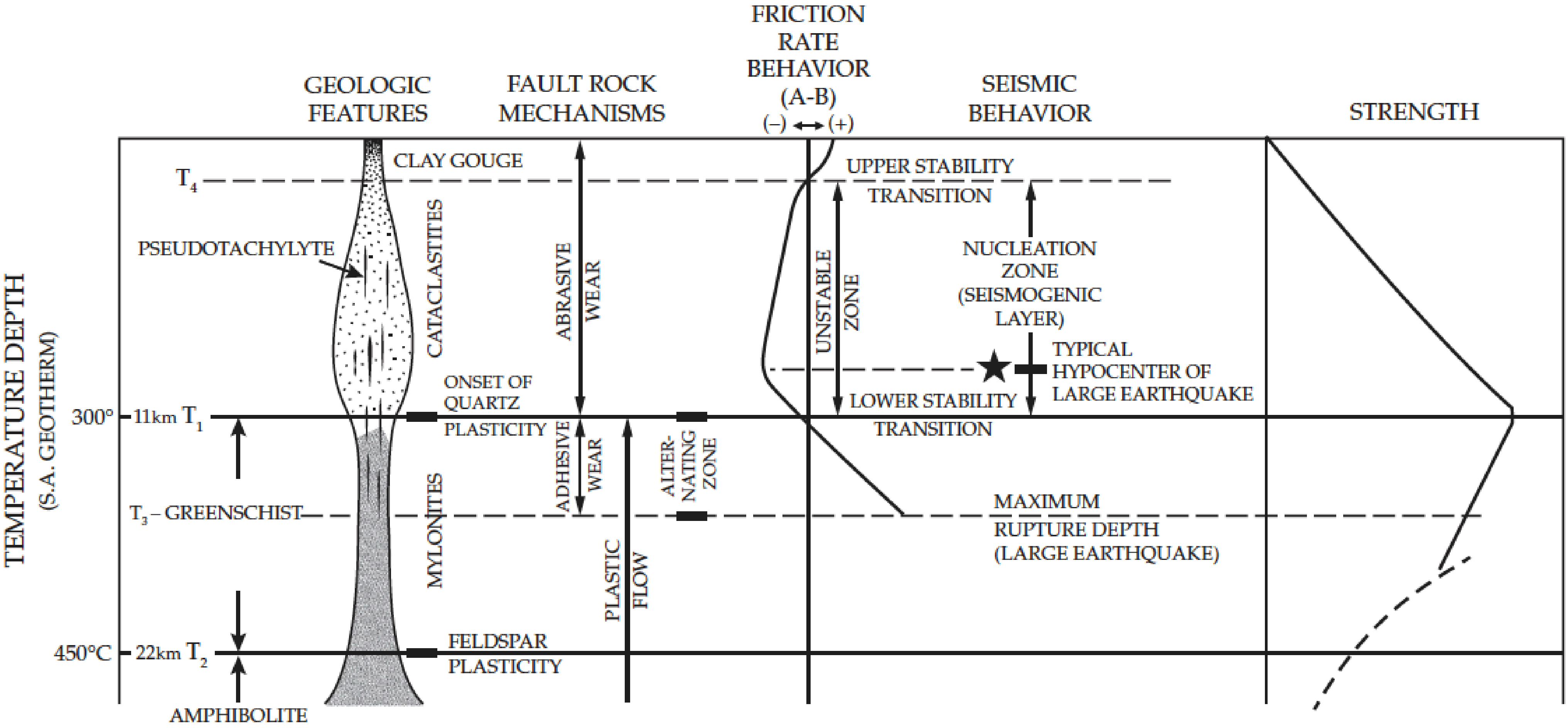


Fig. 3.44. Synoptic model of a continental shear zone. See the text for explanation. (Modified from Scholz, 1988b.)

The habitat of megathrust earthquakes

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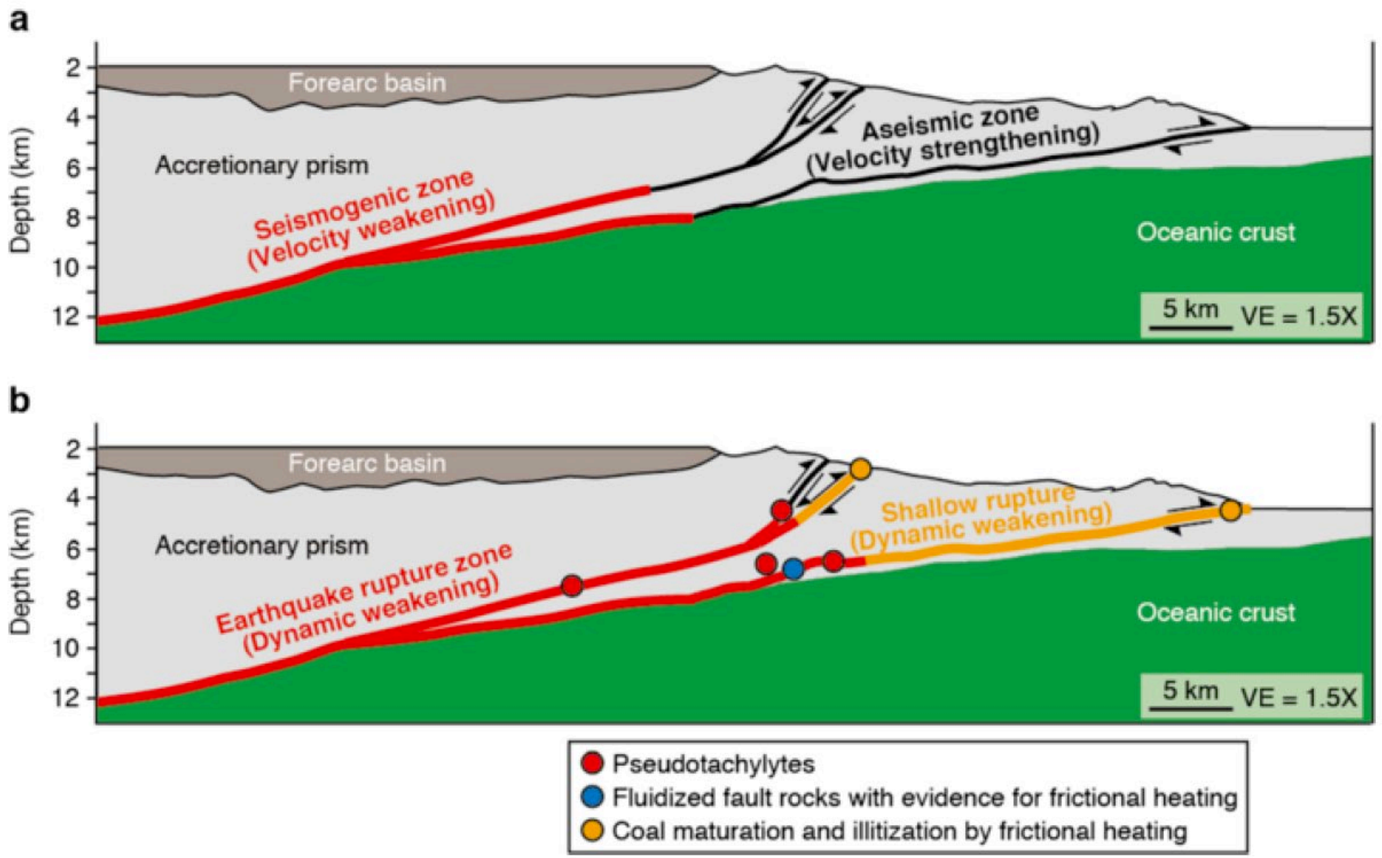
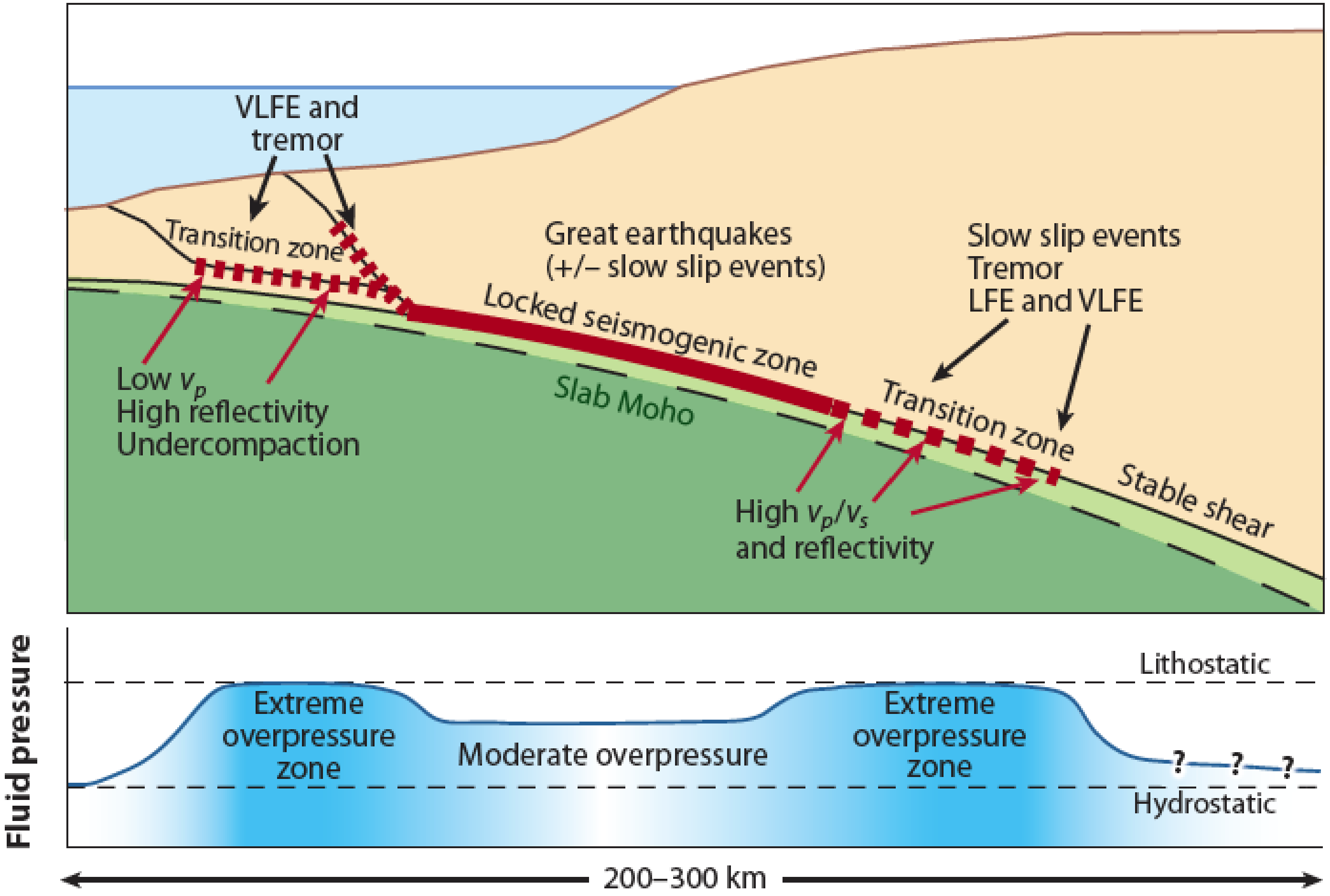


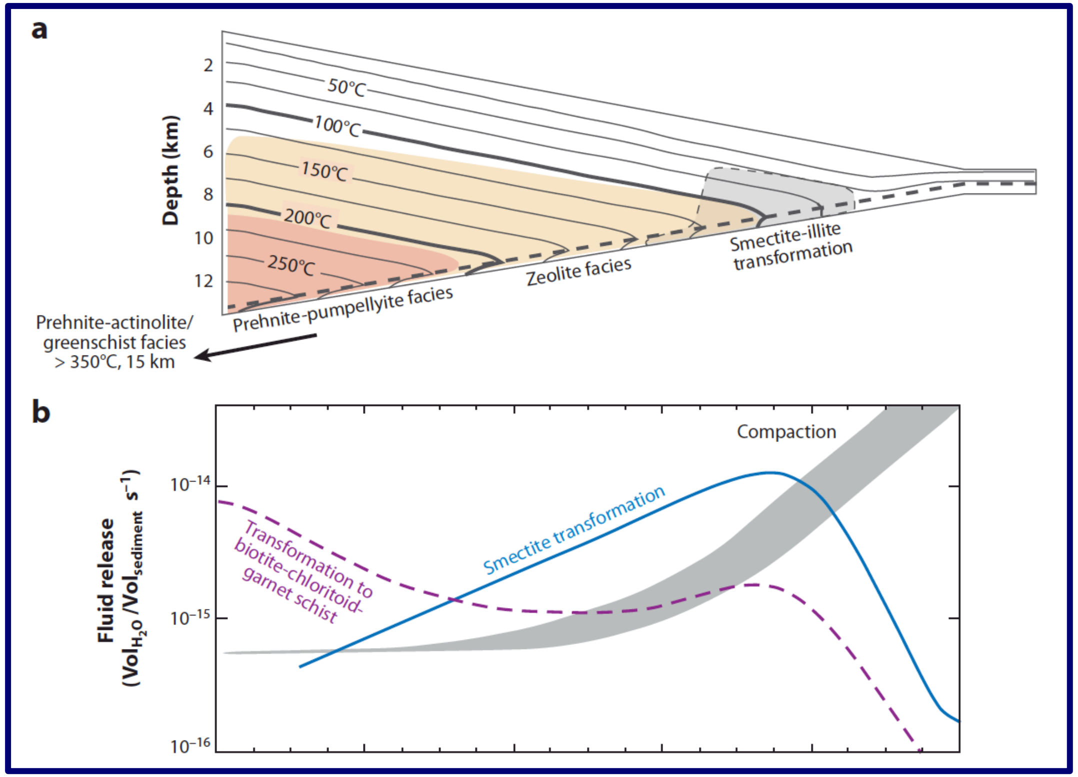
Ujiie et al., 2014

One current paradigm:
Locked seismogenic zone is flanked by aseismic or conditionally stable regions, controlled at least in part by fluid pressure

Hydrogeology and Mechanics of Subduction Zone Forearcs: Fluid Flow and Pore Pressure

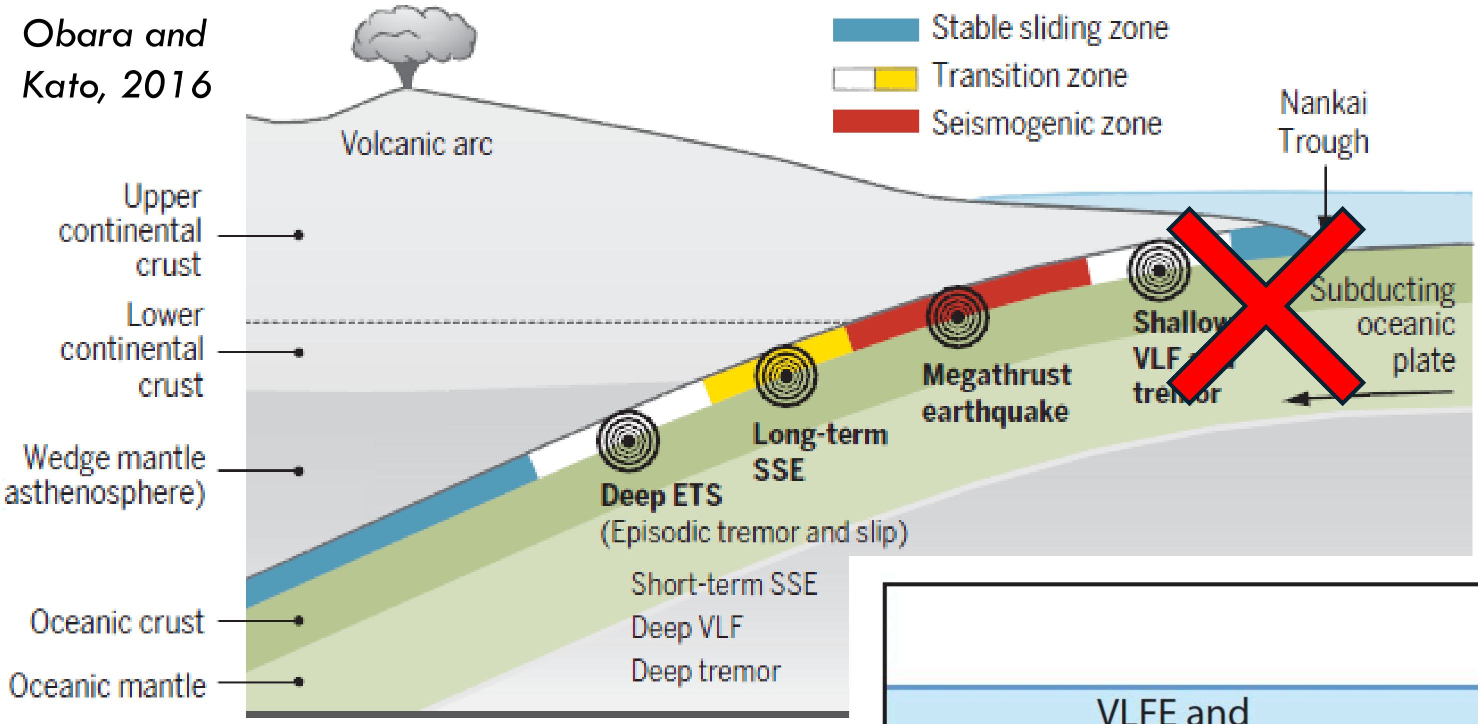
Demian M. Saffer[1] and Harold J. Tobin[2]



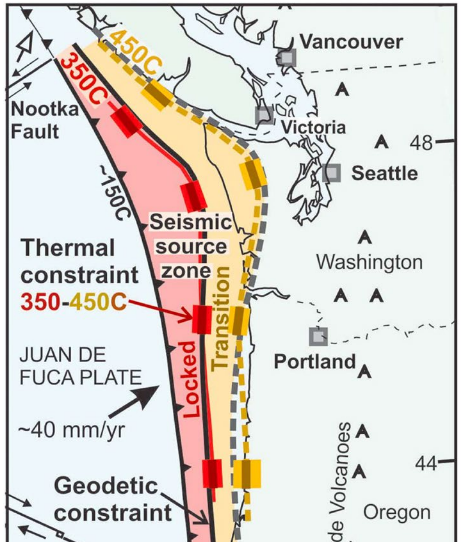


How well does this model fit Cascadia?

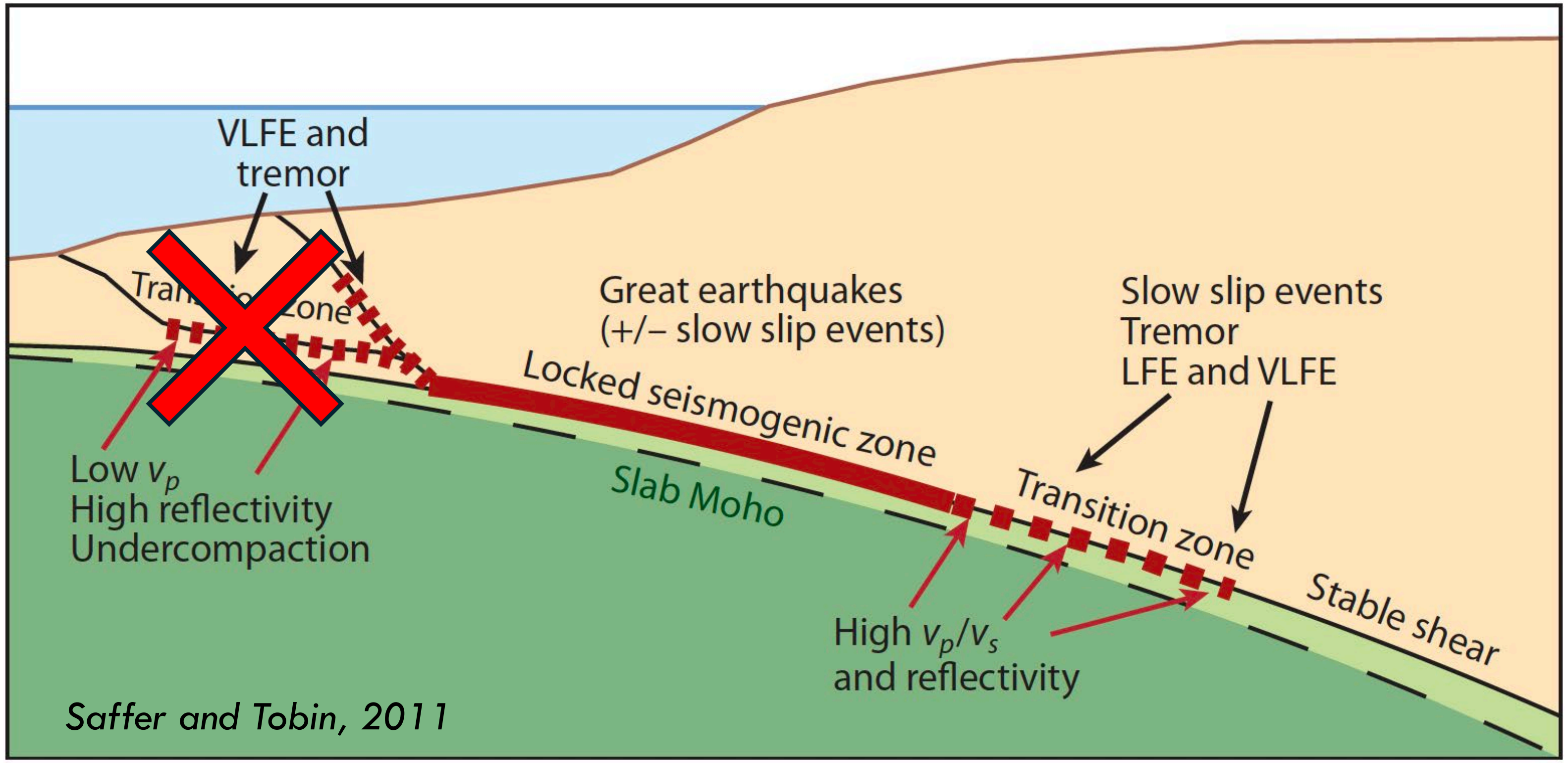
Obara and Kato, 2016



These are generic models, assuming globally typical temperature gradients and incoming sediment thickness.



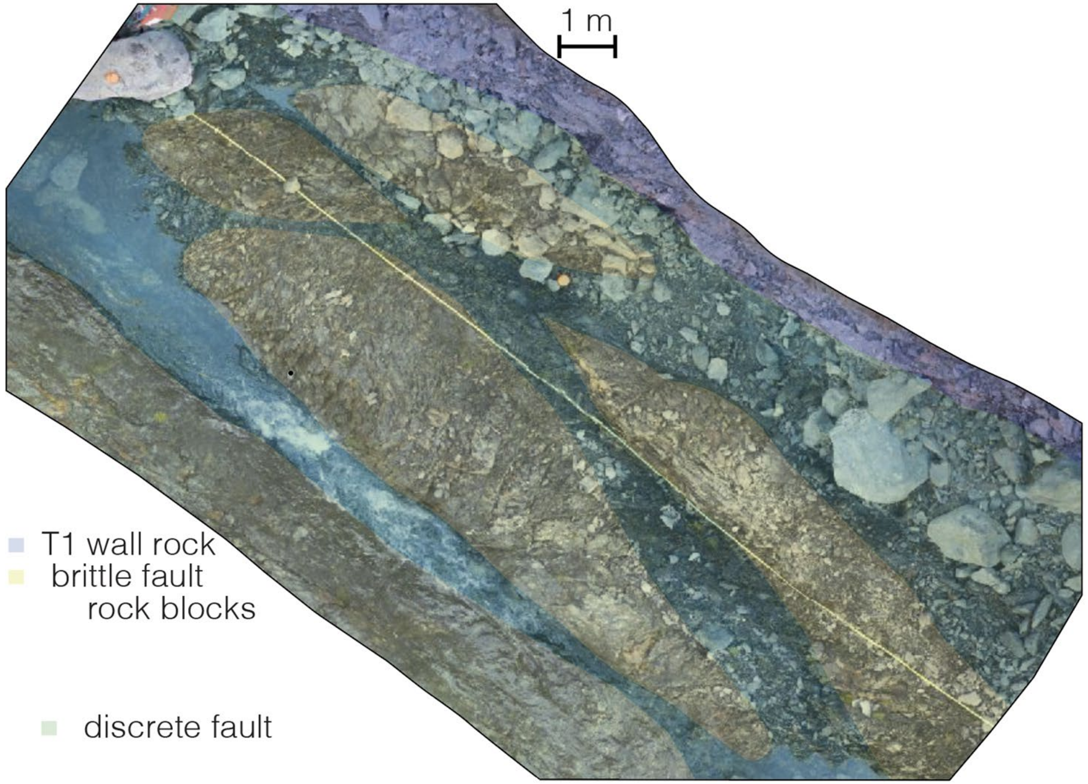
Hyndman et al., 1995, 2015



Saffer and Tobin, 2011

Exhumed fault geology is an integrated record of both seismic and aseismic processes

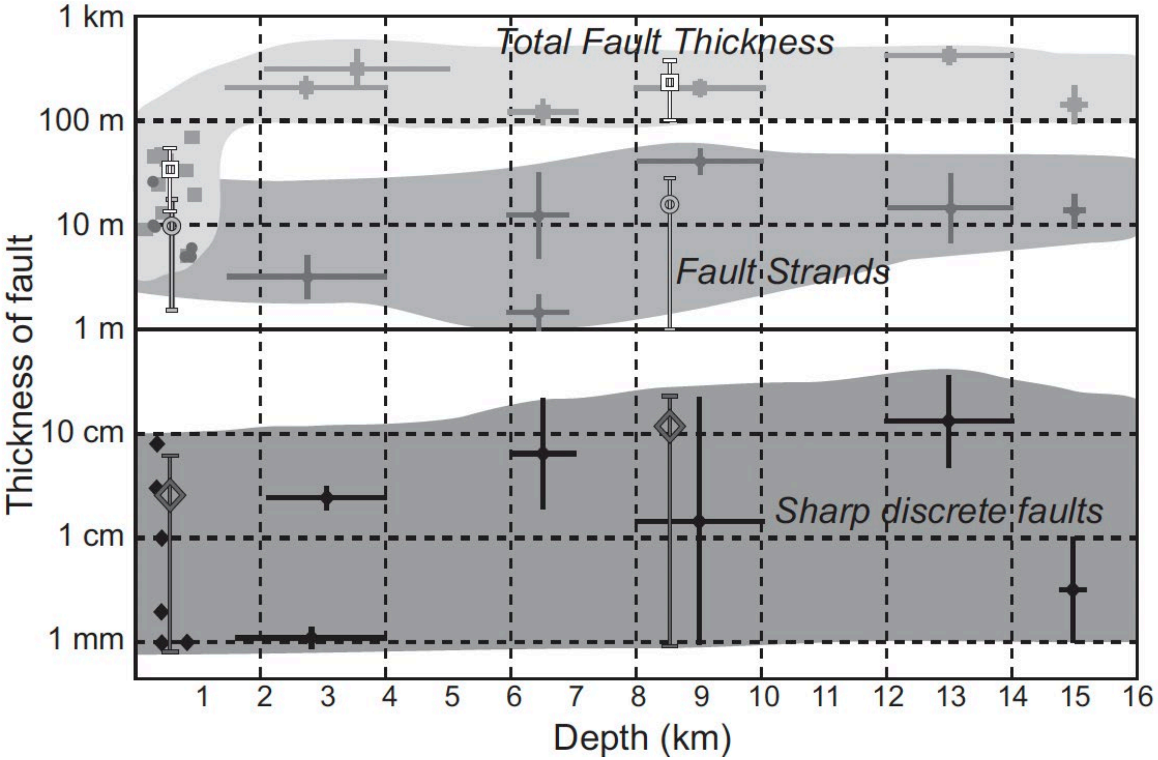
- Structures, fabrics, timing relations in exhumed rocks preserve all aspects of the seismic cycle EXCEPT elastic loading
- Provides a window into the controlling factors: mineralogy; deformation mechanisms; fluid composition, abundance, and pressures; at each stage of deformation
- Provides a model for geophysical insight into inaccessible fault systems of interest – like the Cascadia megathrust

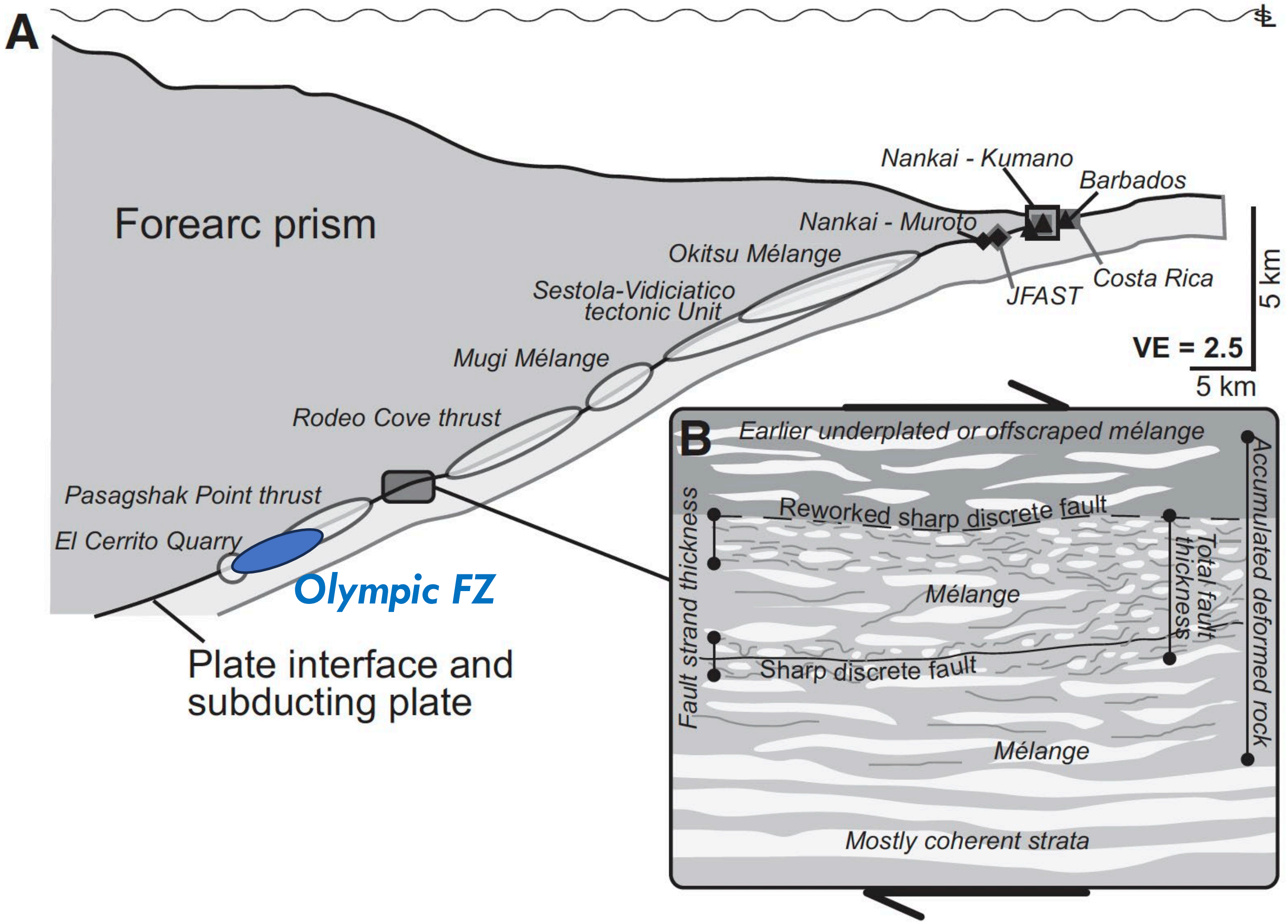


SfM model of a fault strand in the Olympic fault zone – after Ledeczi et al. (in review)

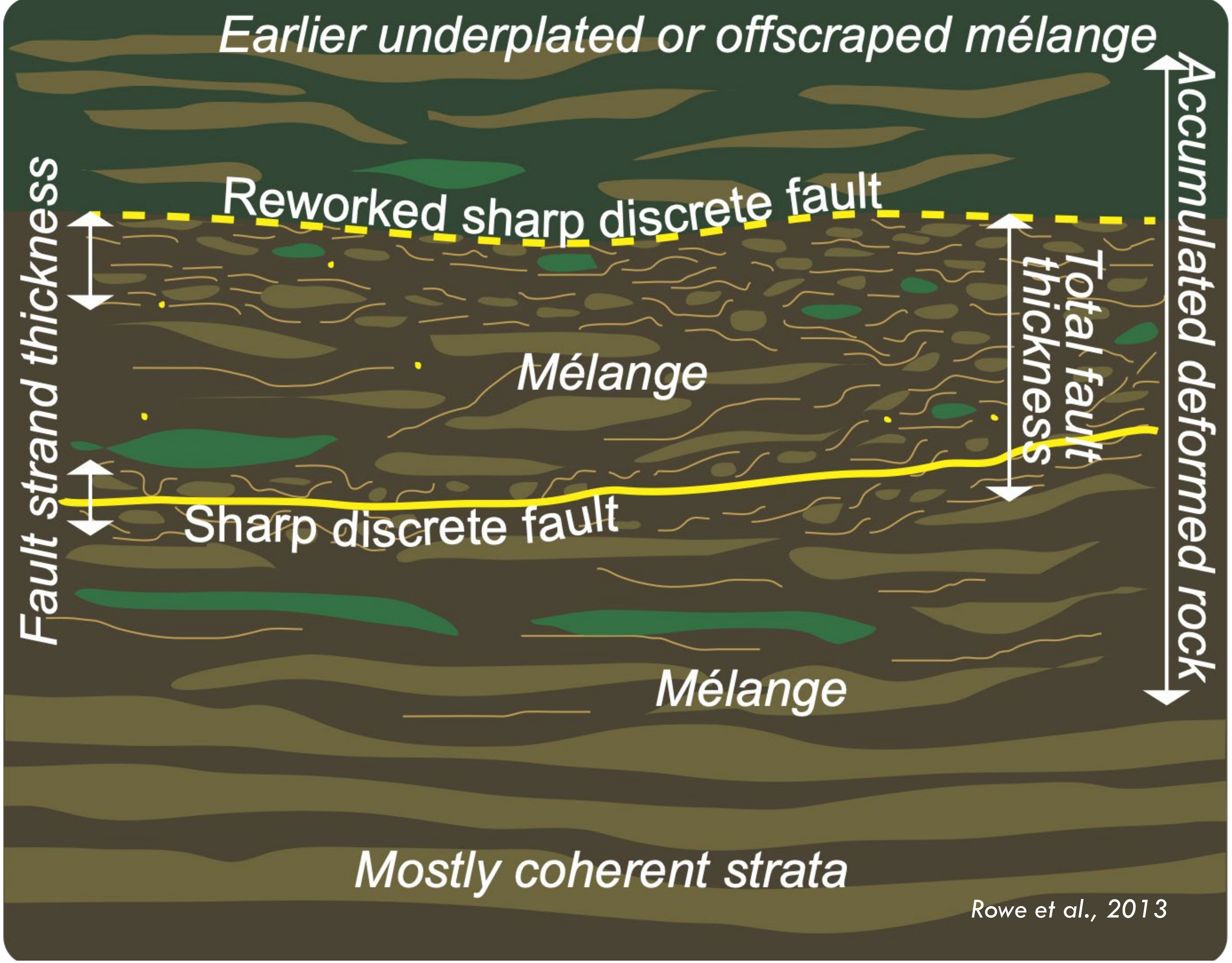
A global context of exhumed paleo-megathrusts:

Kodiak Island, Shimanto Belt, N. Appenines, Franciscan, Cascadia Olympics, and others





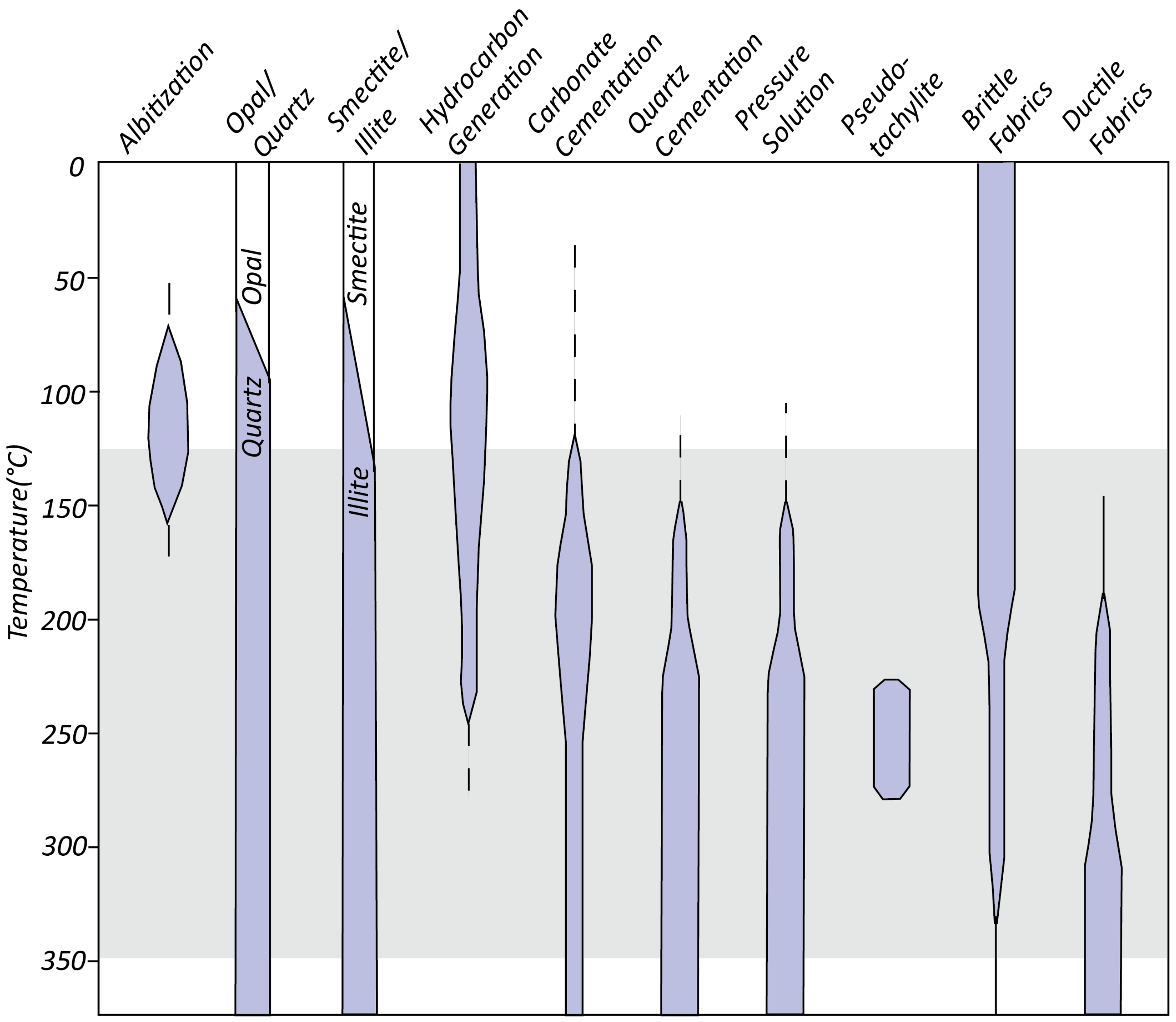
Rowe et al., 2013



Rowe et al., 2013

What controls onset of frictional locking of the shallow subduction zone décollement?

- Fault-normal stress magnitude (burial)
- Strength (rigidity) at fault depth: lithification and cementation
- Pore fluid pressure
- Wall-rock strength (compliance) especially the upper plate

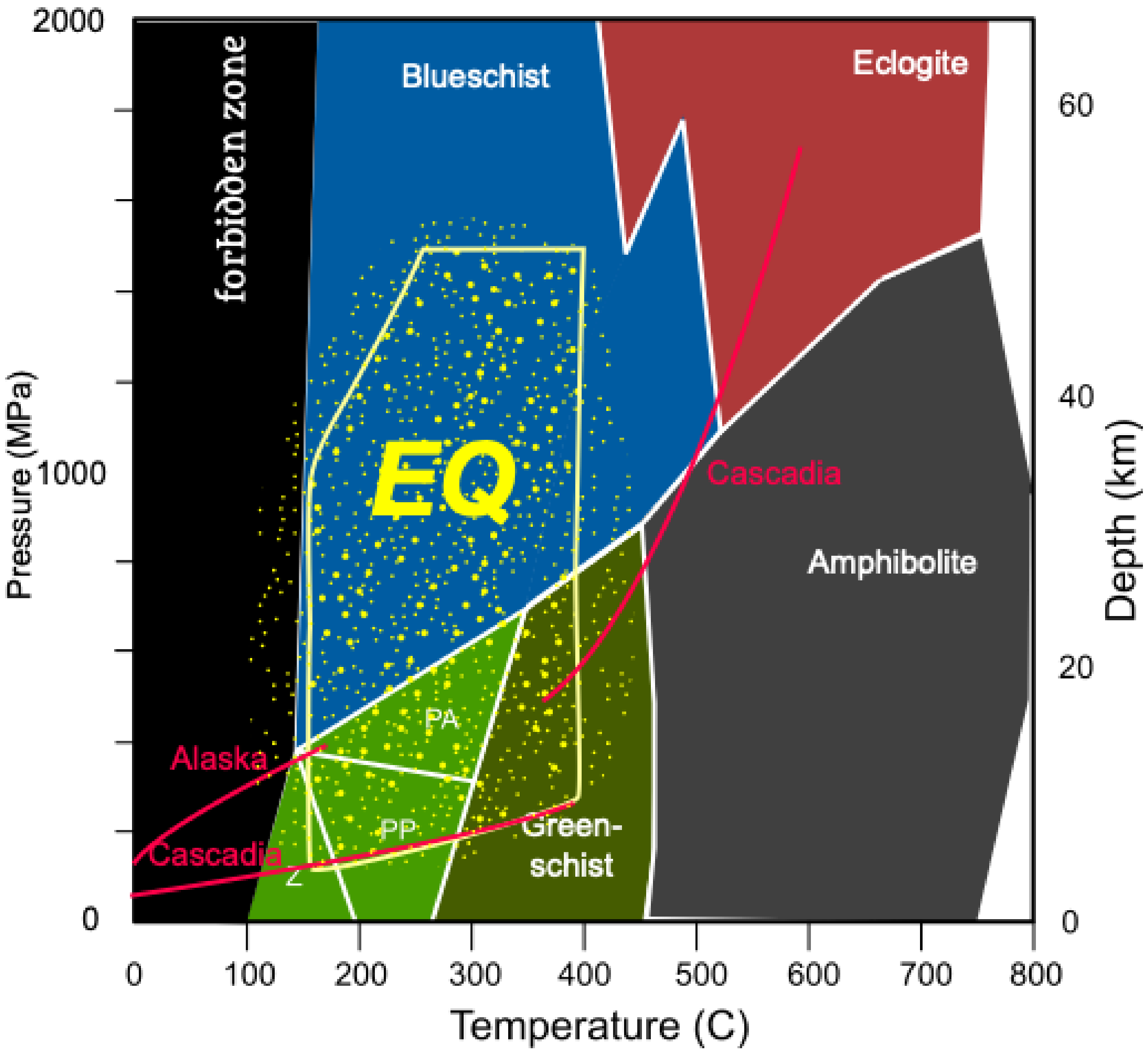


Moore, Rowe, and Meneghini, 2007

- Earthquakes inhabit a temperature range mostly between 100 and 400 C

- Cascadia plate boundary traces a very high T, low P path

- Constrains the diagenetic & metamorphic environment for the seismogenic fault zone

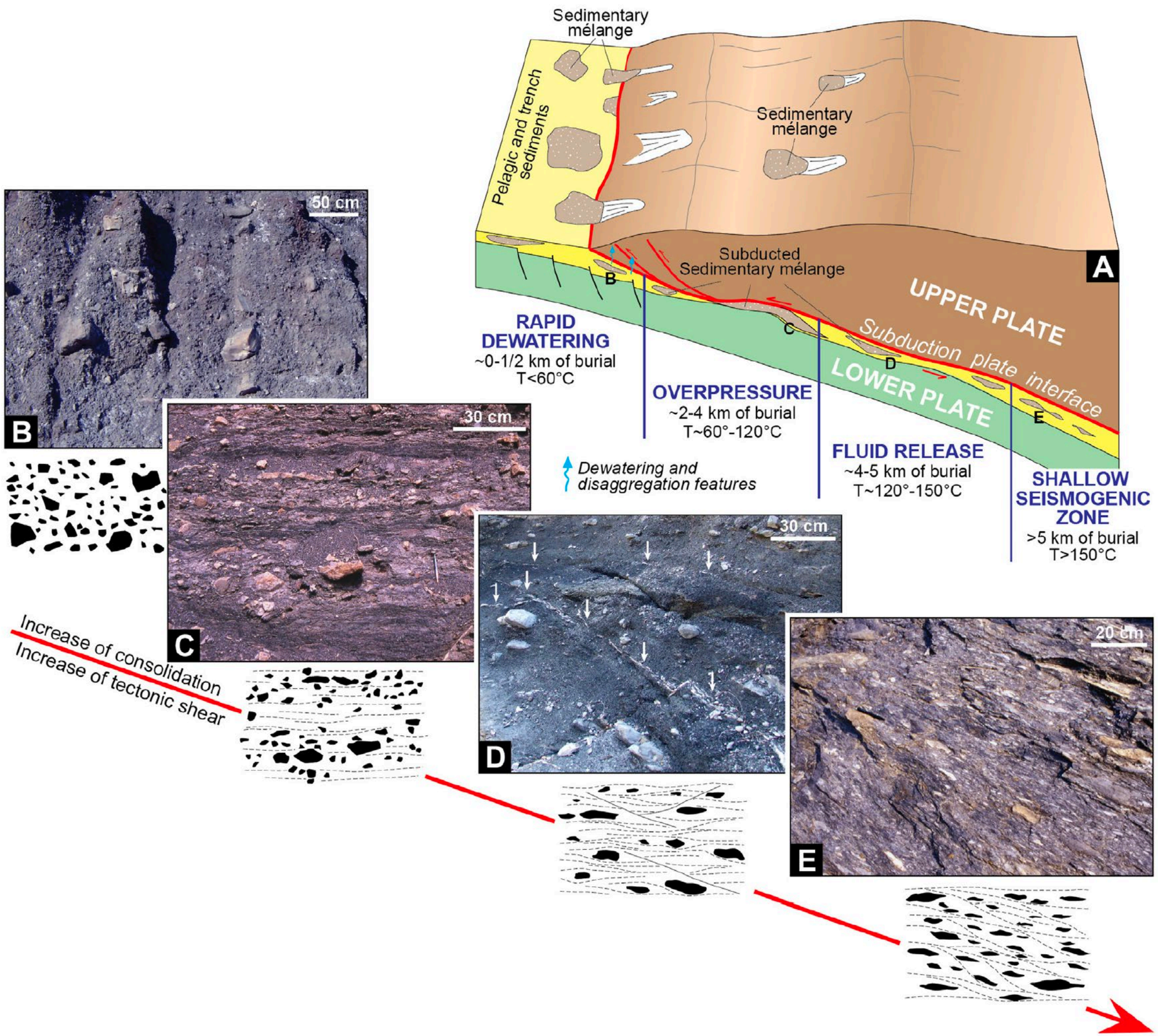


Update from Moore et al. (2007) provided by C. Rowe

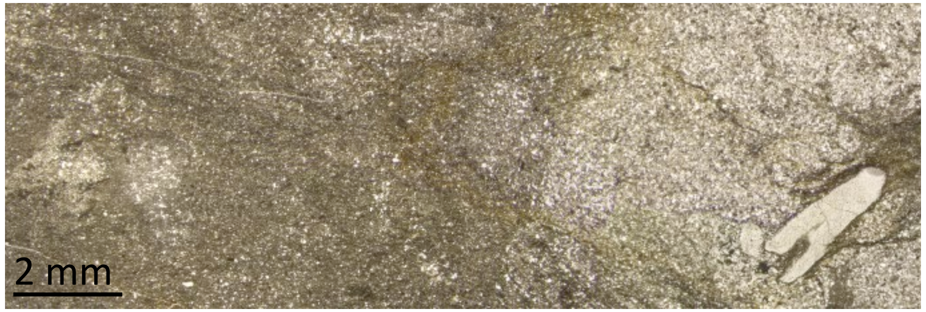
Shallow evolution of the plate boundary zone

- Intact stratigraphy +/- sedimentary mélange or mass transport complexes (disordered)
- Progressive burial, temperature, and tectonic stresses → development of quasi-planar scaly foliation & block-in matrix fabric
- Veins can be abundant, carbonate to qtz
- 10s to 100s of meters in width can develop

A. Festa et al. / Gondwana Research 74 (2019) 7–30

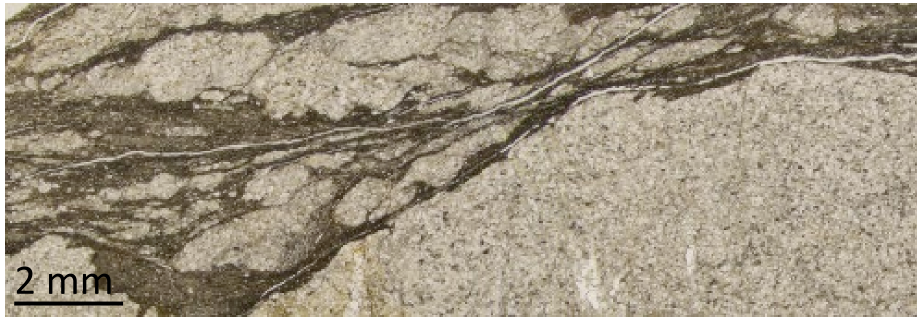


Fabric development (Olympic example)

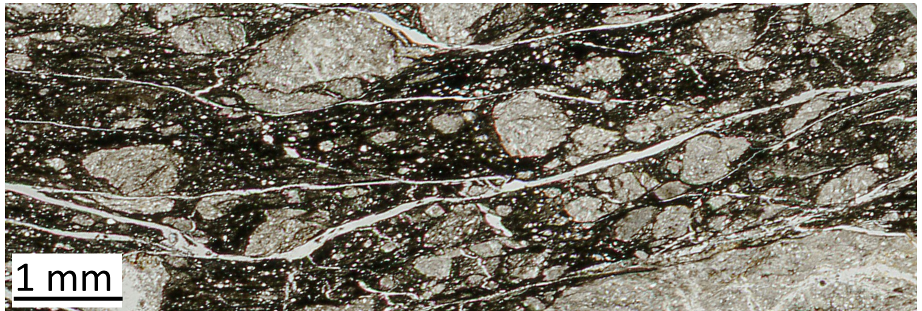


Primary sedimentary structures

Boudinage of sandstones



Formation of **scaly fabrics**



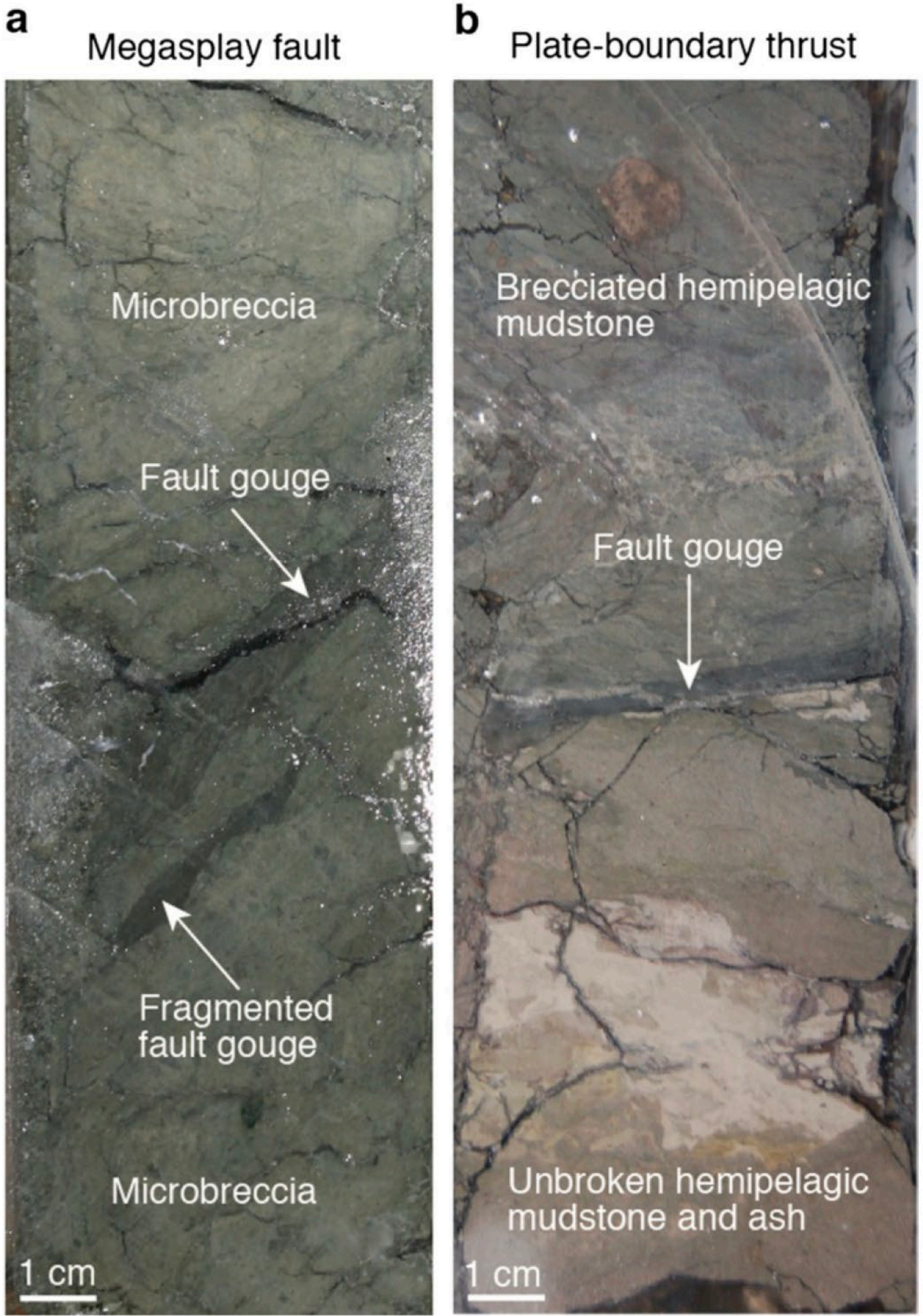
Further **scaly fabric** development

Ledeczi et al. (in review)

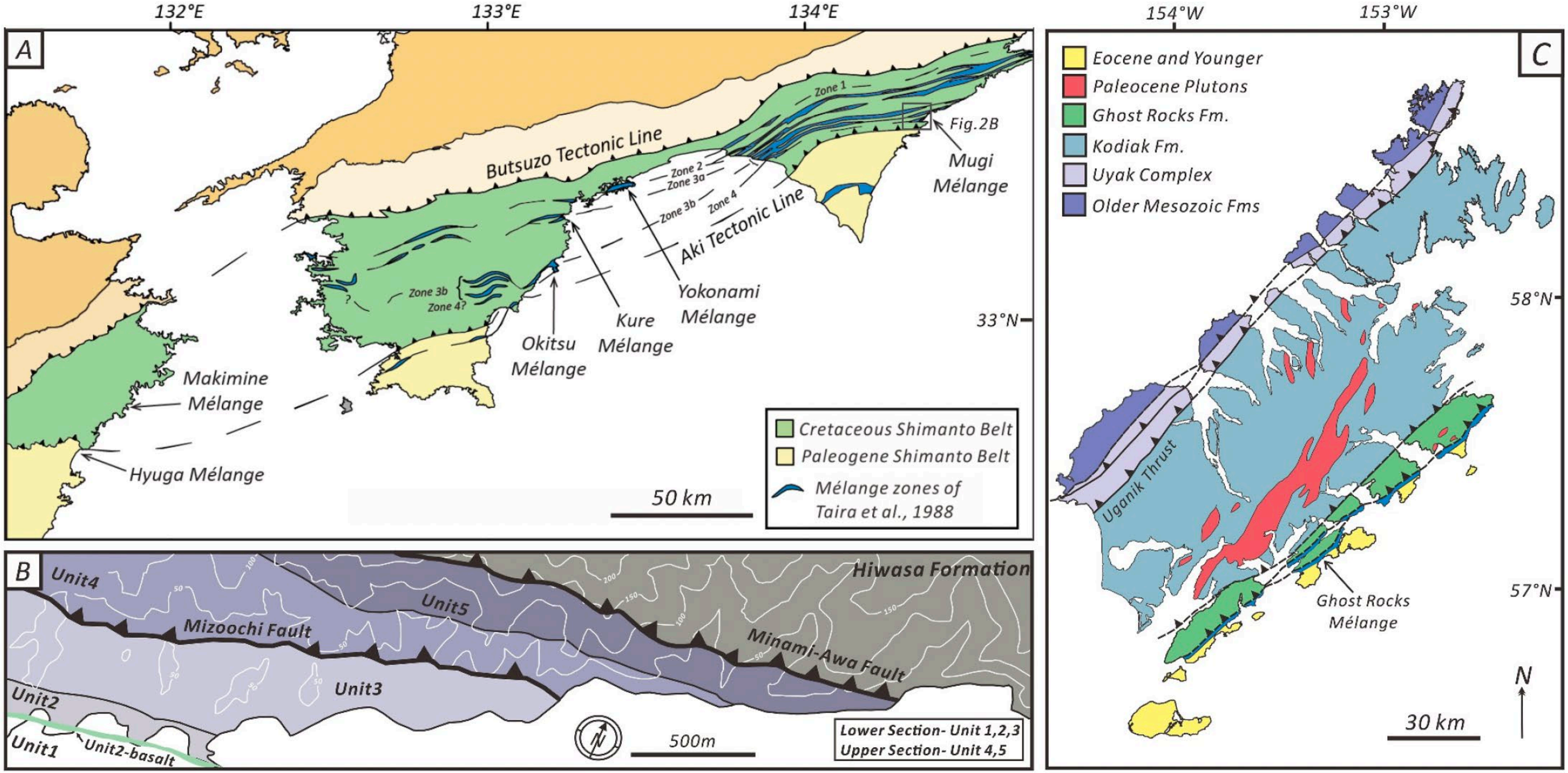
Shallow evolution of the plate boundary zone

- Even in very shallow settings (<1 km below surface), localized brittle fault materials are observed (Nankai Trough and Japan Trench drilling programs) with evidence of seismic frictional heating

- Dynamic rupture to the near-surface is apparently common in megathrust events – even in porous, weakly-lithified sediments



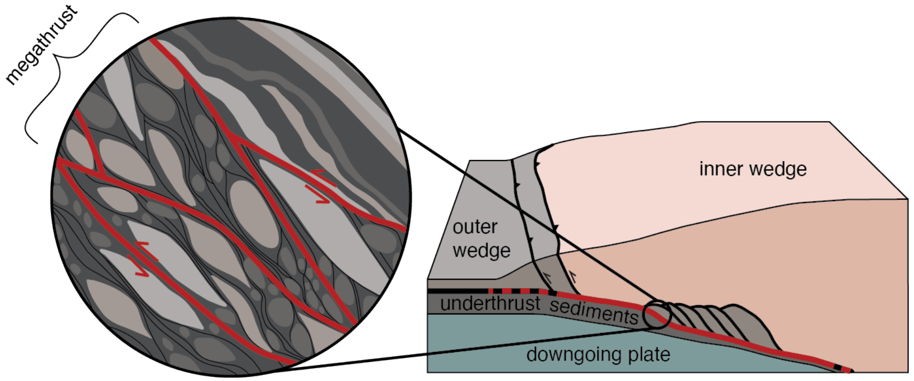
Ujiie and Kimura, 2014



Chen et al., 2024

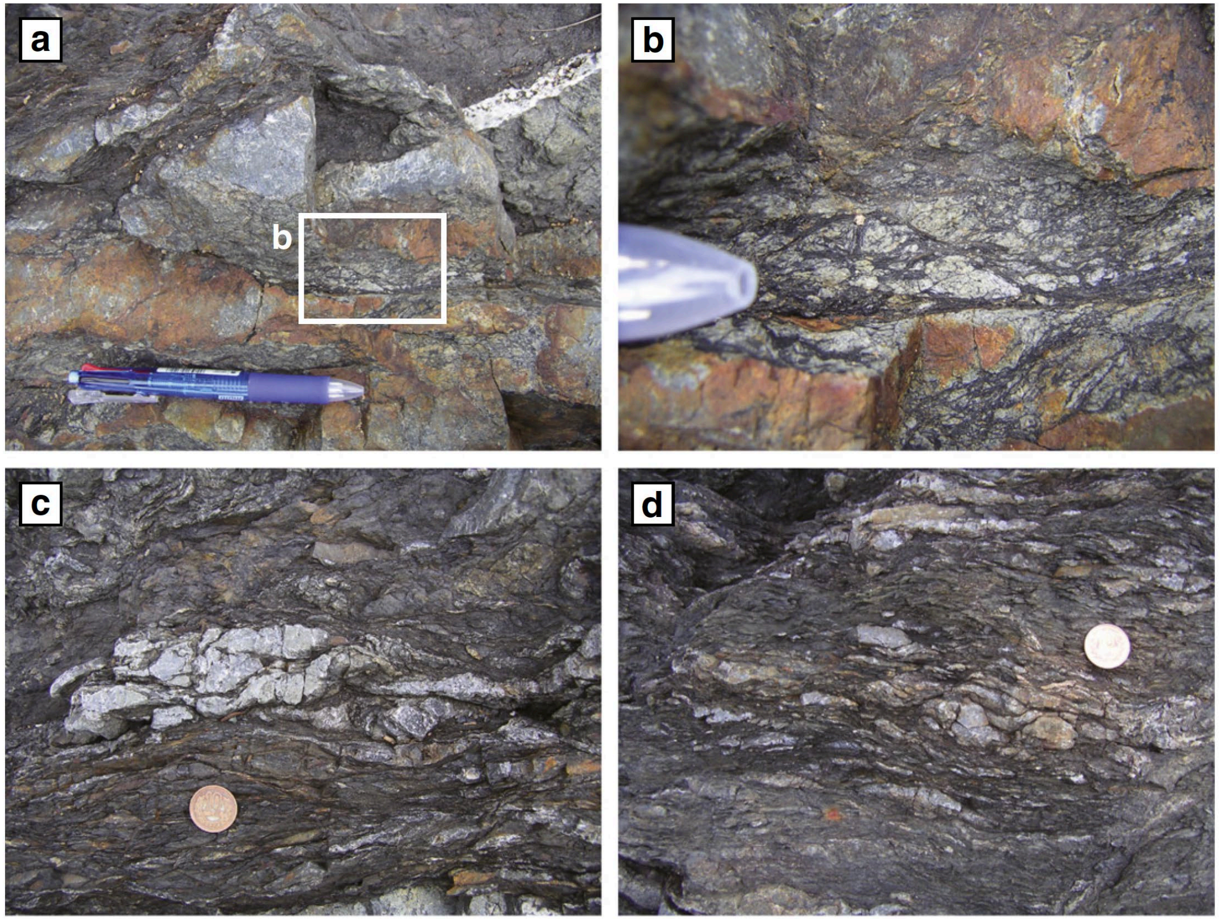
Formation of subduction mélanges

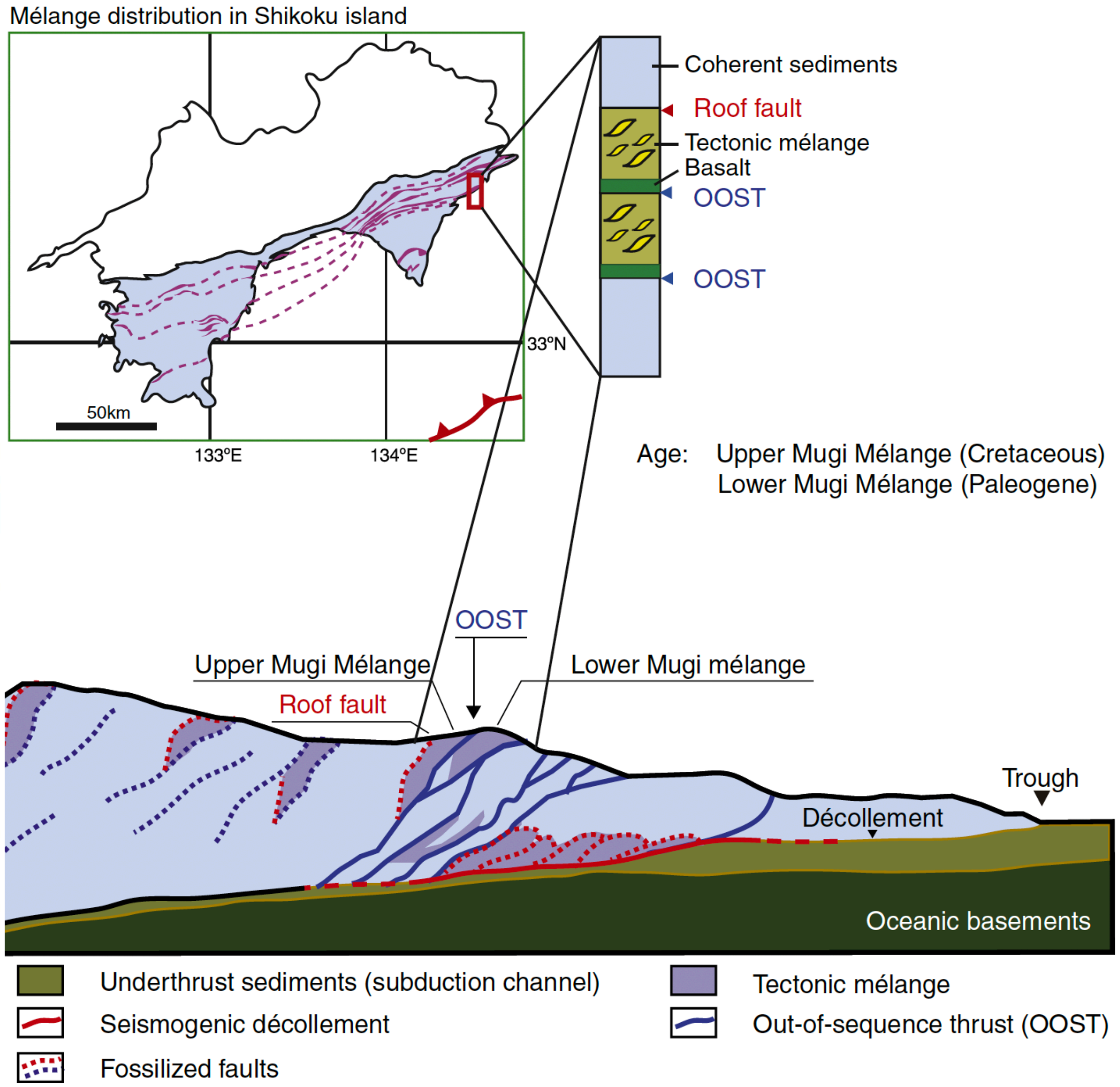
- Regionally extensive, planar zones of disrupted strata parallel to boundaries of identifiable accreted packages
- Many examples globally: Shimanto Belt, Kodiak, Franciscan, Olympic, N. Appennines, etc. etc.
- Block-in-matrix fabric of usually pelitic (mudstone) matrix surrounding blocks of competent : sandstone, basalt, chert, limestone
- Many form during initial underthrusting of sedimentary (+/- upper basaltic units) strata beneath a shallow decollement.
- Pressure-solution (diffusive mass transfer) and layer-parallel shear dominate. Melange is <u>not</u> the rock of fast seismic slip.



Mugi mélange system setting

Macroscopically "ductile" fabrics built by frictional cataclastic damage and particulate flow



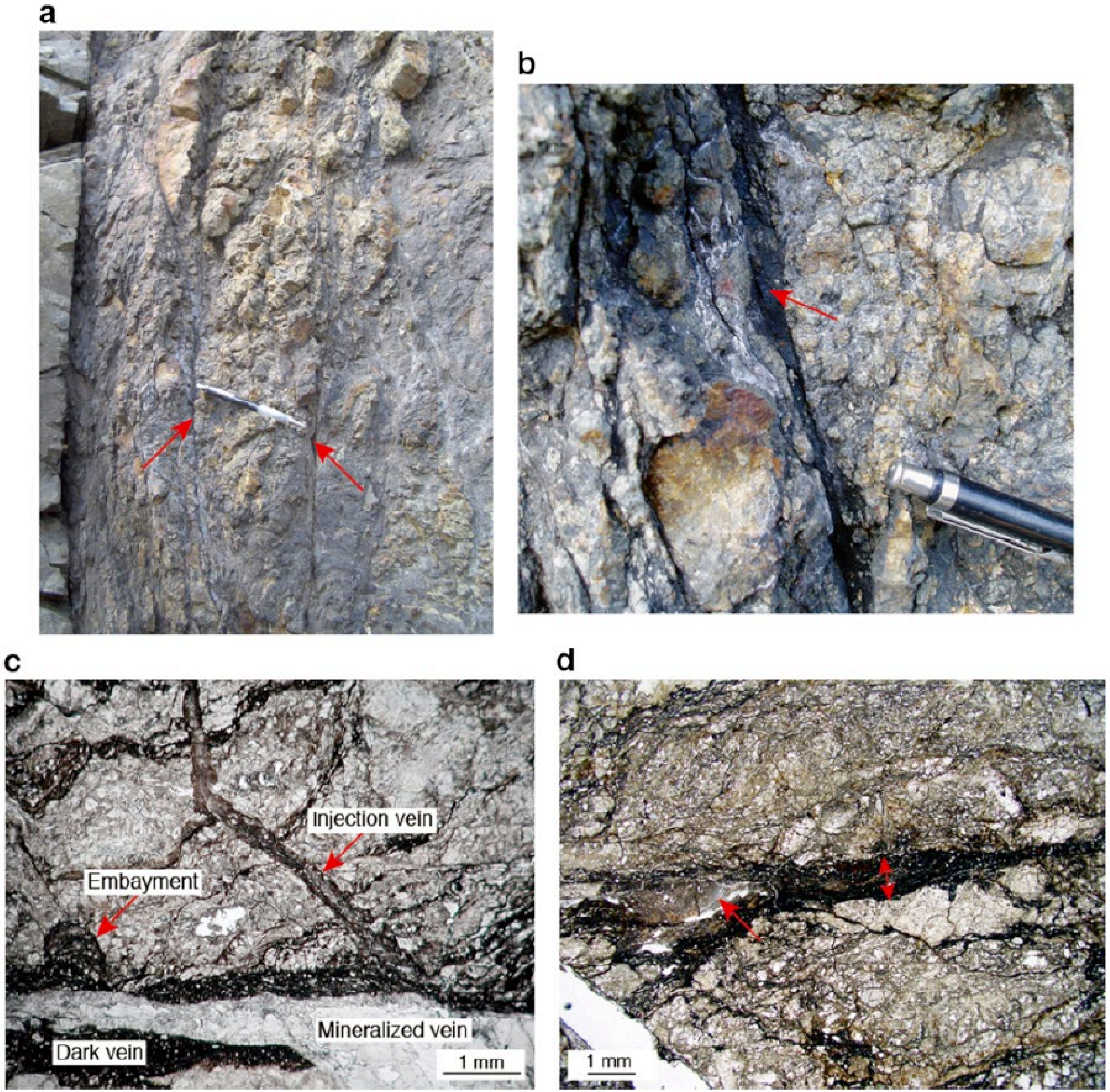


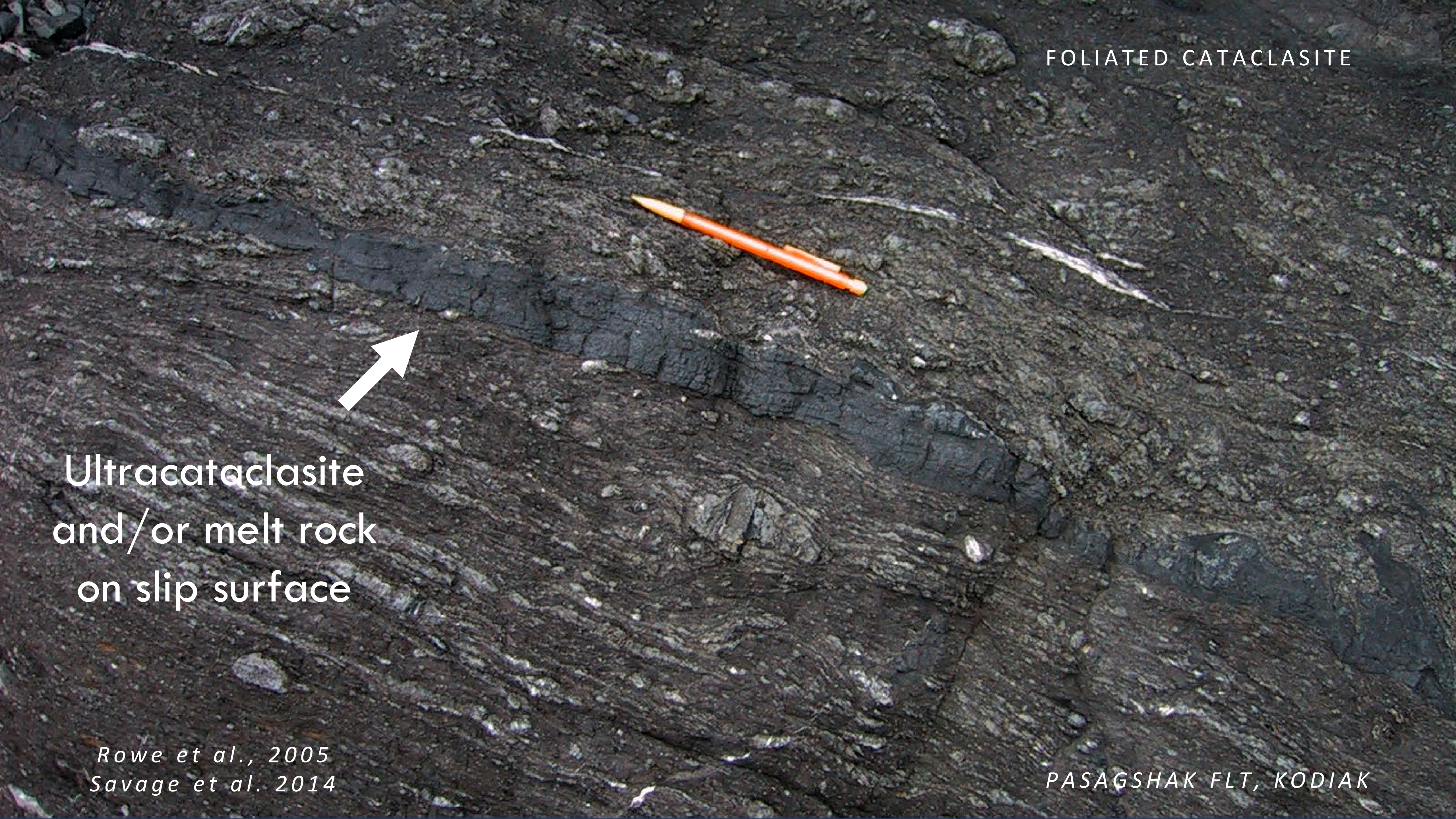
Kitamura & Kimura, 2012

Localized “fault strands” and principal slip surfaces

- Hosted within the broader mélange environment
- Concentrated brittle features:
  - Riedel systems of fractures
  - Breccia, cataclasite and ultracataclasite (“black fault rock”)
  - maybe pseudotachylite
  - Mineralized veins, slickensided surfaces, etc.
- Total thickness of <1 to 20 m

Ujiie and Kimura, 2014



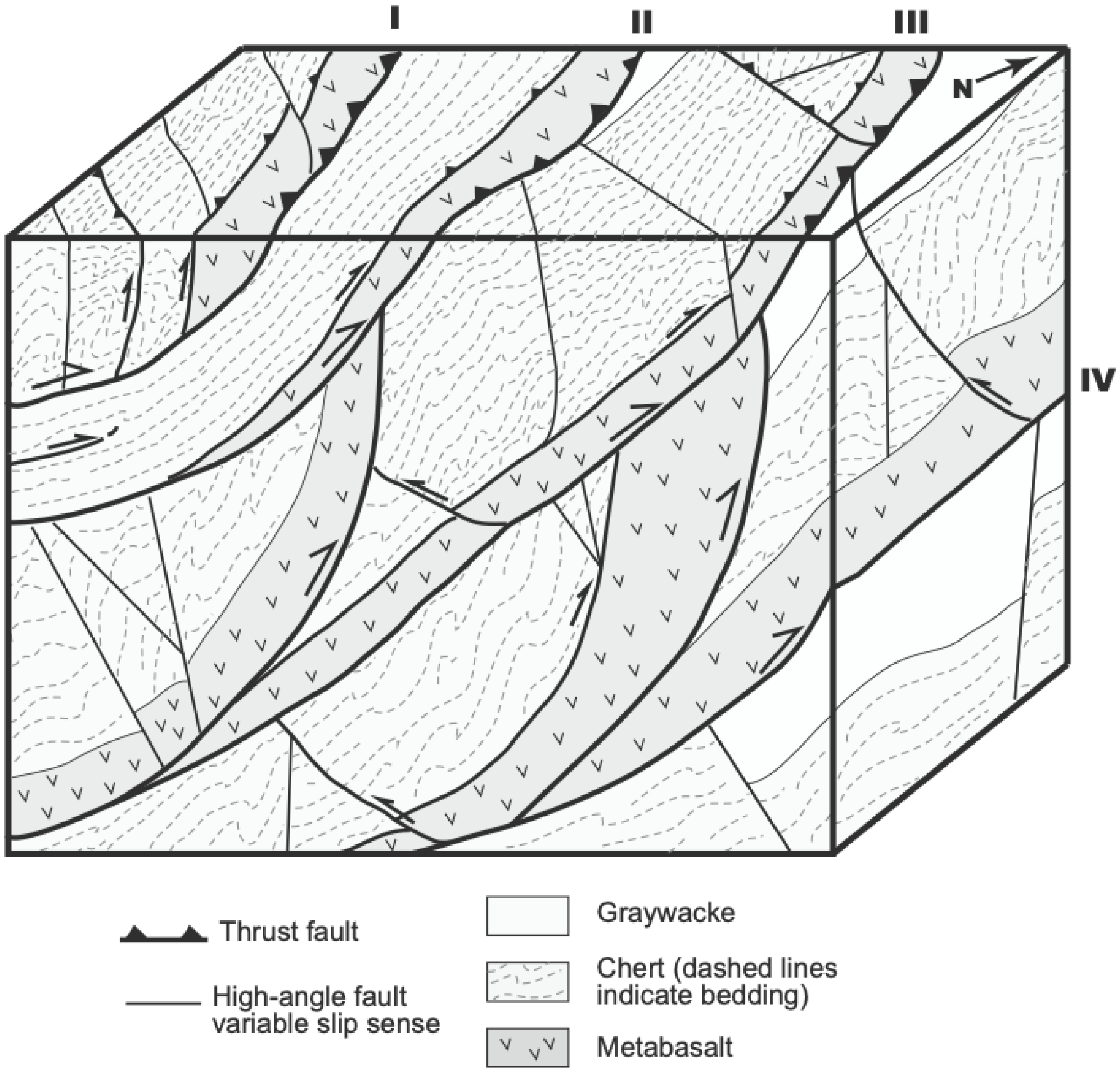

FOLIATED CATACLASITE
Ultracataclasite
and/or melt rock
on slip surface
Rowe et al., 2005
Savage et al. 2014
PASAGSHAK FLT, KODIAK


Canon
Brodsky, Rowe et al., 2009

MARIN HEADLANDS TERRANE

Multiple underplating slices on short length scale are recognized

- Each imbricate base is basalt, requires that decollement cut down section into oceanic basement
- Steeper splay faults active at the same time as major thrusts
- Similar architecture to the Mugi mélange in Shimanto



Regalla et al. 2018

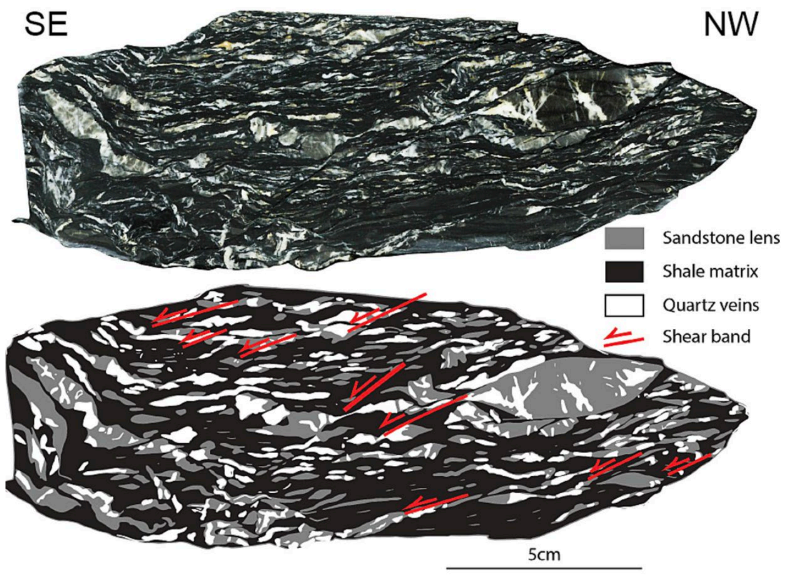

Weathered meta-basalt
Sandstone-shale mélange
Regalla, Rowe et al. 2018

Vein evidence of fluid involvement

Quartz and carbonate veins are more abundant in the shallow and deep transitions, relatively less abundant in the main seismogenic zone

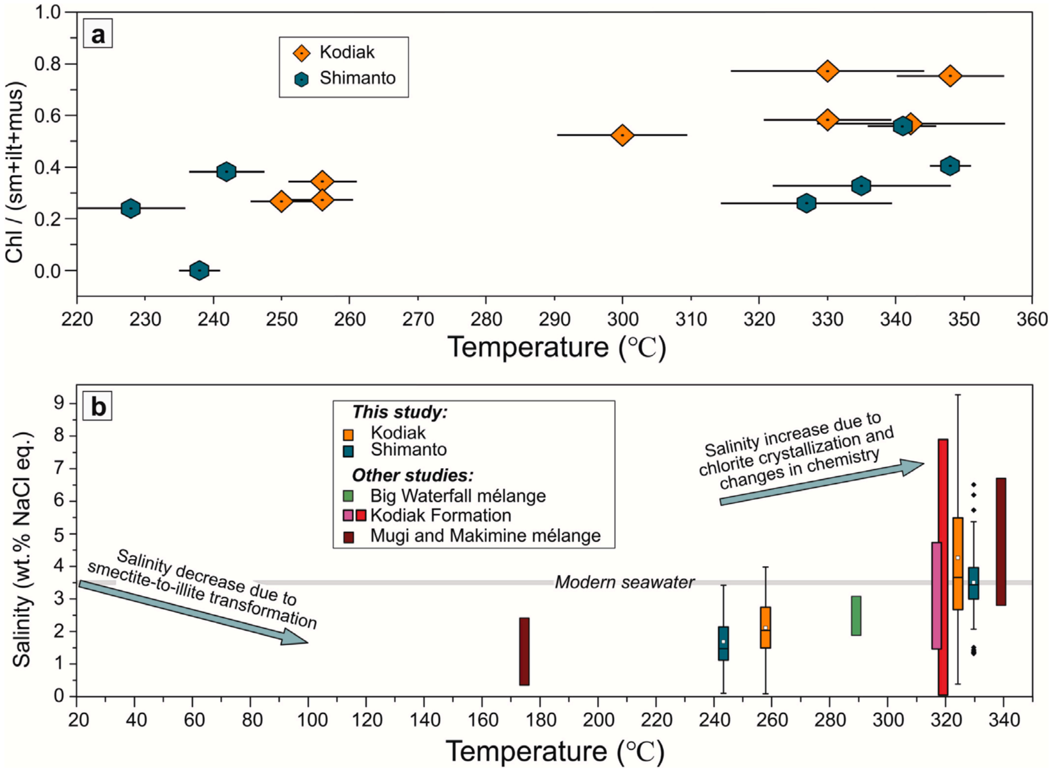
Vein chemistry in SZ is generally host-rock buffered, indicating local sources of the silica and carbonate.

Chloritization consumes pore fluids at ~250 – 350 C and limits circulation in the seismogenic zone. e.g., Rajic et al., 2023; Chen et al., 2024

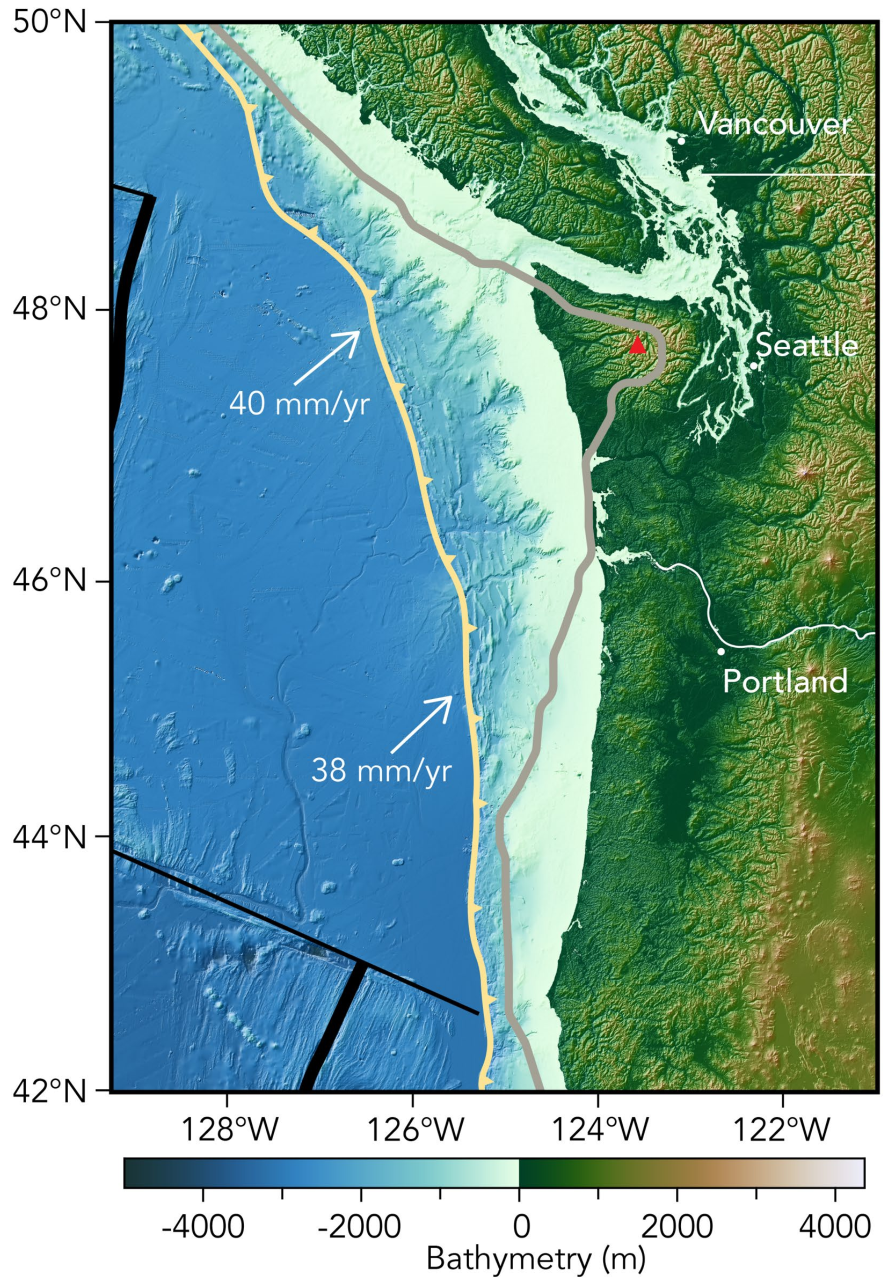


Rajic et al., 2023

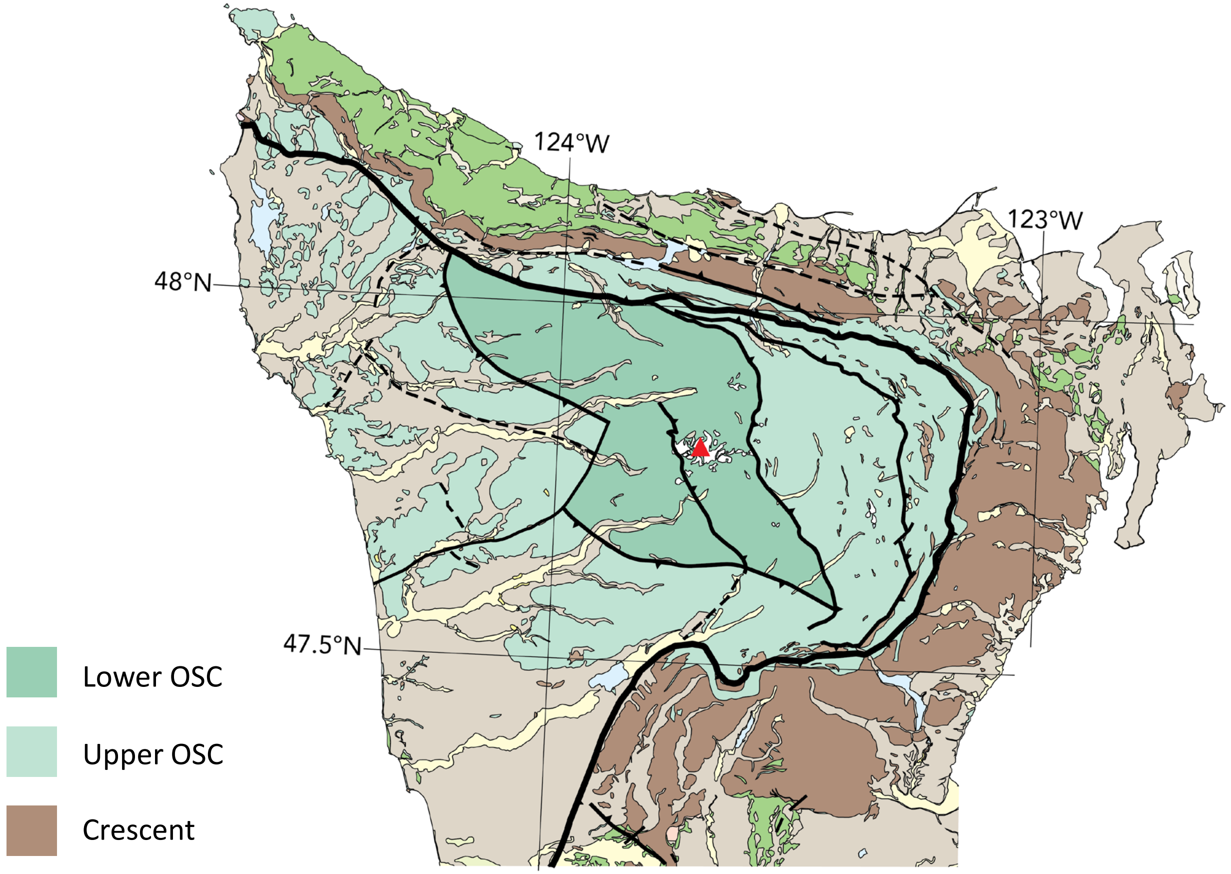
Ghost Rocks, Kodiak Island: Photo by Christie Rowe



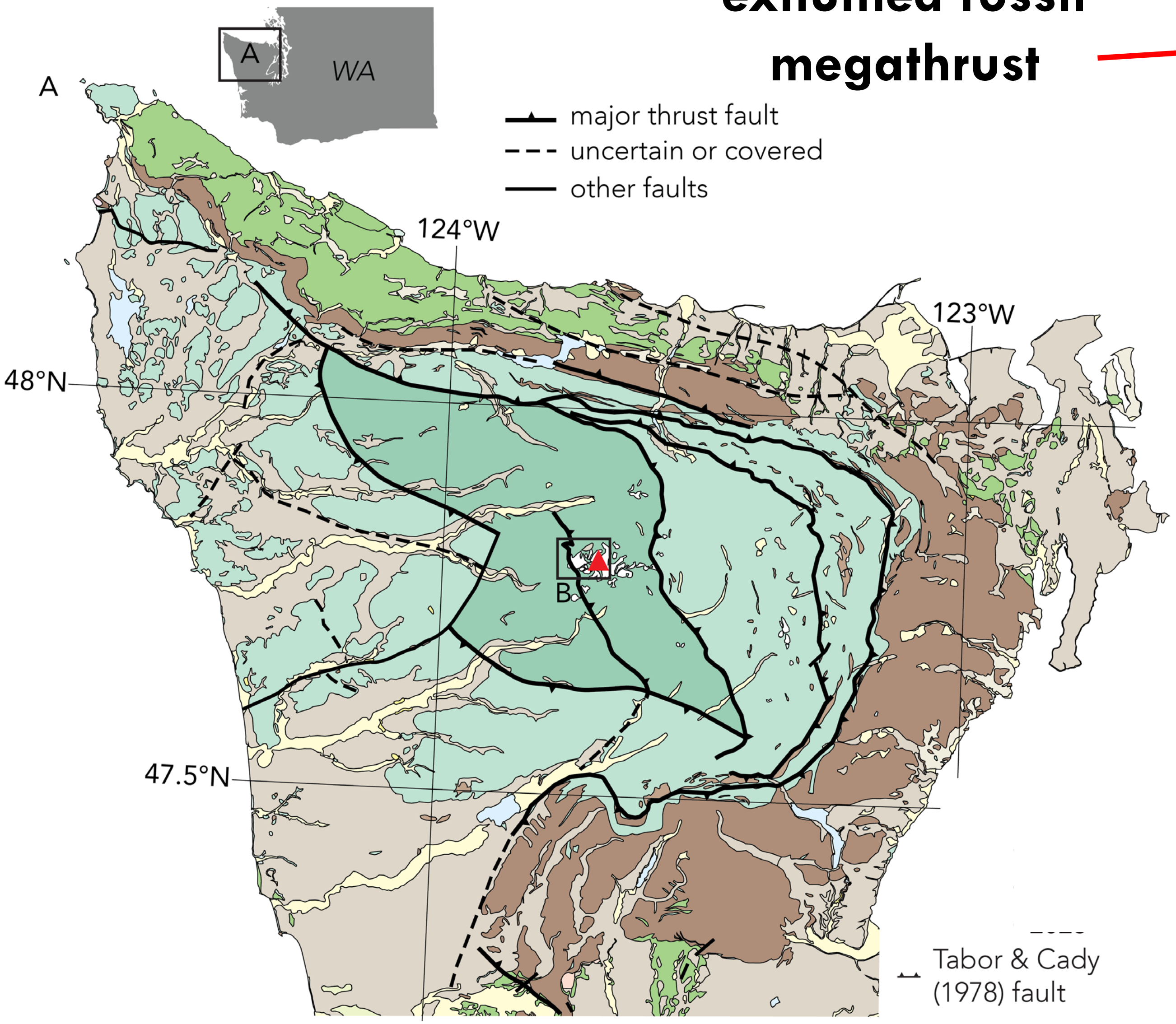
Bringing it to Cascadia: The Olympic Subduction Complex

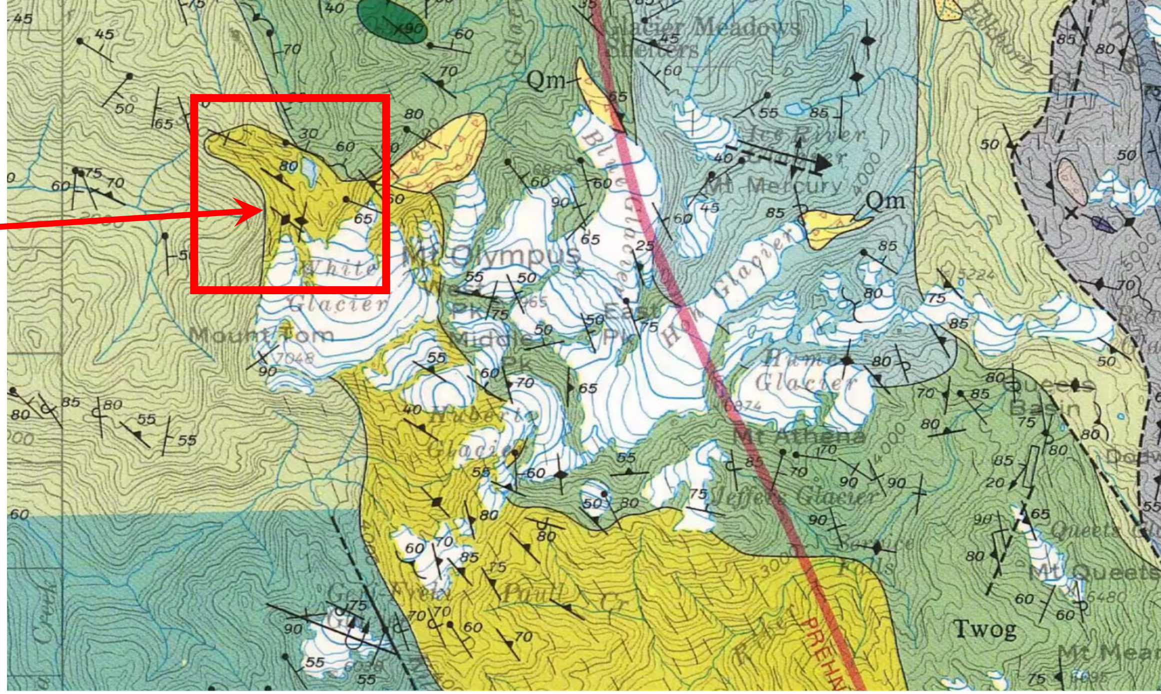


- Internal portions of Cascadia's large, clastic accretionary wedge are exposed onshore only on the Olympic Peninsula
- Continuous subduction of similar age crust and voluminous sediment delivery makes onshore portions a good analog for the modern system

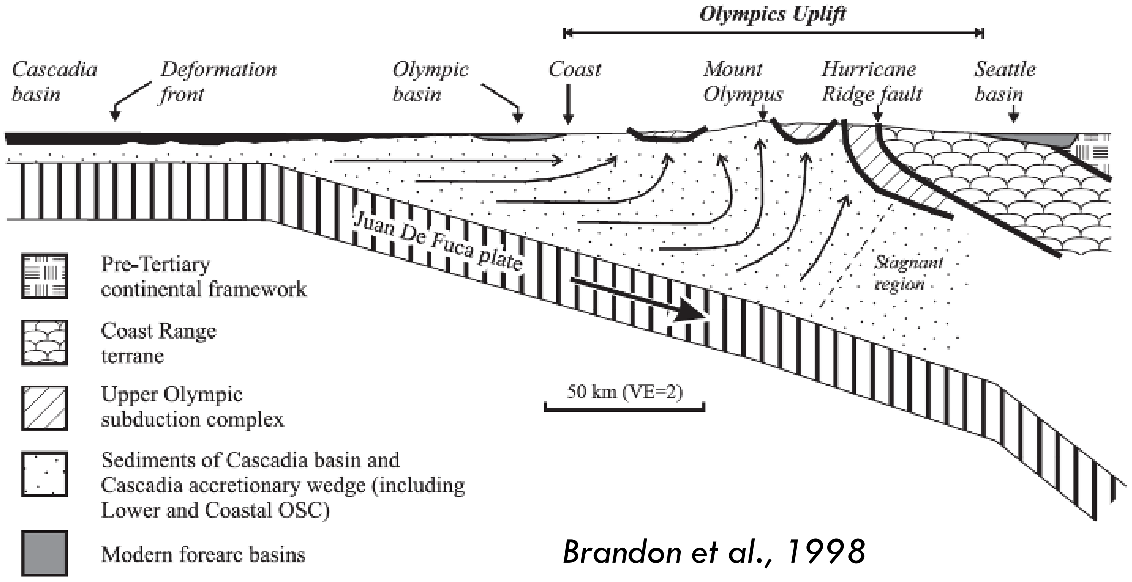


Candidate exhumed fossil megathrust





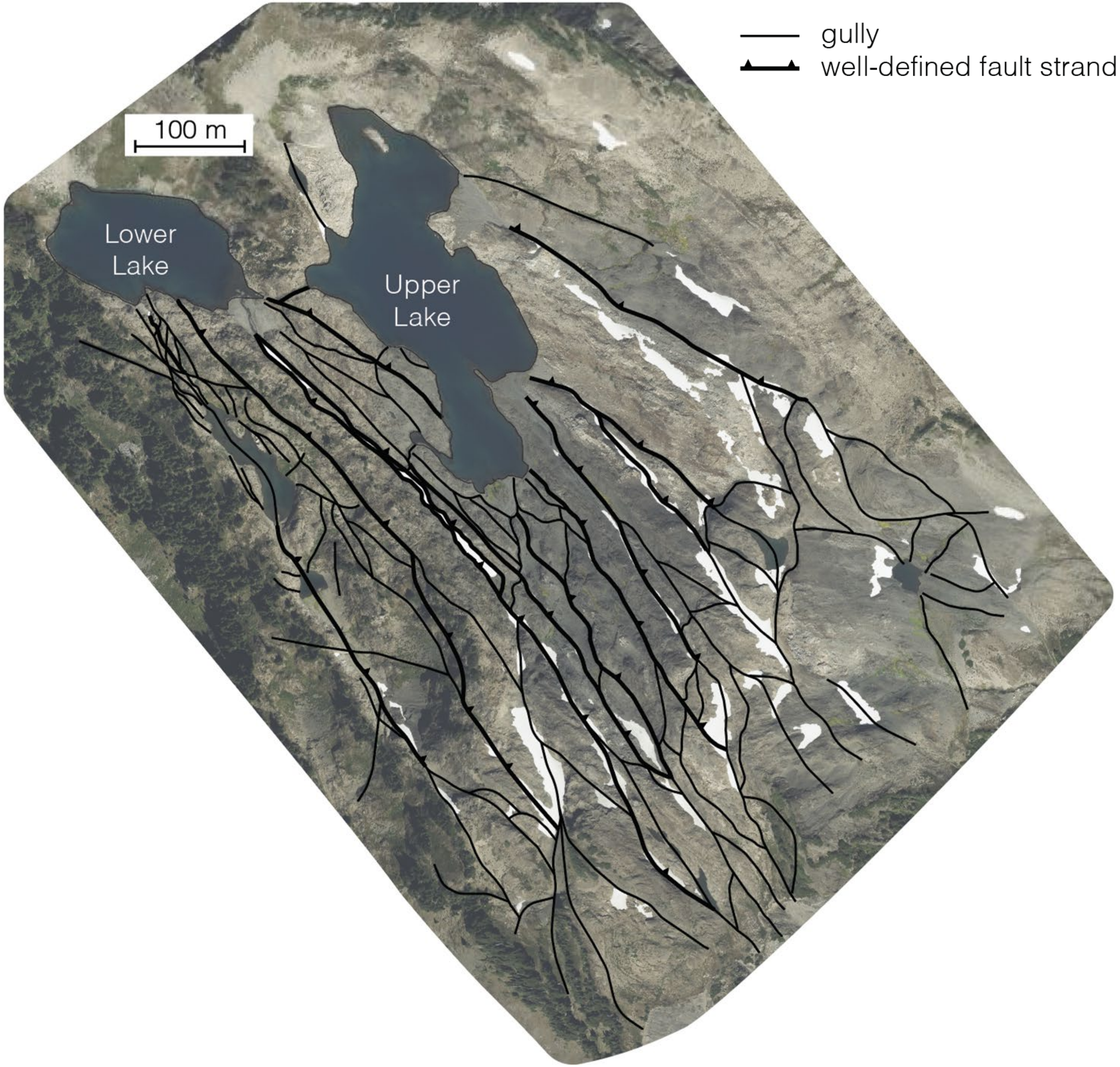
Tabor & Cady (1978)



Brandon et al., 1998

Lakes of the Gods

- Structure
  - ~10 major anastomosing fault strands
  - Surrounded by deformed mélange ~500 meters in thickness
  - Each fault strand contains sharp, discrete principal slip surfaces

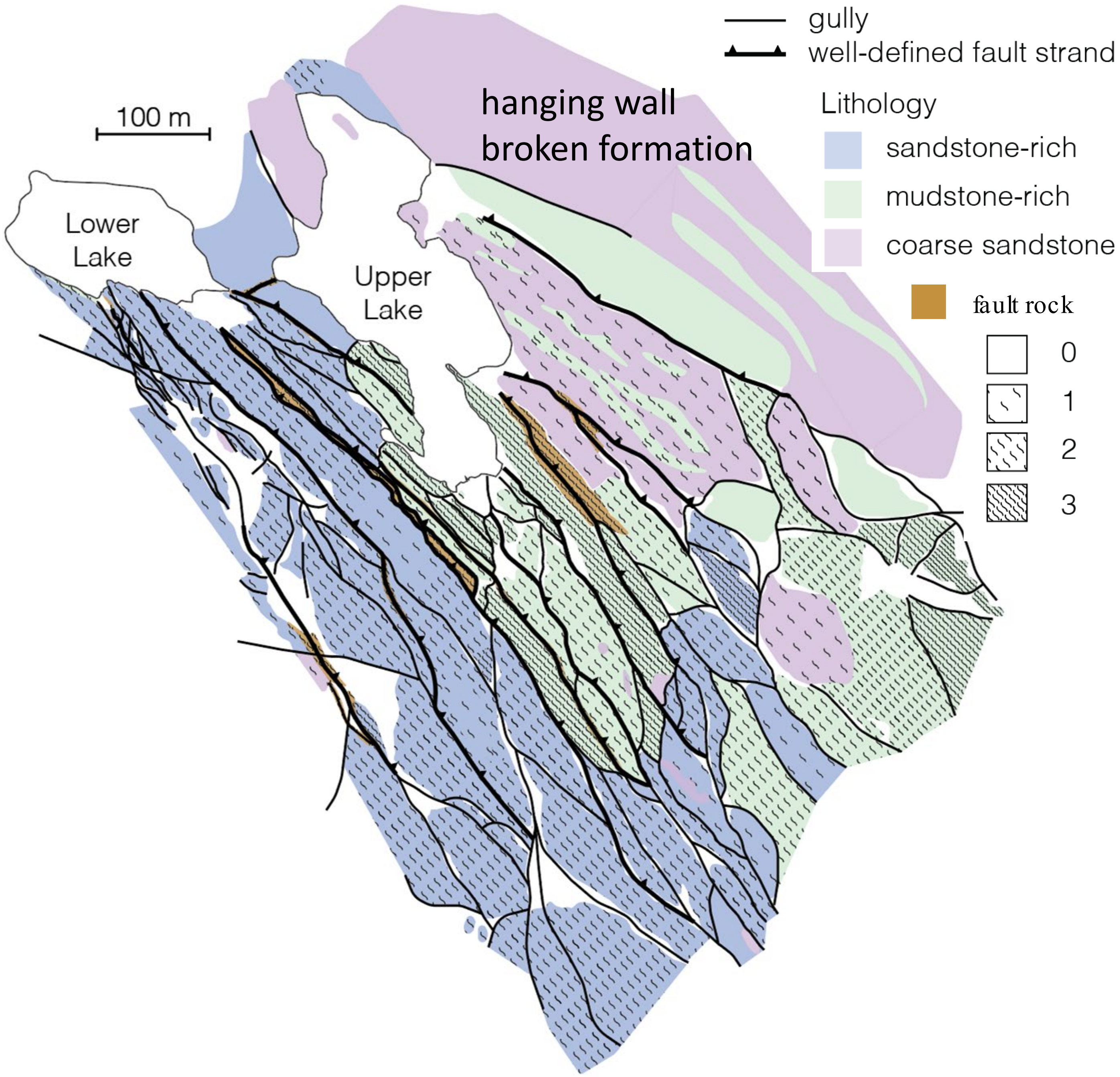


Ledeczi et al. (in review)

Lakes of the Gods

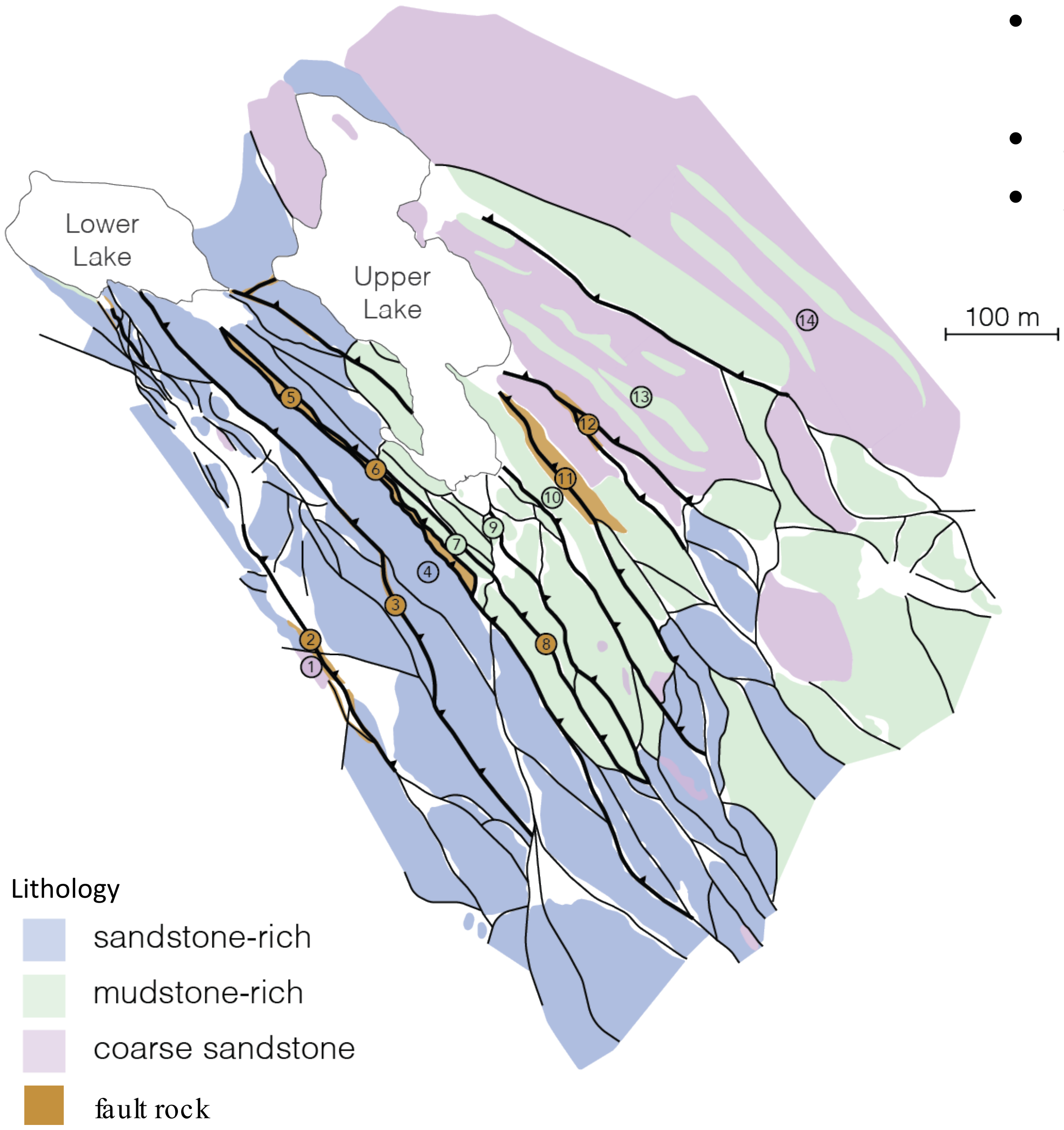
- Structure
  - ~10 major anastomosing **fault strands**
  - Surrounded by deformed **mélange** ~500 meters in thickness
  - Each fault strand contains sharp, discrete **principal slip surfaces**

- Lithologies
  - Sandstones and mudstones only
- Structural Fabrics
  - Quantify degree of development

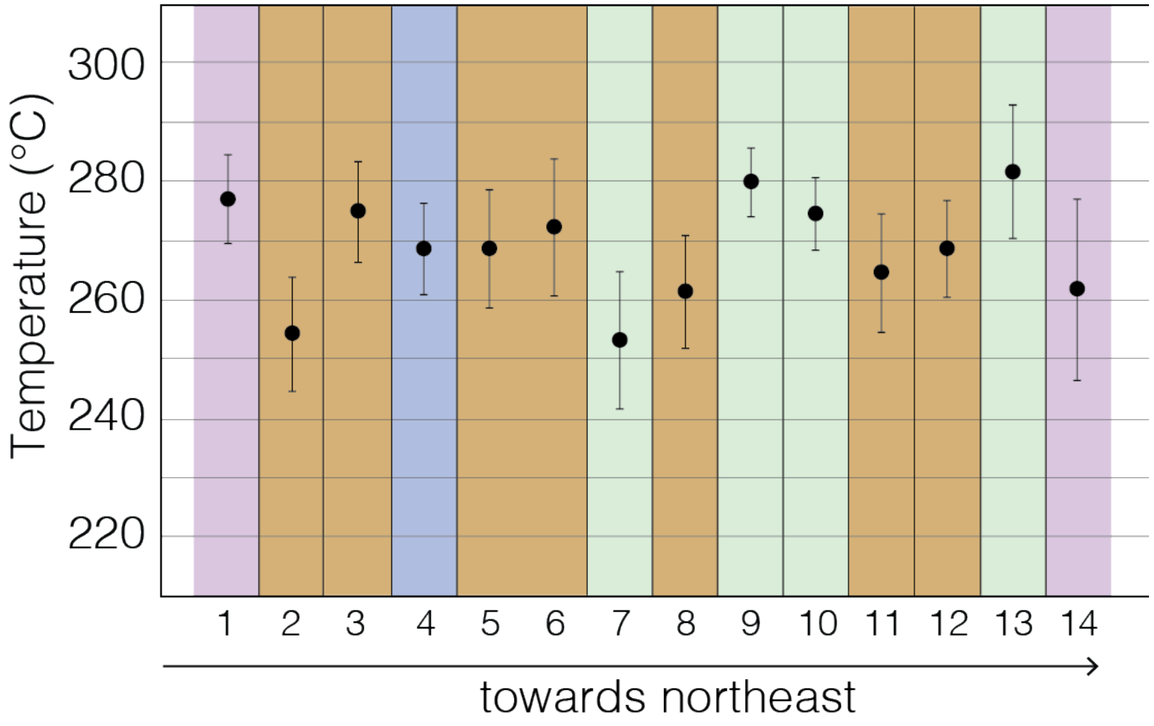


Ledeczi et al. (in review)

Paleotemperature with RSCM

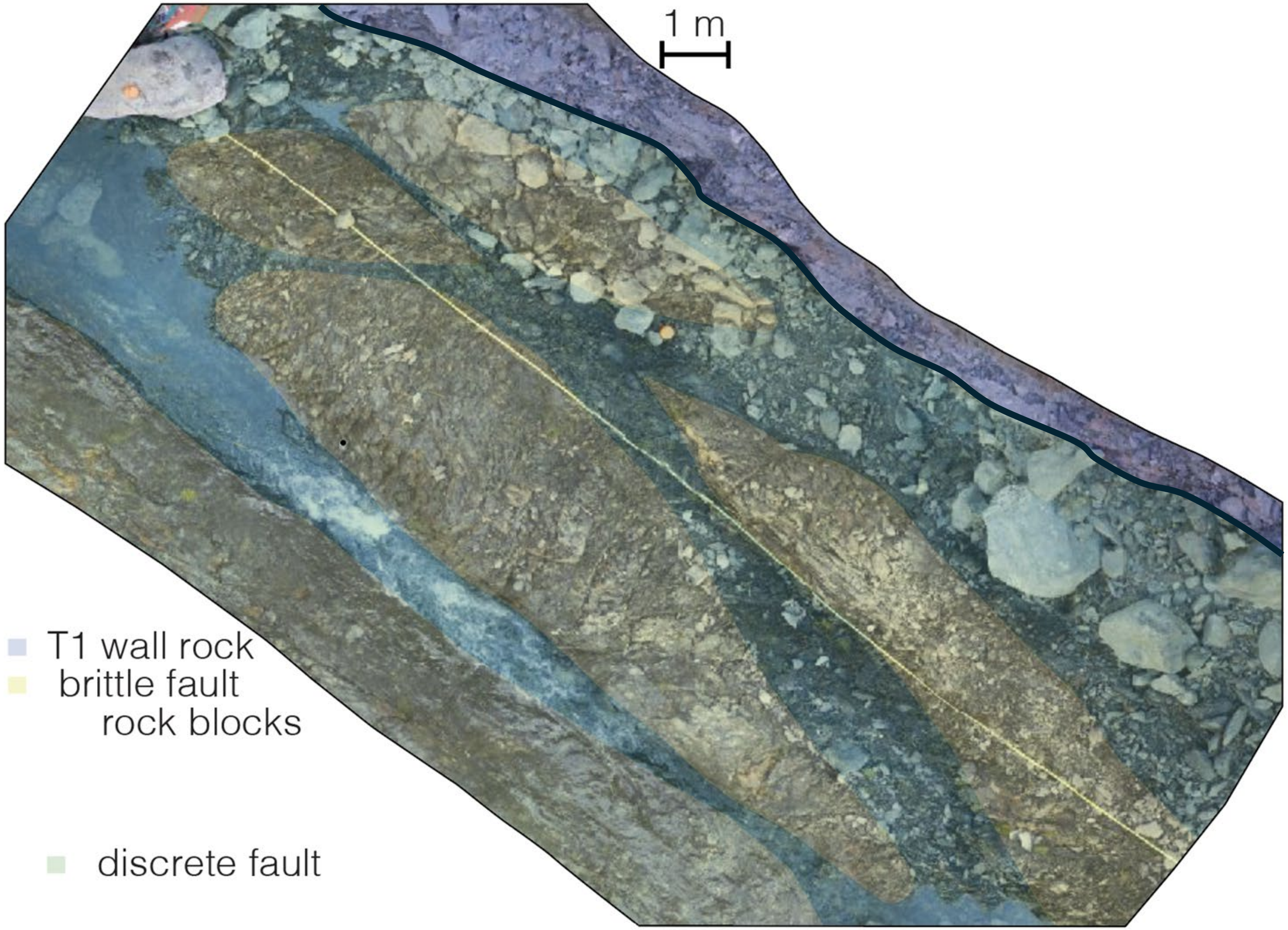


- Paleotemperature using Raman spectroscopy of carbonaceous material (RSCM)
- Seismogenic zone temperatures of 255 to 280°C
- Suggests the entire fault zone was accreted as one package and does not represent an intra-wedge fault

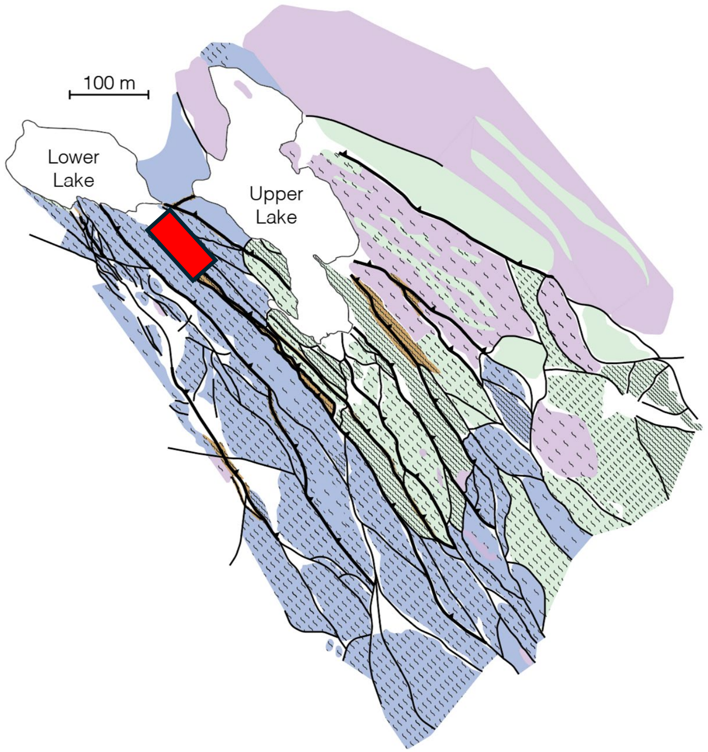


Ledeczi et al. (in review)

Discrete fault strands



- Discrete faults anastomose around blocks of brittle fault rock



Ledeczi et al. (in review)


VERSIONS
TO FIND
centimeters
centimeters
meters
kilometers
inches
inches
feet
yards
miles
grams
kilograms
ounces
pounds
milliliters
liters
liters
liters
fluid ounces
liters
gallons
Millimeters
1.5875
3.1750
4.7625
6.3500
7.9350
9.5250
12.700
15.875
19.050
22.225
25.400
50.800
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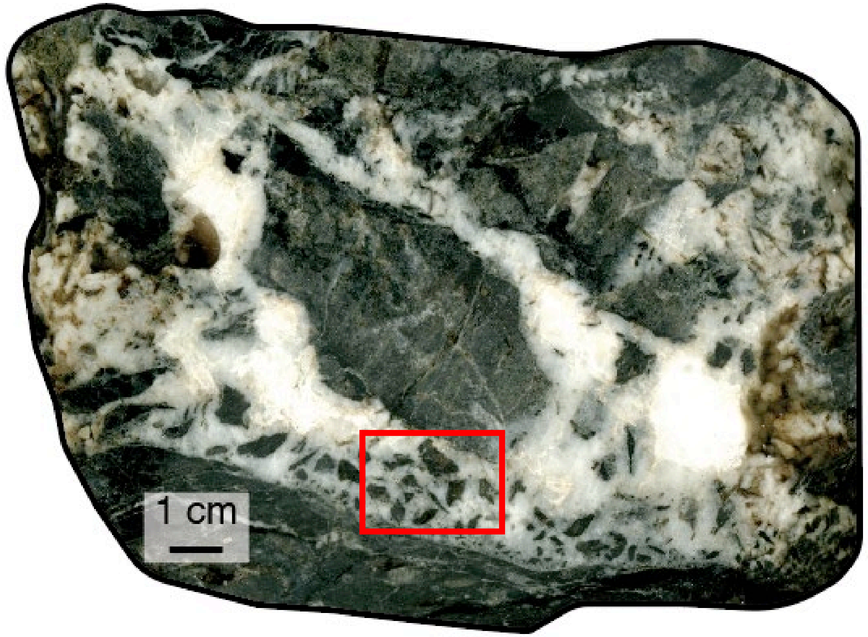
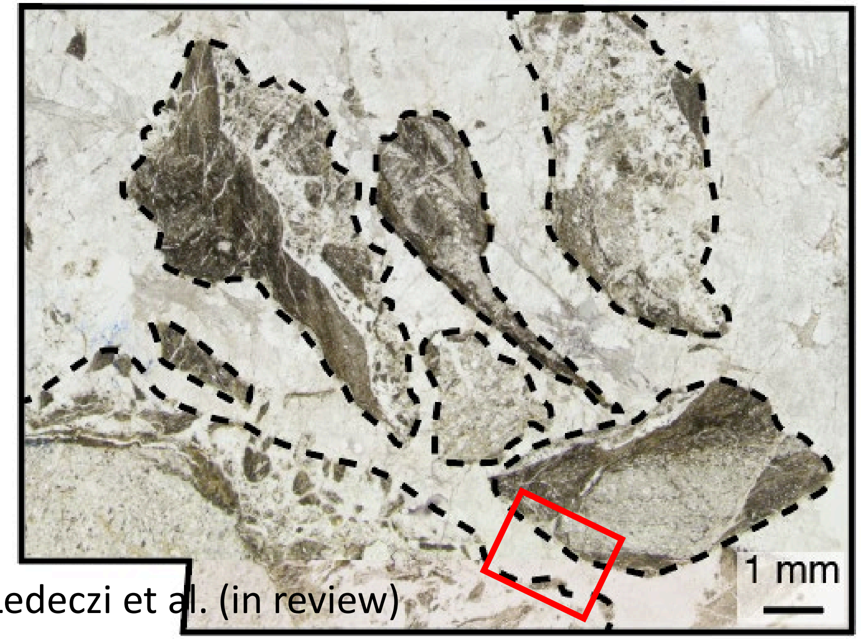
101.60
127.00
152.40
177.80
203.20
228.60
254.00
279.40
304.80

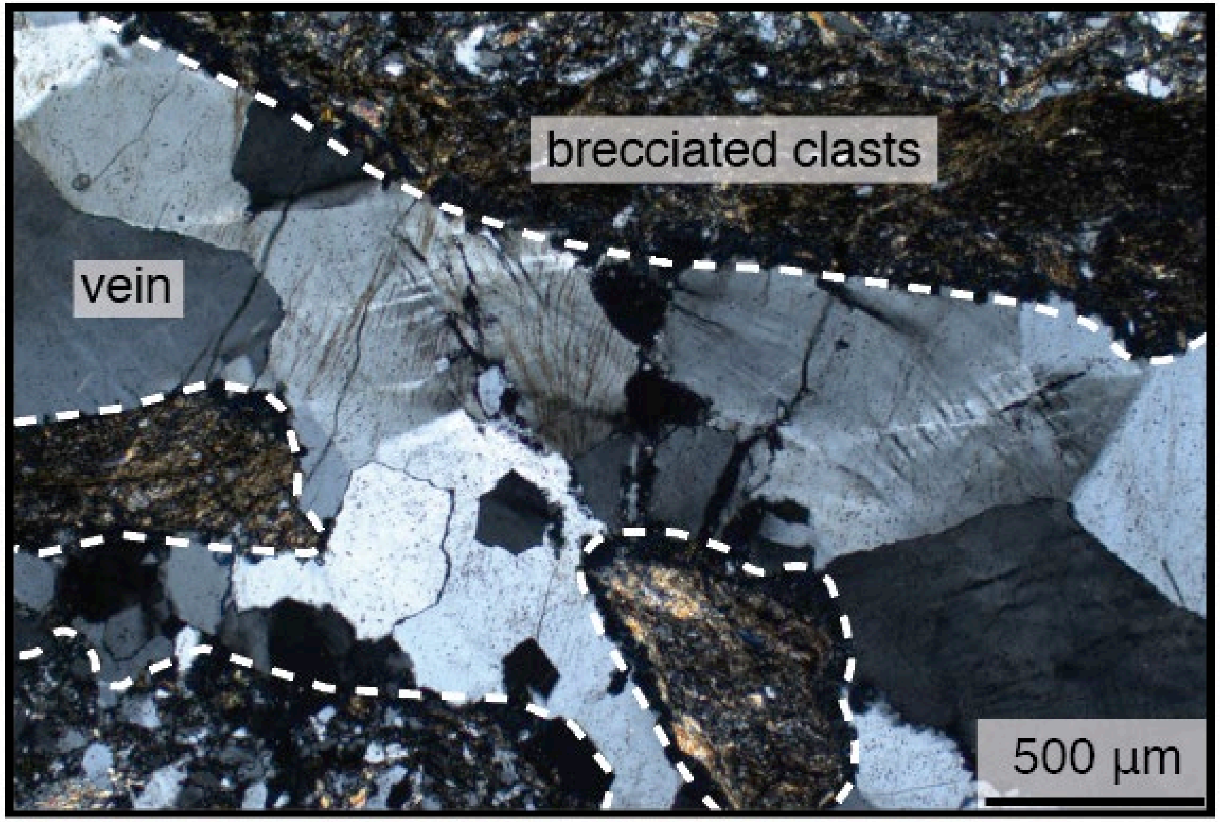
Brittle deformation





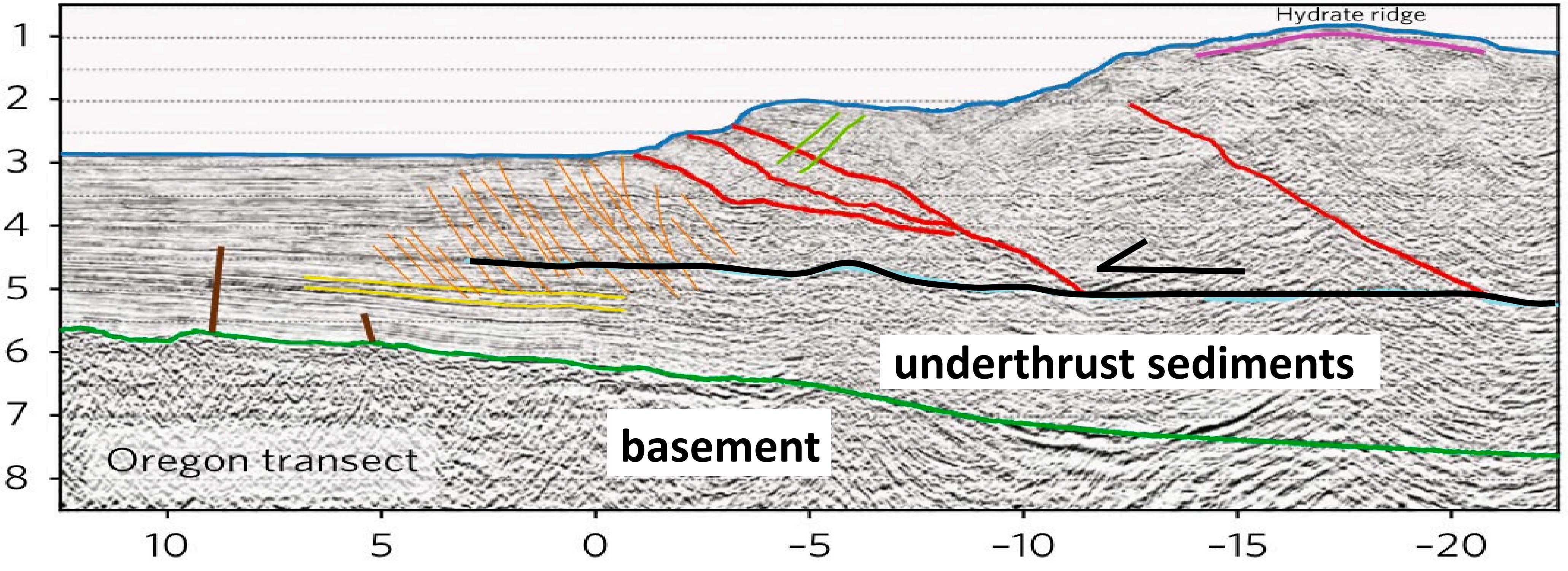
Ledeczi et al. (in review)

- Fault rocks display multiple stages of brecciation and veining
- Veins surrounding last breccia stage contain chlorite and deformed quartz
- **Cyclical deformation mode variations at peak P-T**



LOTG is a paleomegathrust interface hosted in the sediments

- The lack of basalt suggests that LOTG represents a paleomegathrust interface hosted in the sediments rather than at the igneous basement

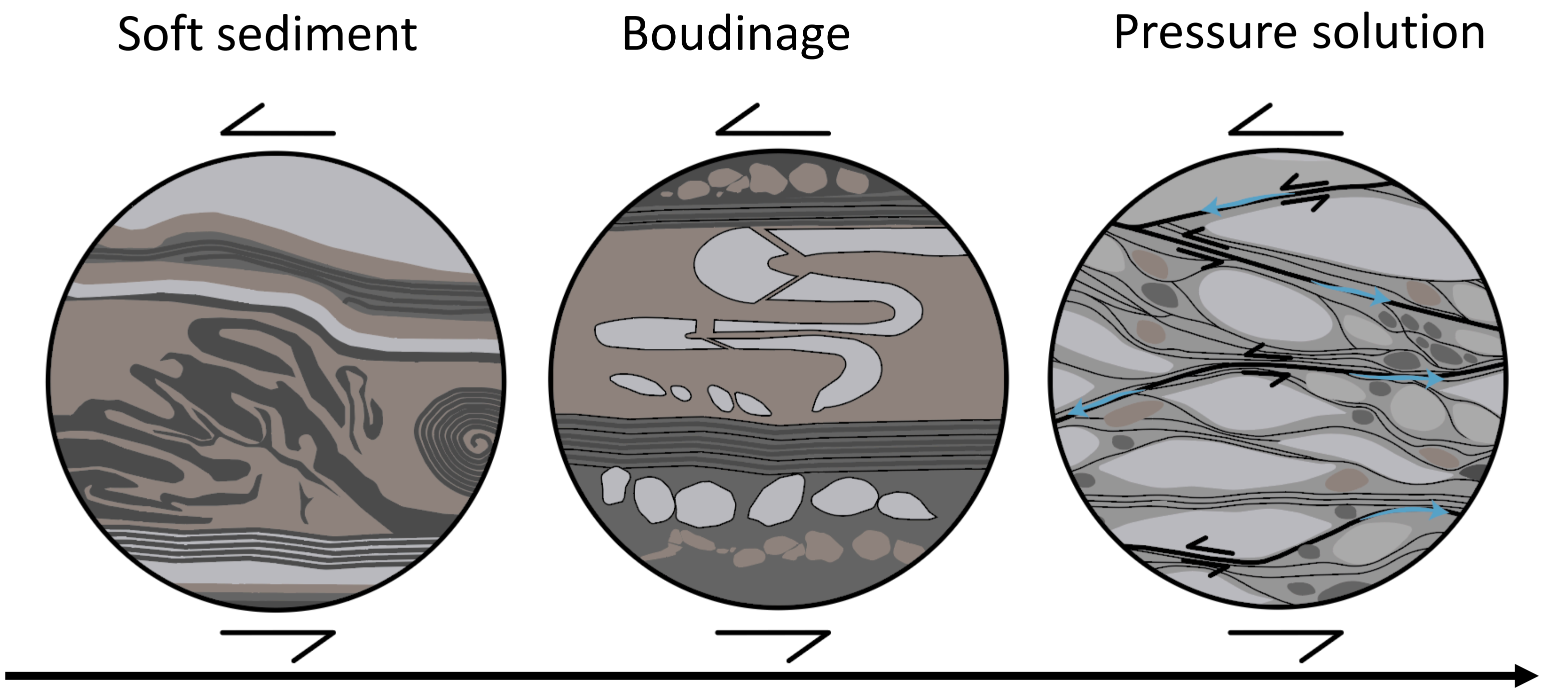


Han et al., 2017

Integrated deformation in the seismogenic zone

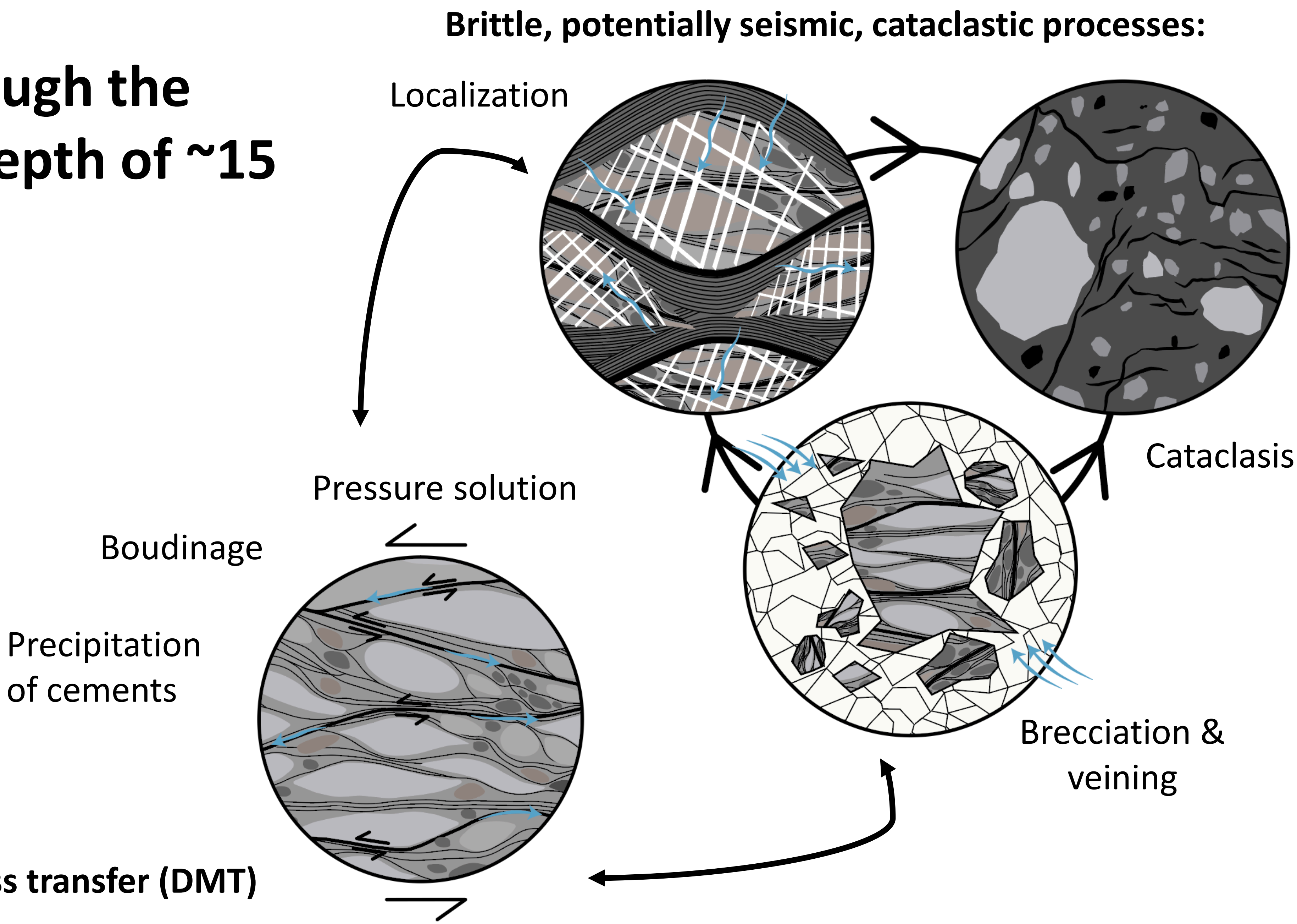
- The ambient paleotemperatures and rock record at LOTG allow us to directly link micro- and macro-structures with megathrust earthquake processes

Prograde, bulk viscous deformation: mélange-forming



Ledeczi et al. (in review)

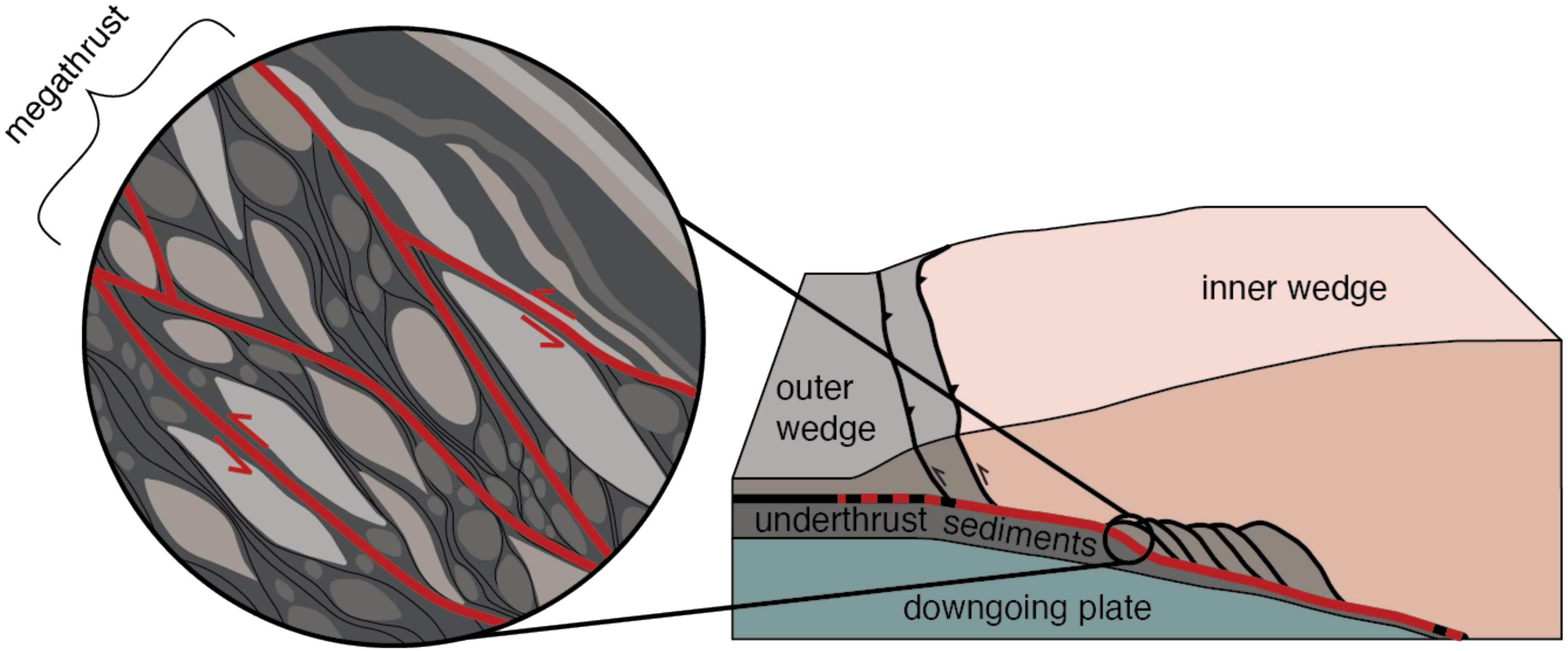
Deformation through the seismic cycle at depth of ~15 km (250° – 280° C)

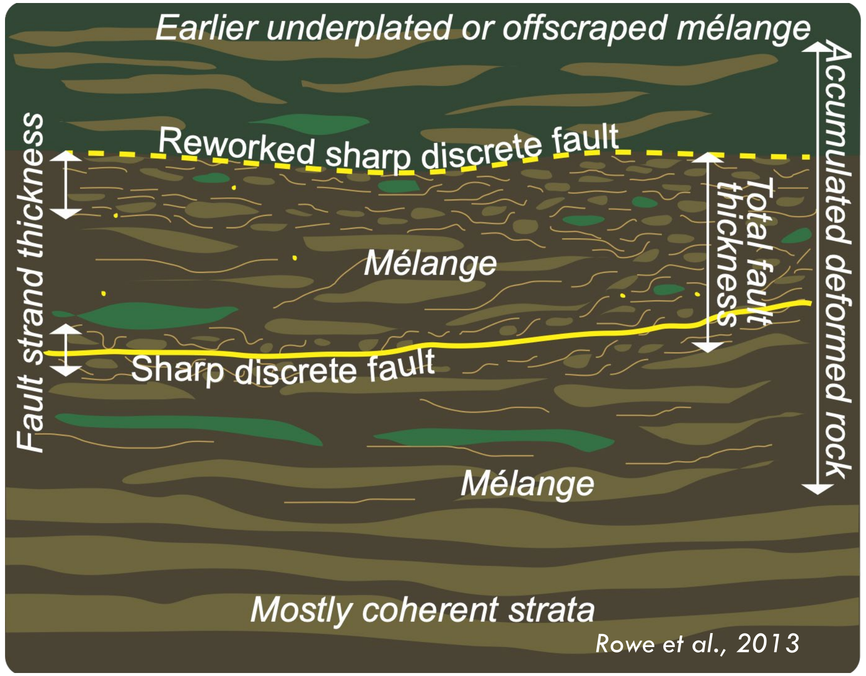


Ledeczi et al. (in review)

Consistent with model of Rowe et al. (2013) and our observations in Olympic FZ:

- Accumulated mélange zone ~100s of meters in thickness, containing:
- Individual fault strands ~1 – 10(s) meters wide, which in turn contain:
- Principal slip surfaces <1 – 20 cm thick.
- Individual seismic slip events are likely highly localized to one or very few strands
- Continued block-in-matrix mélange development reworks PSSs, prevents single fault core from developing





Single vs multiple PSS and/or strands?

Contrast continental-type faults vs. megathrusts

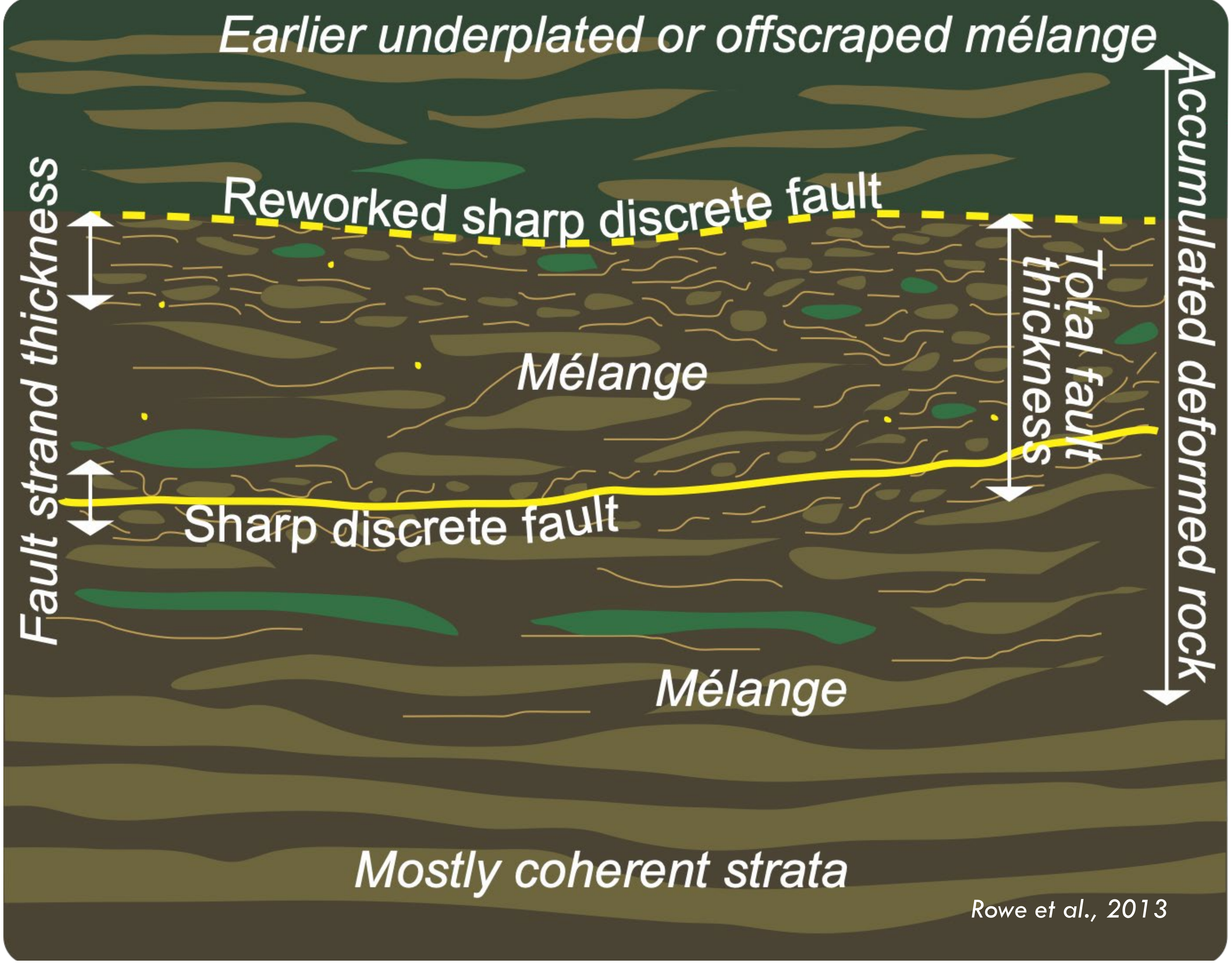
“Hard rock” hosted

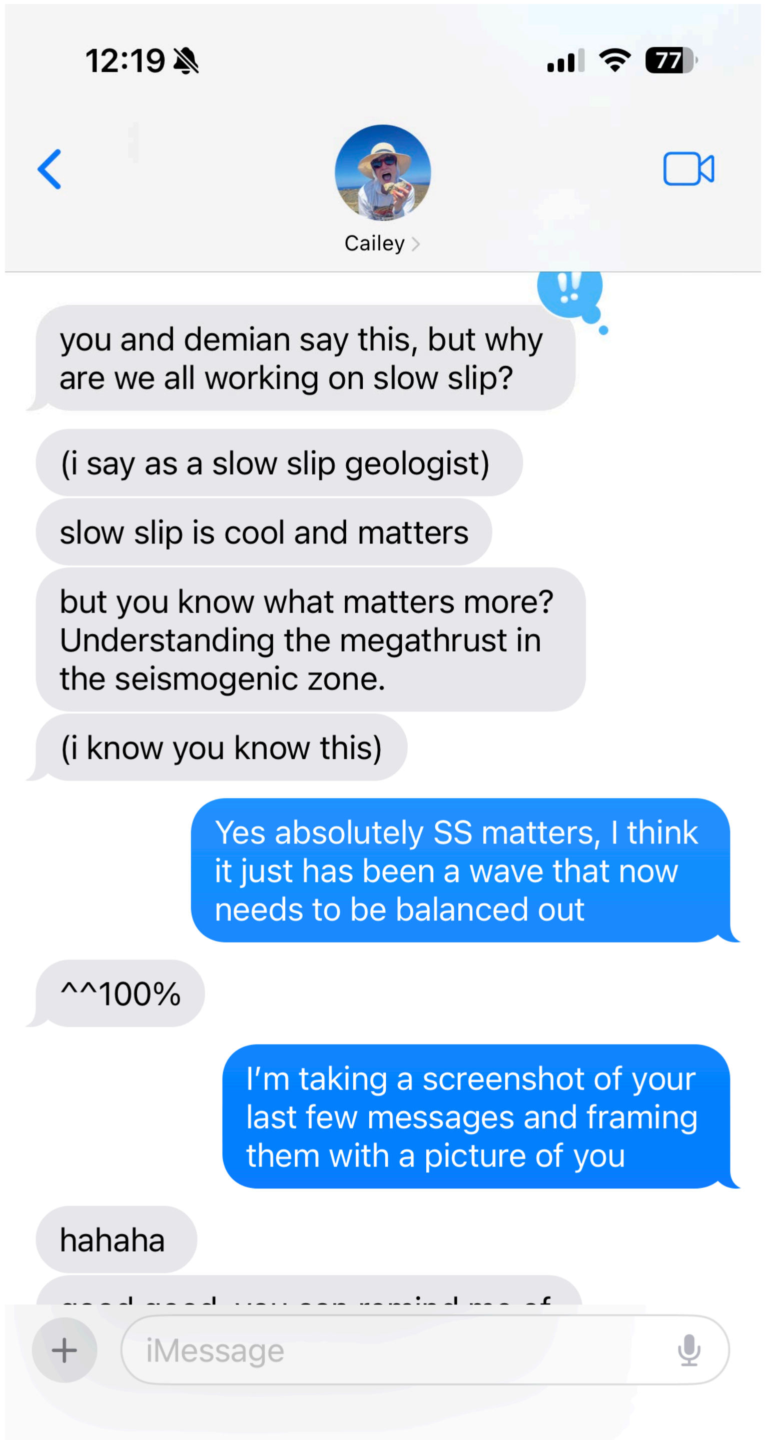
- Development of PSZ creates gouge and fractured damage zone
- Pronounced weakening leads to continual re-use of same core zone, and even same slip surfaces

Glarus Thrust, Swiss Alps

“Soft rock” or mélange hosted

- Porous host rock means shear collapse of porosity = shear densification, less gouge
- Scaly fabric continuously evolves interseismically
- Net effect may be overall strengthening of core, leads to development of new PSZ and perhaps fault strands


Earlier underplated or offscraped mélange
Reworked sharp discrete fault
Mélange
Sharp discrete fault
Mélange
Mostly coherent strata
Fault strand thickness
Total fault thickness
Accumulated deformed rock
Rowe et al., 2013


12:19
77
Cailey
you and demian say this, but why are we all working on slow slip?
(i say as a slow slip geologist)
slow slip is cool and matters
but you know what matters more? Understanding the megathrust in the seismogenic zone.
(i know you know this)
Yes absolutely SS matters, I think it just has been a wave that now needs to be balanced out
^^100%
I'm taking a screenshot of your last few messages and framing them with a picture of you
hahaha
iMessage