Volatile Fluxes at Subduction Zones: the Model Perspective

Motivation

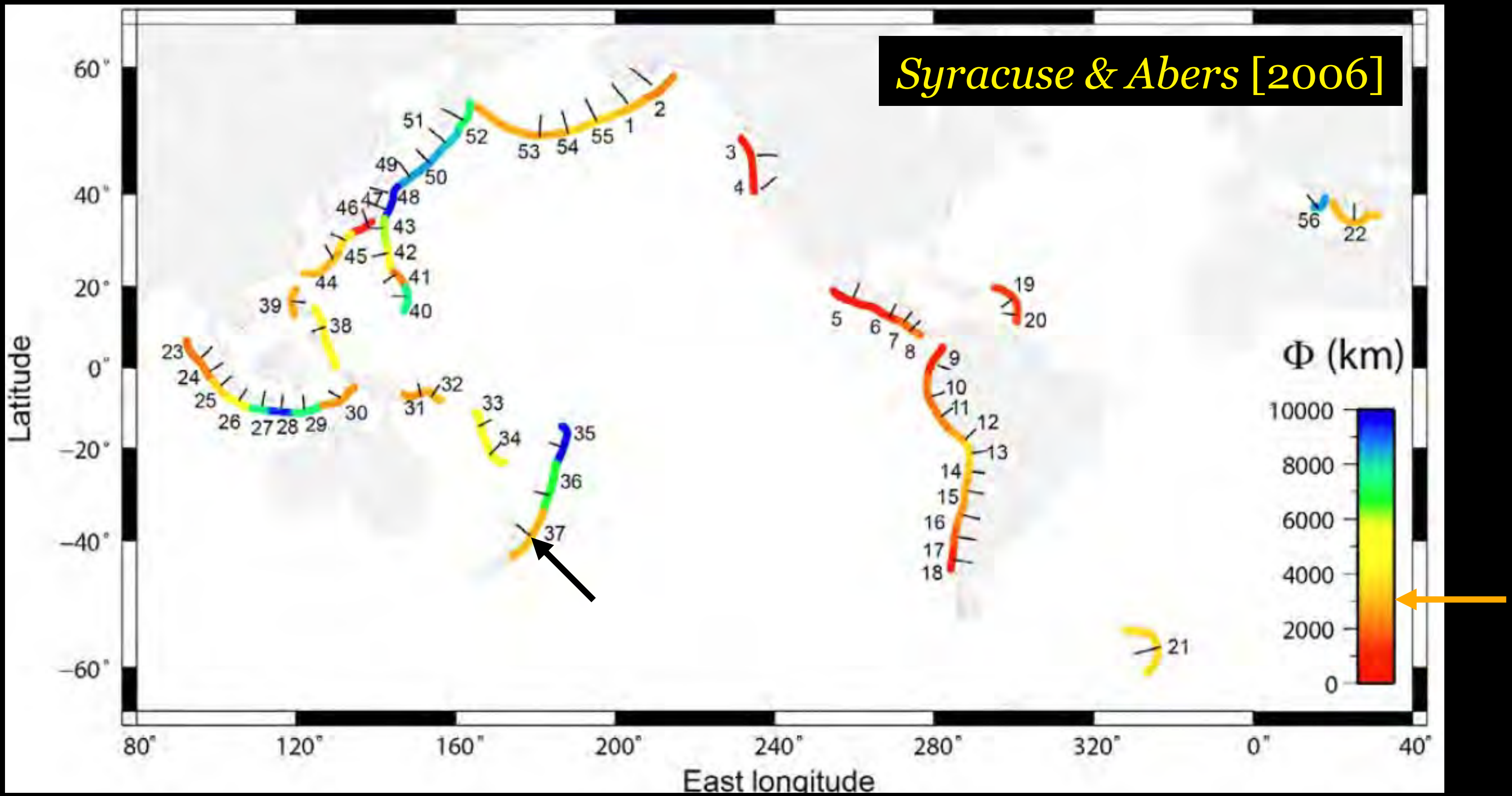
How much H_2O is transported in & expelled from subducting slabs, and by what processes?

- mass transport (m scale to Earth scale)
- wedge & slab melting
- fate of slabs
- isotopic evolution
- rheology of slab & wedge
- interpretation of geophysical data
- seismicity

Calculate $H_2O = H_2O\ (t, x, y, z)$

1. Global subduction-zone database
2. Slab thermal model
3. Subducted sediment type & thickness
4. Hydration of slab @ trench
5. Phase relations f(P,T,X)
6. H_2O distribution & loss

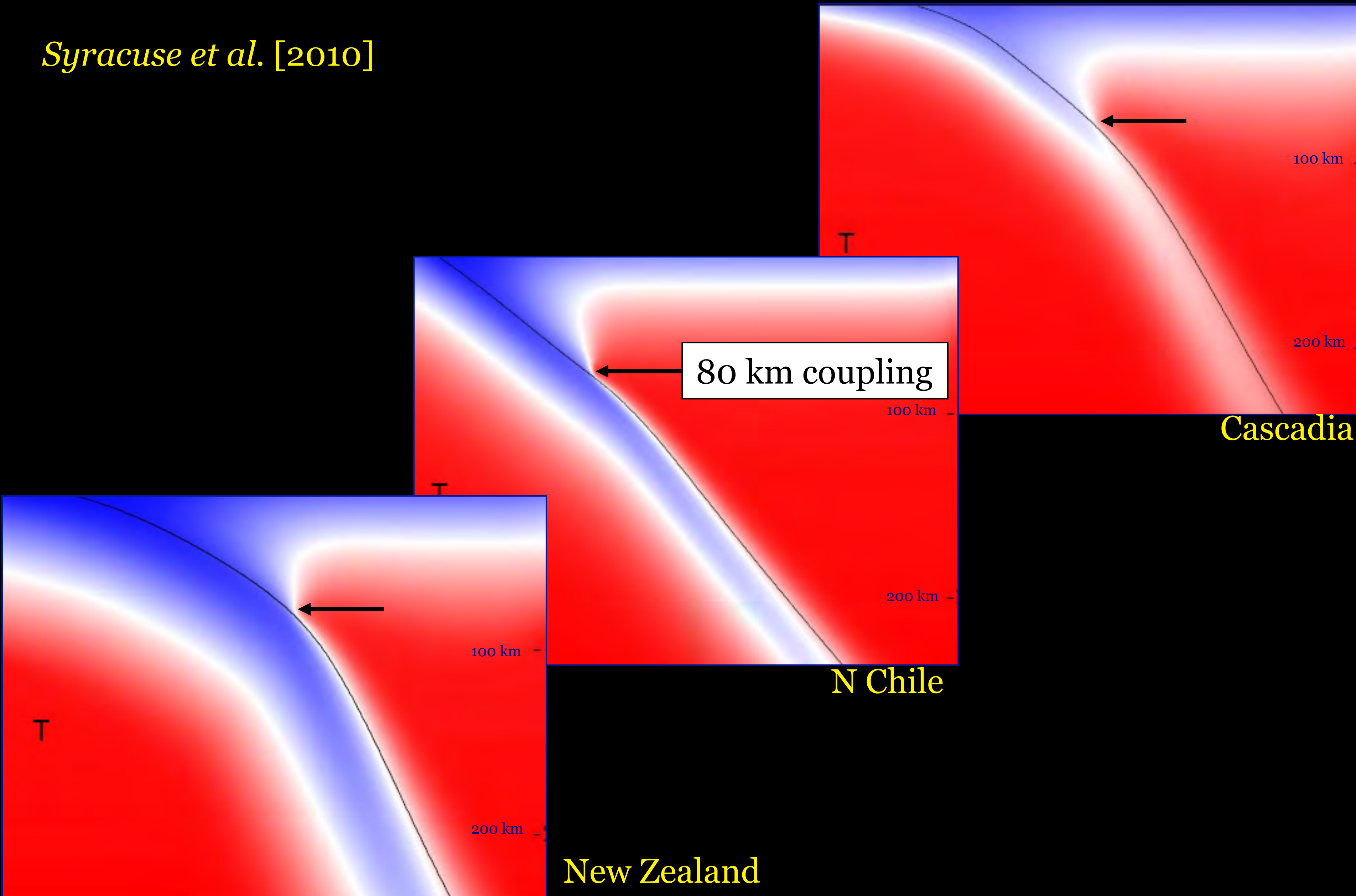
1. Subduction-Zone Database



- velocity; NZ = 30 mm/a (slow; median = 65 mm/a)
- plate age; NZ = 100 Ma (old; median = 55 Ma)

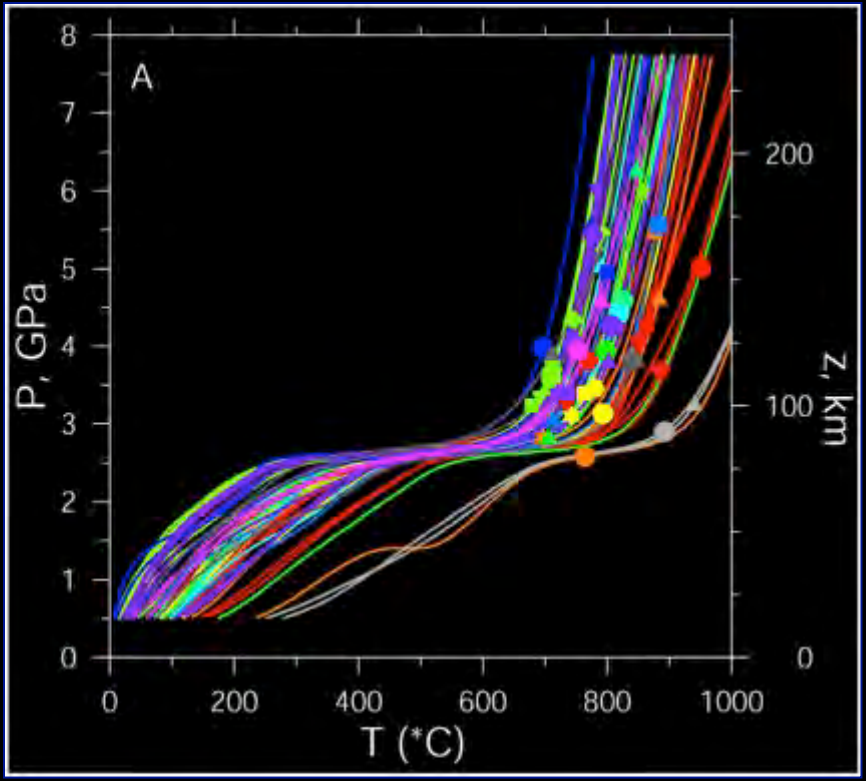
2. Thermal Models

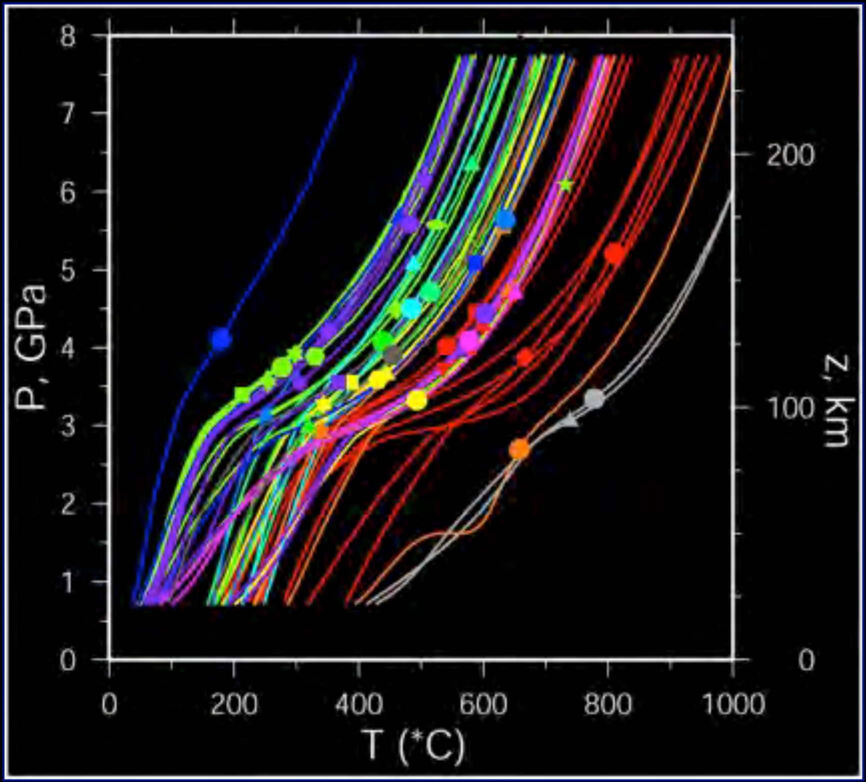
Syracuse et al. [2010]



2. Thermal Models

Syracuse et al. [2010]



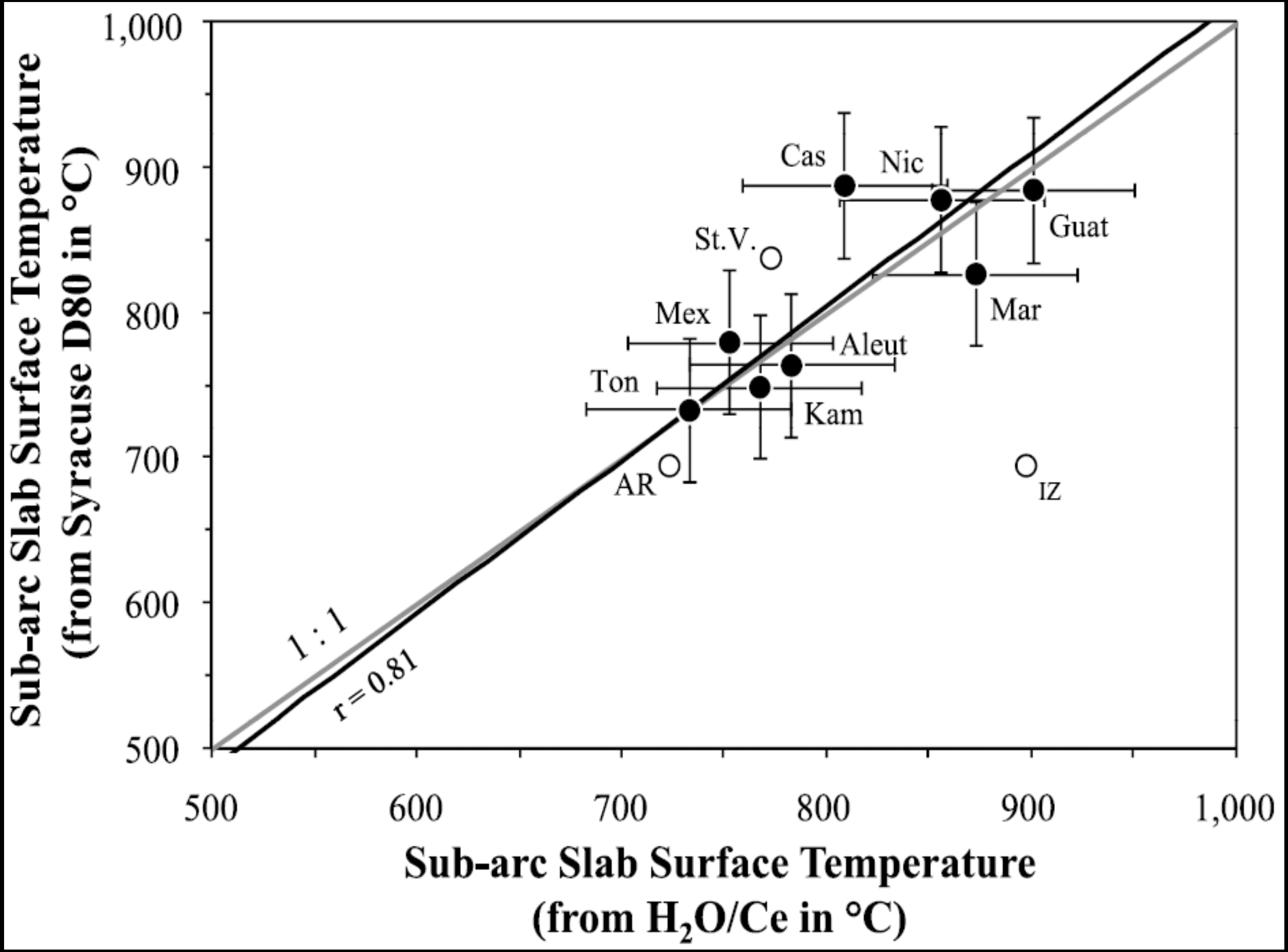


slab top:
675–925°C beneath arc

slab Moho:
150–800°C beneath arc

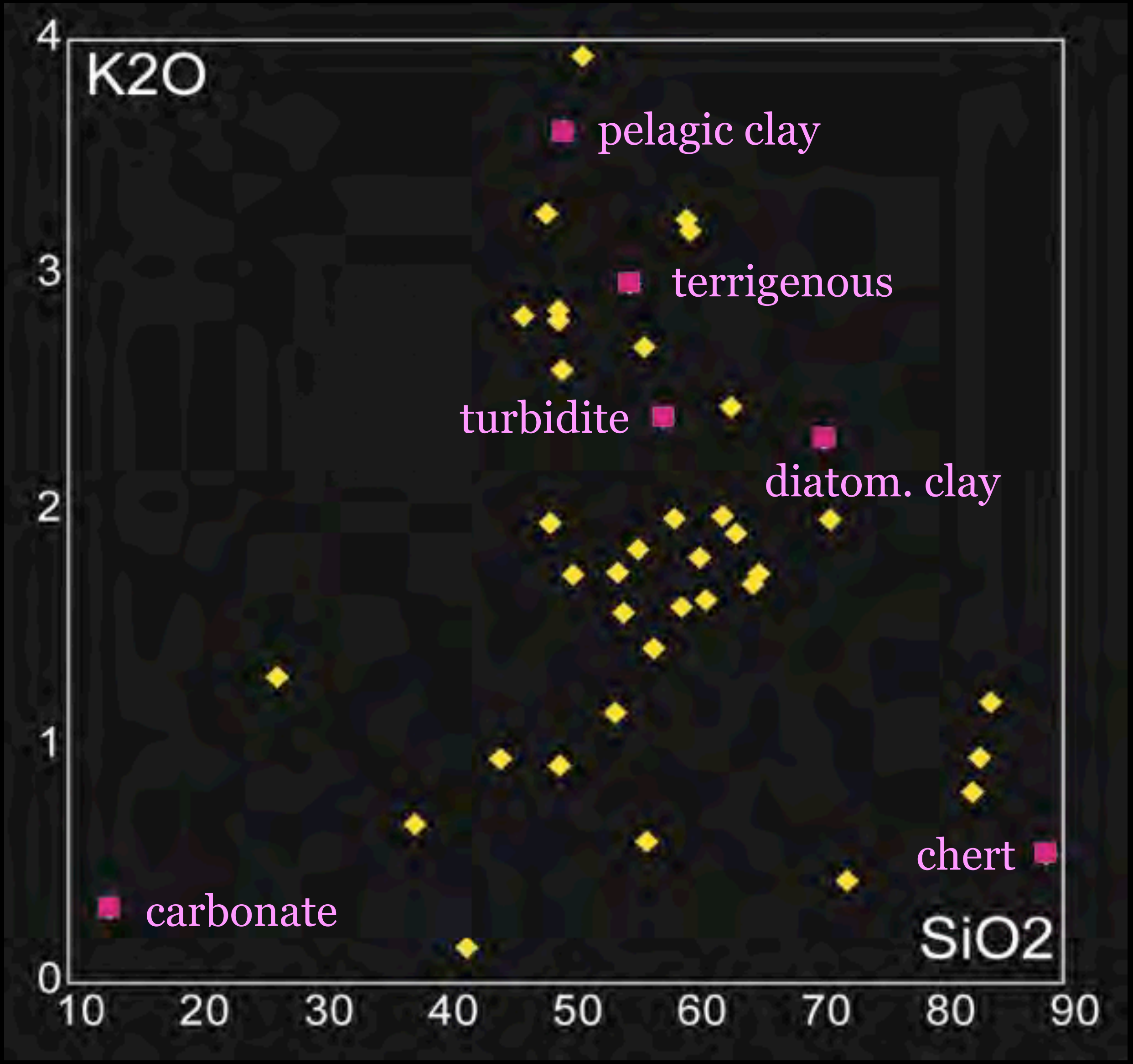
more variation among arcs

Temperatures Match H_2O/Ce



Cooper et al [2012]

3. Sediment Composition

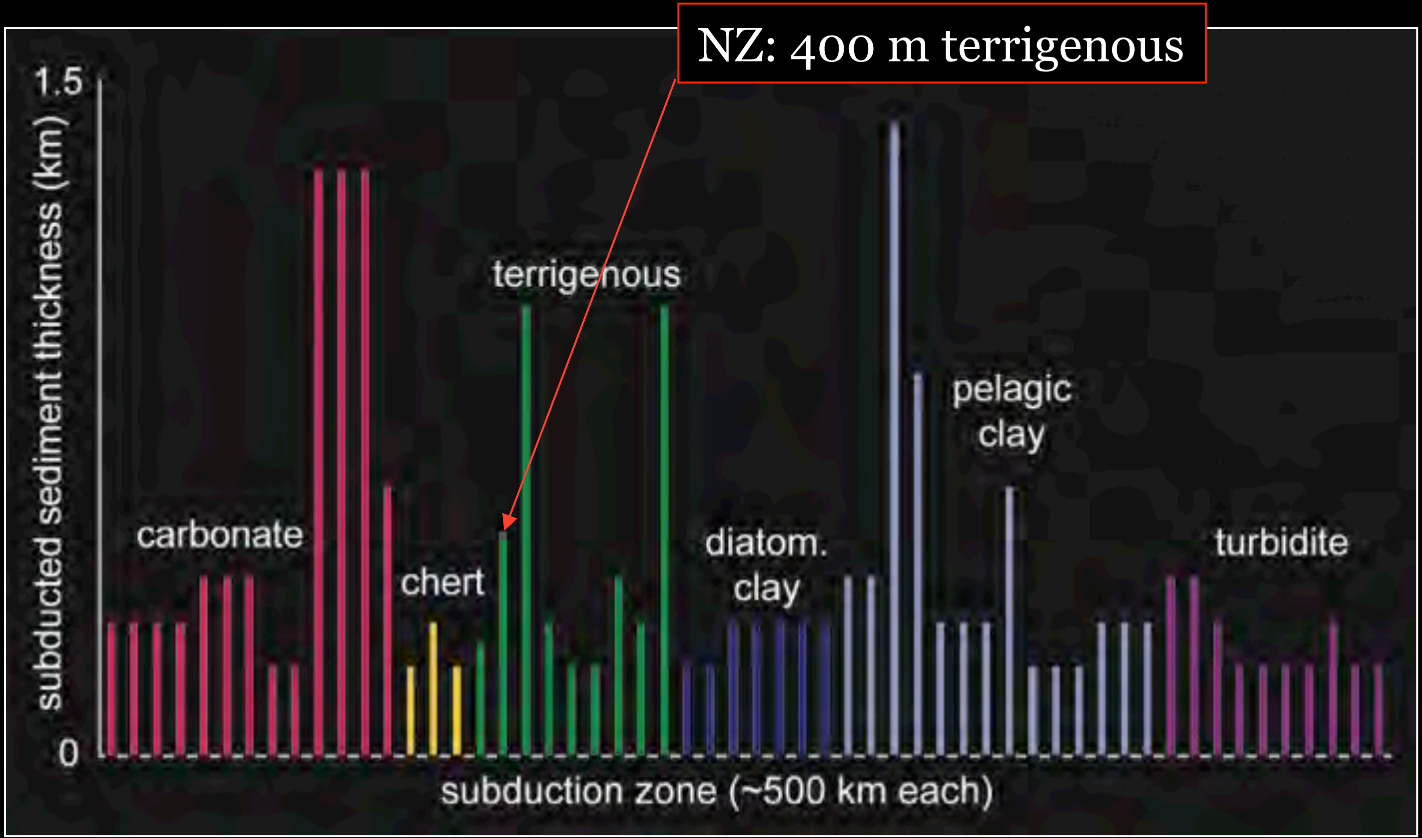


Plank & Langmuir [1998]

3. Subducted Sediment Thickness

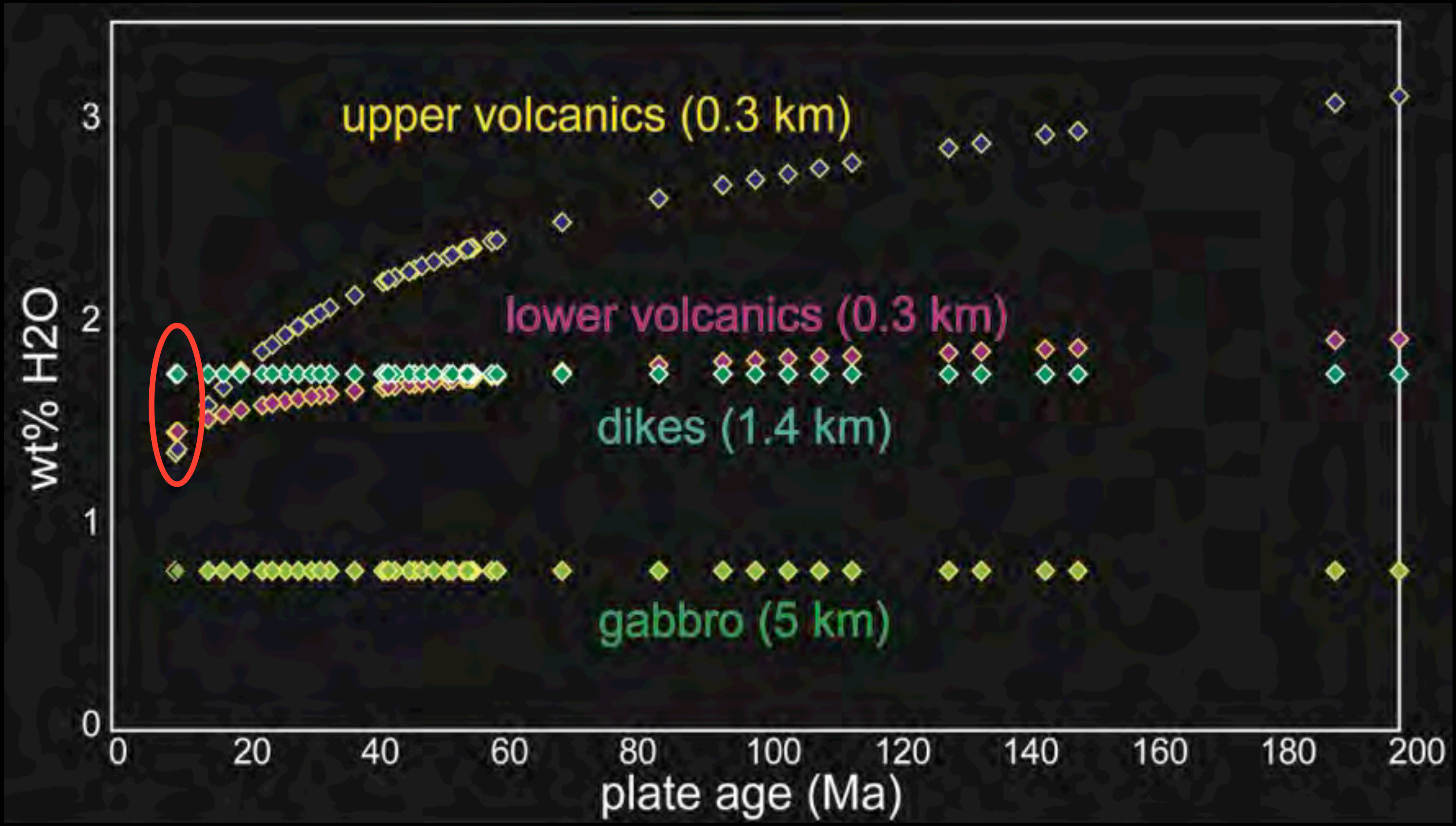
Clift & Vannucchi [2004]; *Scholl & von Huene* [2007; 2009]

account for sediment accretion & closing of pore space



4. Hydration of Incoming Crust

Jarrard's [2003] age-based alteration model; does not consider spreading rate



4. Hydration of Incoming Mantle

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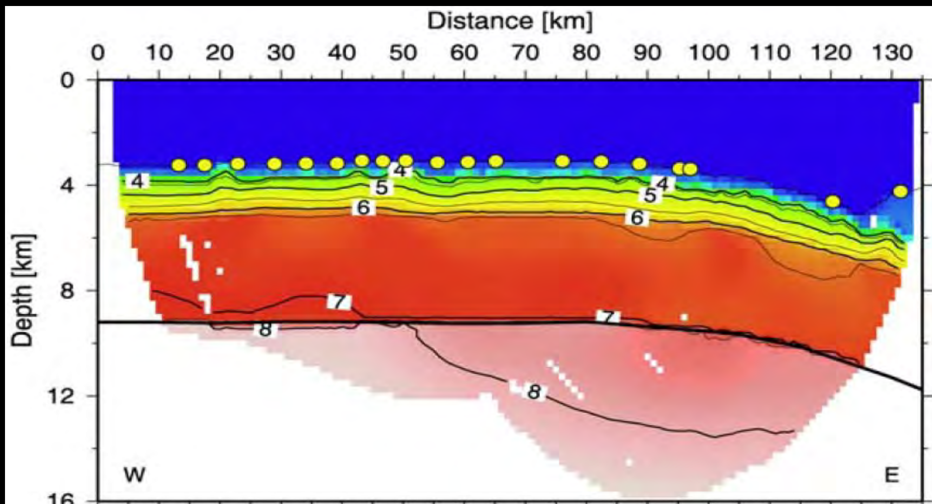
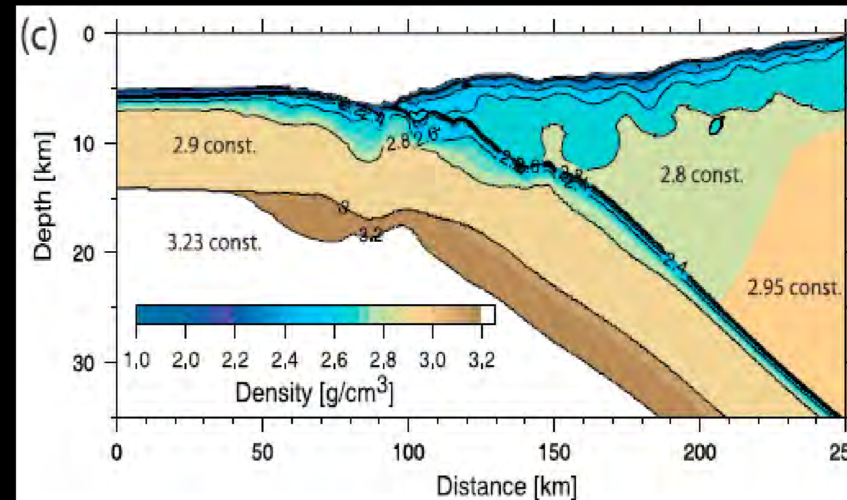


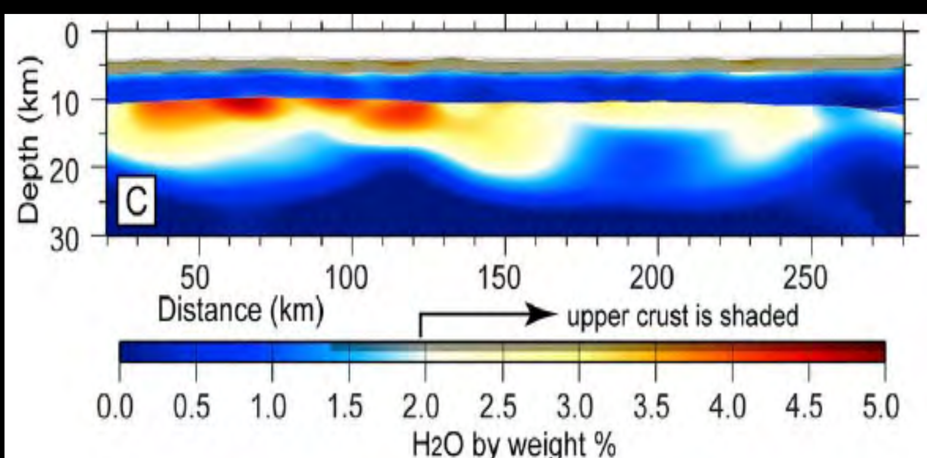
Nicaragua: 10 km of 15% serpentine

Ivandic et al. [2010]; *Lefeldt et al.* [2012]



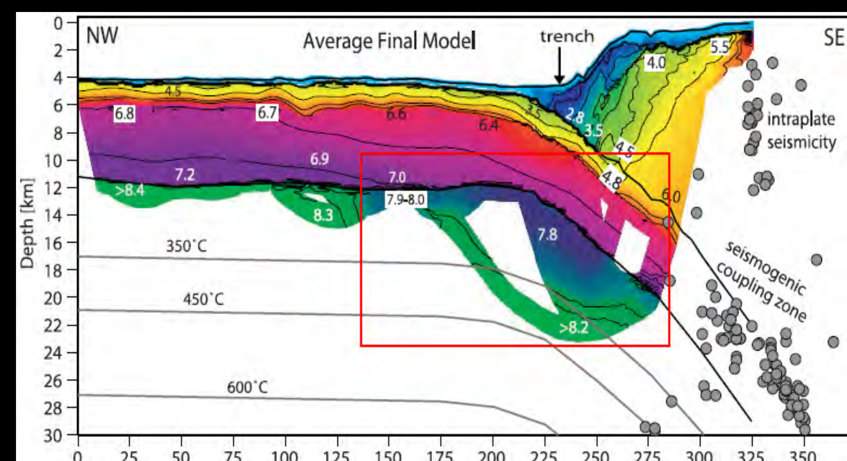
Lombok: 5 km of 20% serpentine

Planert et al. [2010]



Costa Rica: 5 km of ≤30% serpentine

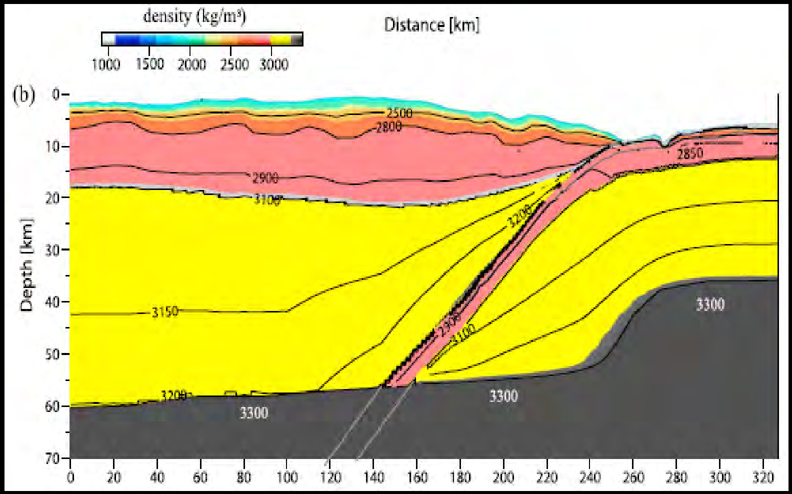
van Avendonk et al. [2011]



Chile: 7 km alteration

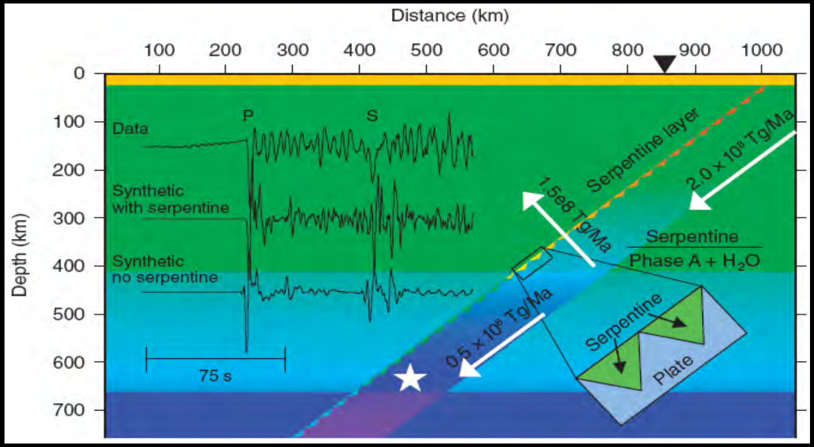
Contreras-Reyes et al. [2008]

4. Hydration of Incoming Mantle



Tonga: 24 km of 30% serpentine

Contreras-Reyes et al. [2011]



Tonga: ≤8 km of 60% serpentine

Savage [2012]

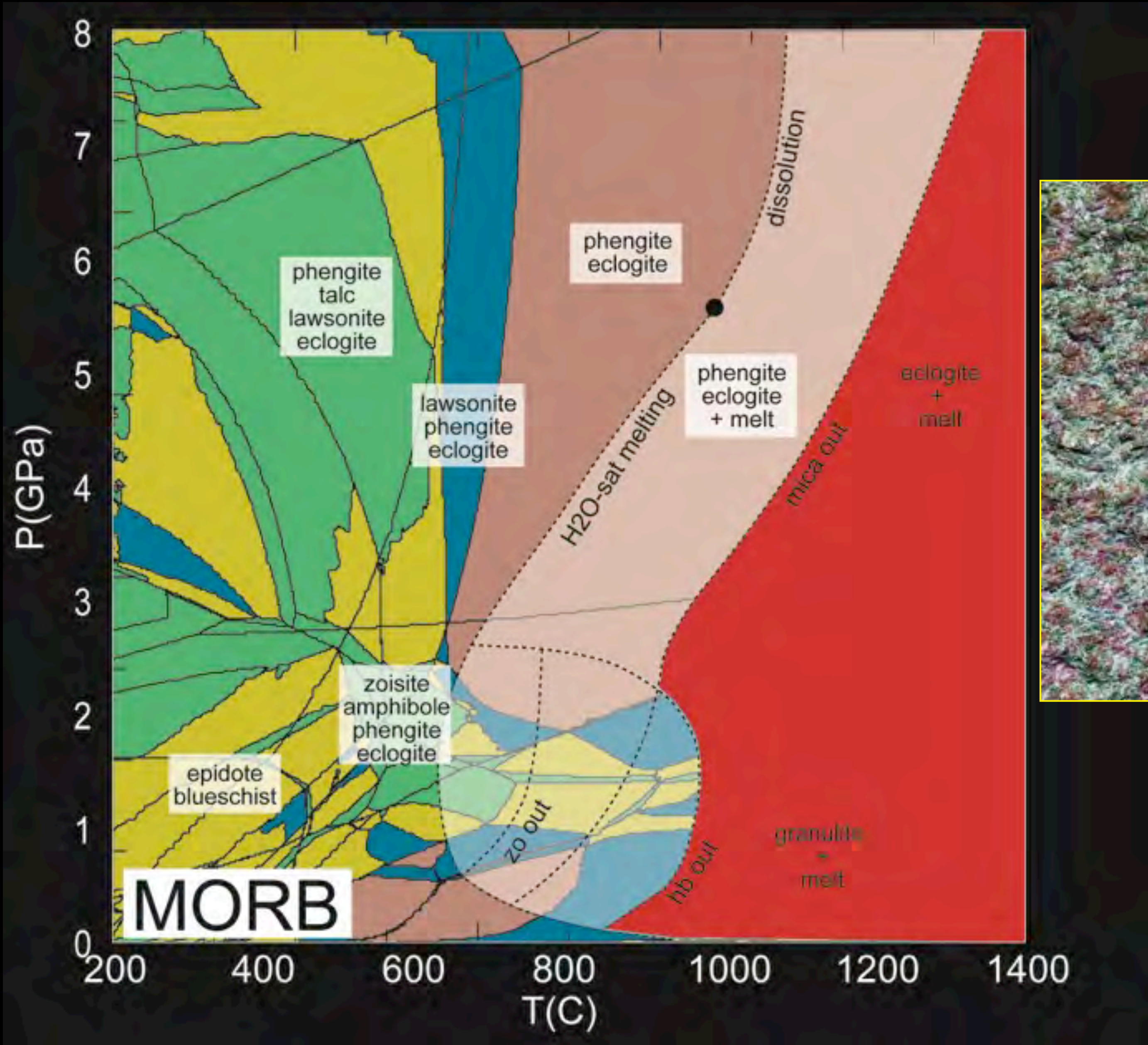
conclusion:
15 km of 2 wt% H_2O ??

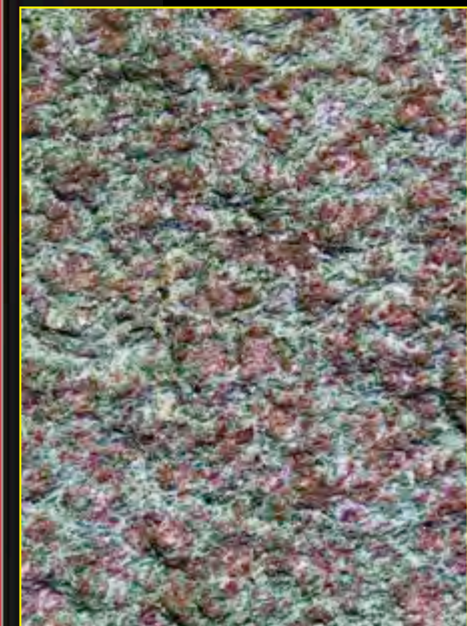
model:
2 km of 2% H_2O

5. Calculate Phase Relations *ƒ*(P,T,X)

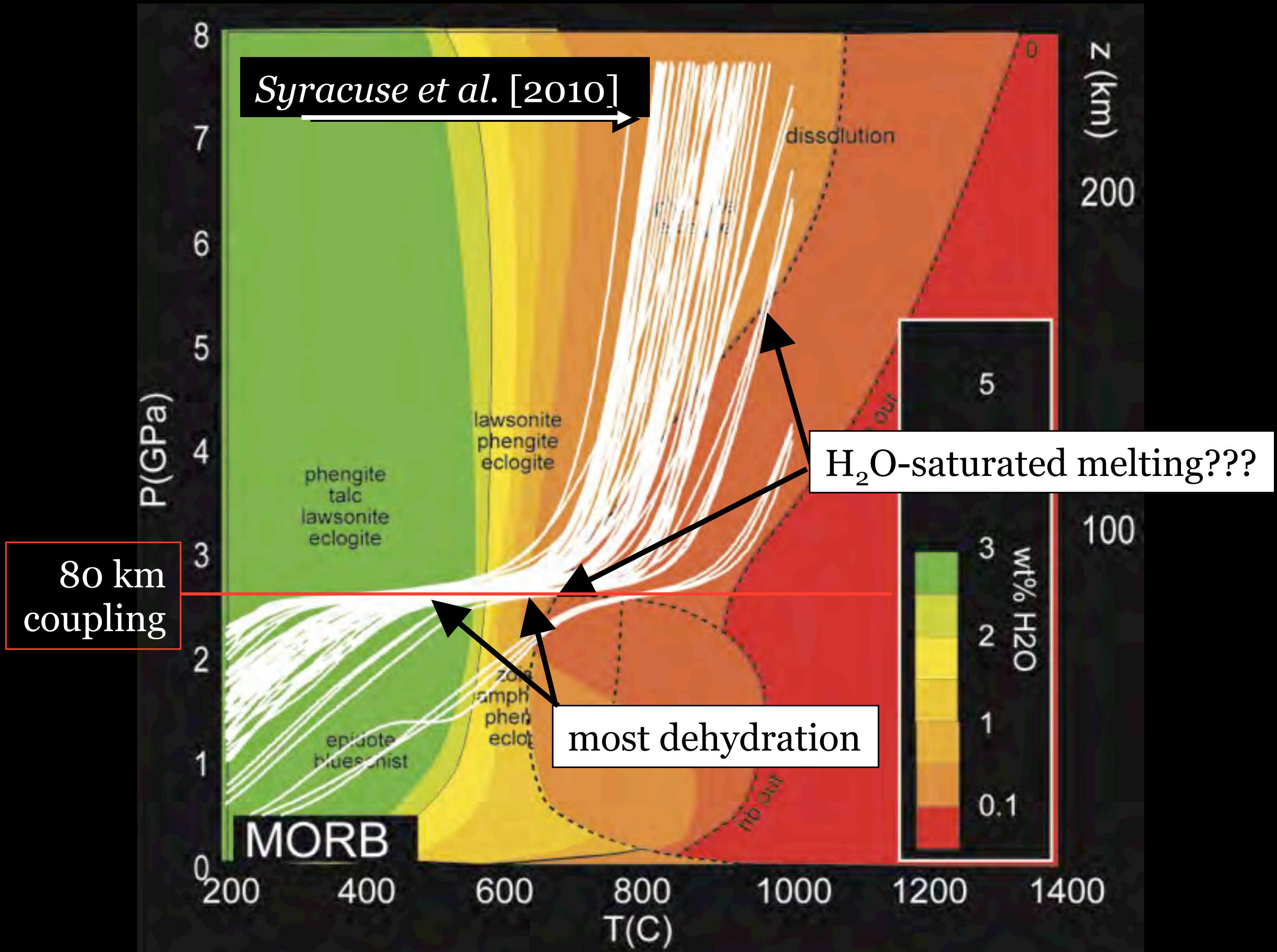
- *Perple_X* Gibbs free energy minimization [*Connolly & Petrini*, 2002]
- Na_2O-CaO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2 ± Cr_2O_3 ± MnO ± CO_2 (NCKFMASHT)
- standard solution models
- weaknesses:
  - solution models imperfect (e.g., K_2O in amphibole)
  - no good melt model

5. *Perple_X* Phase Diagram Example

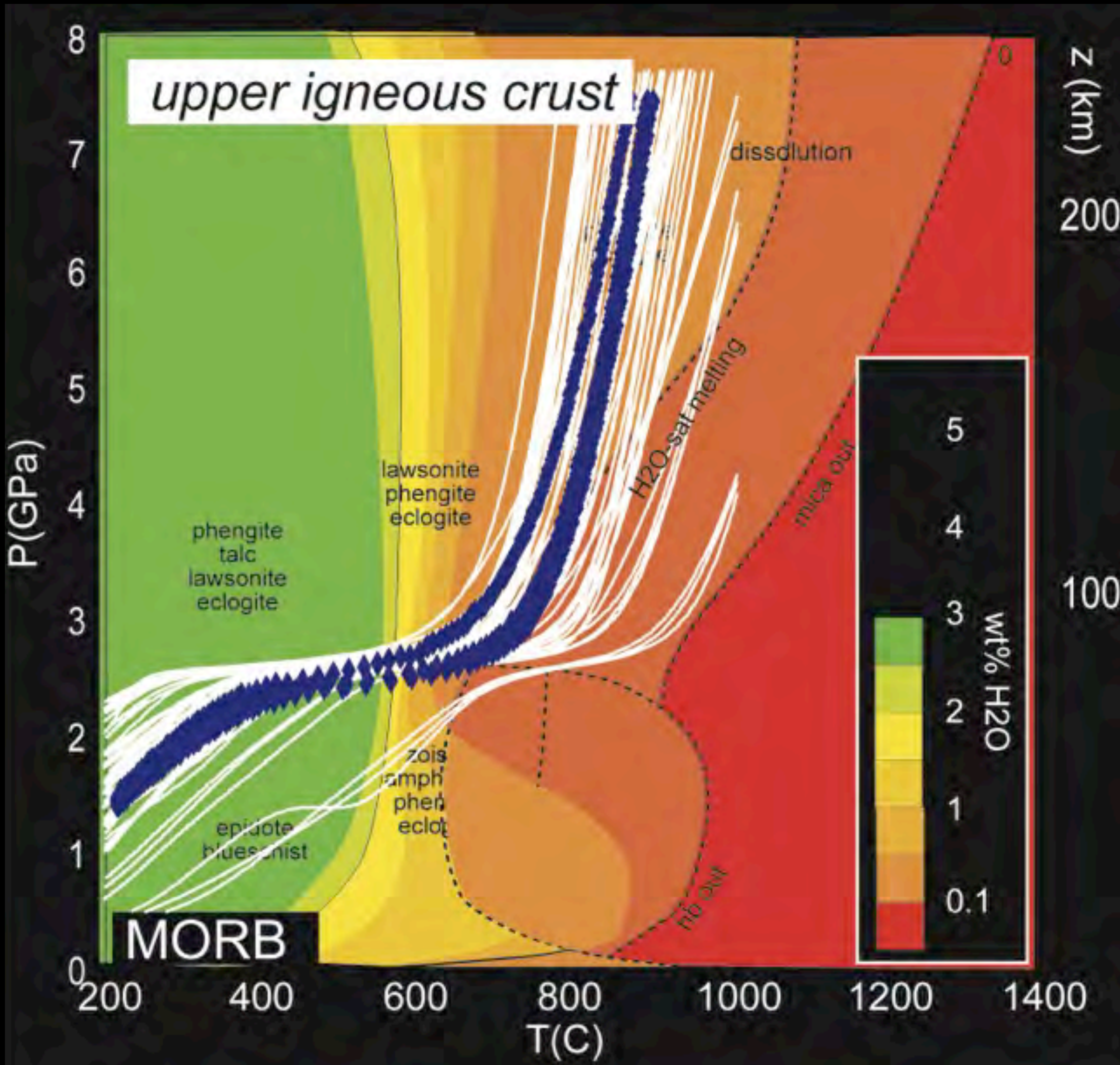




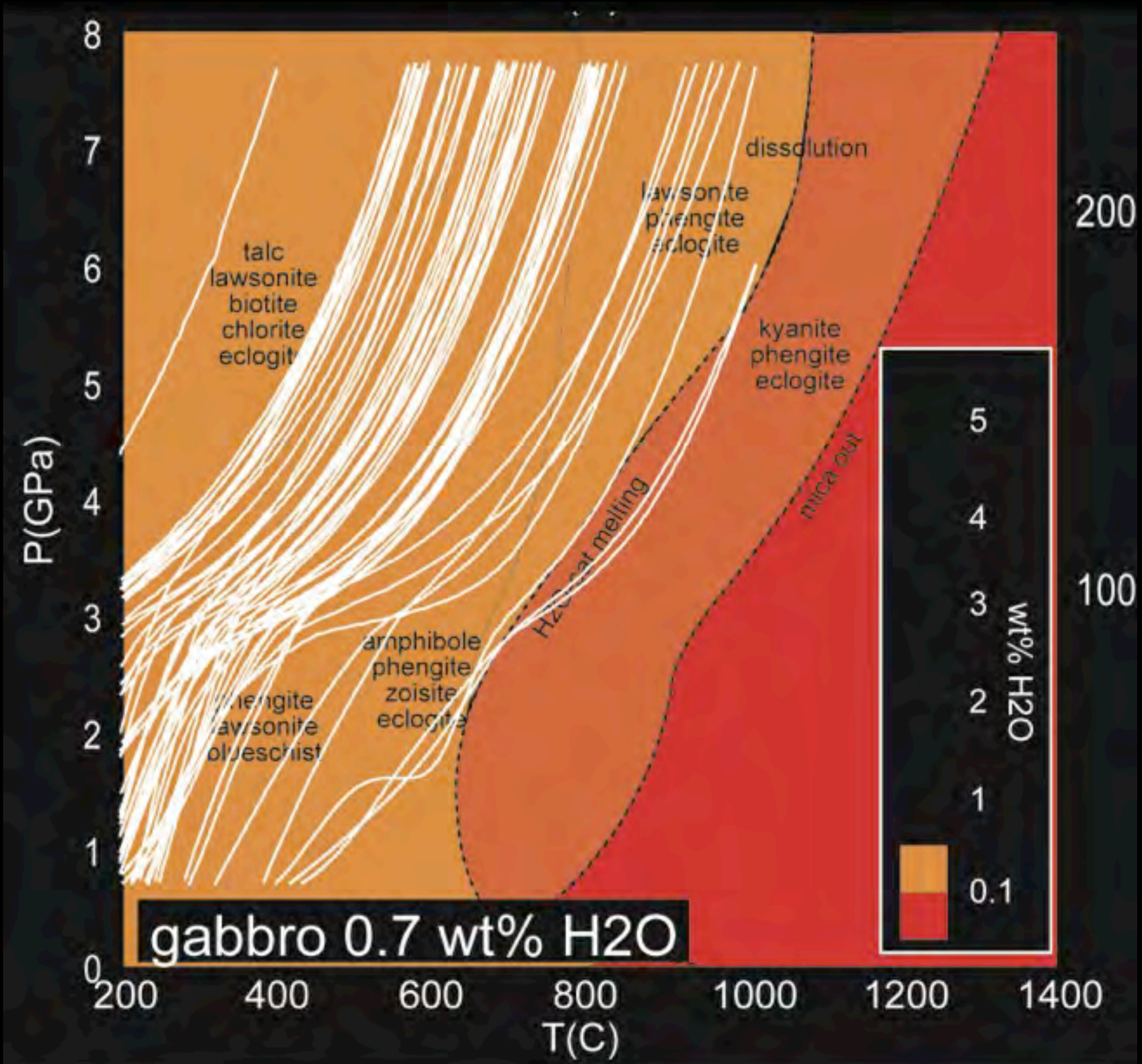
6. H_2O Content: Upper Igneous Crust



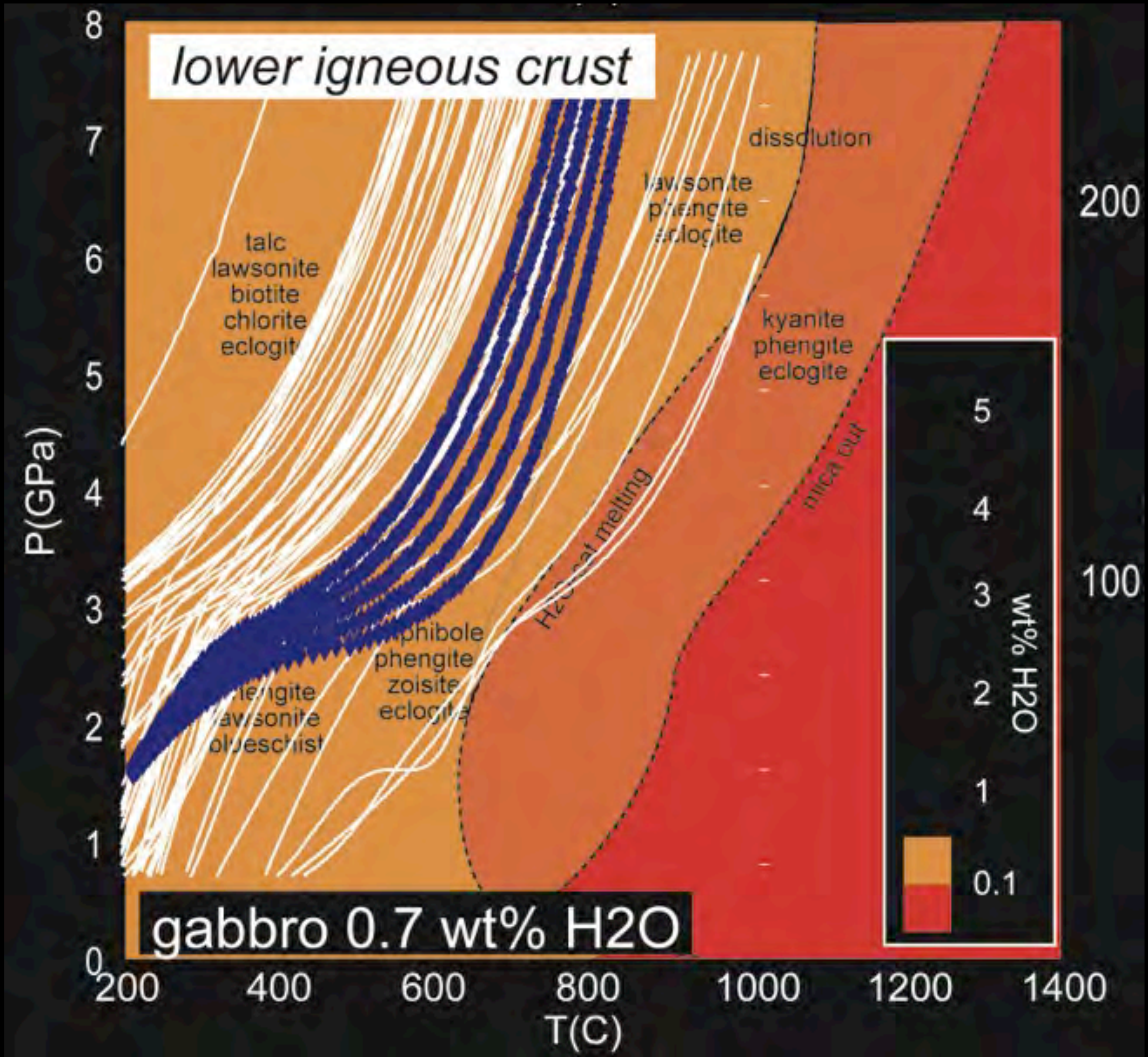
Upper Igneous Crust, NZ



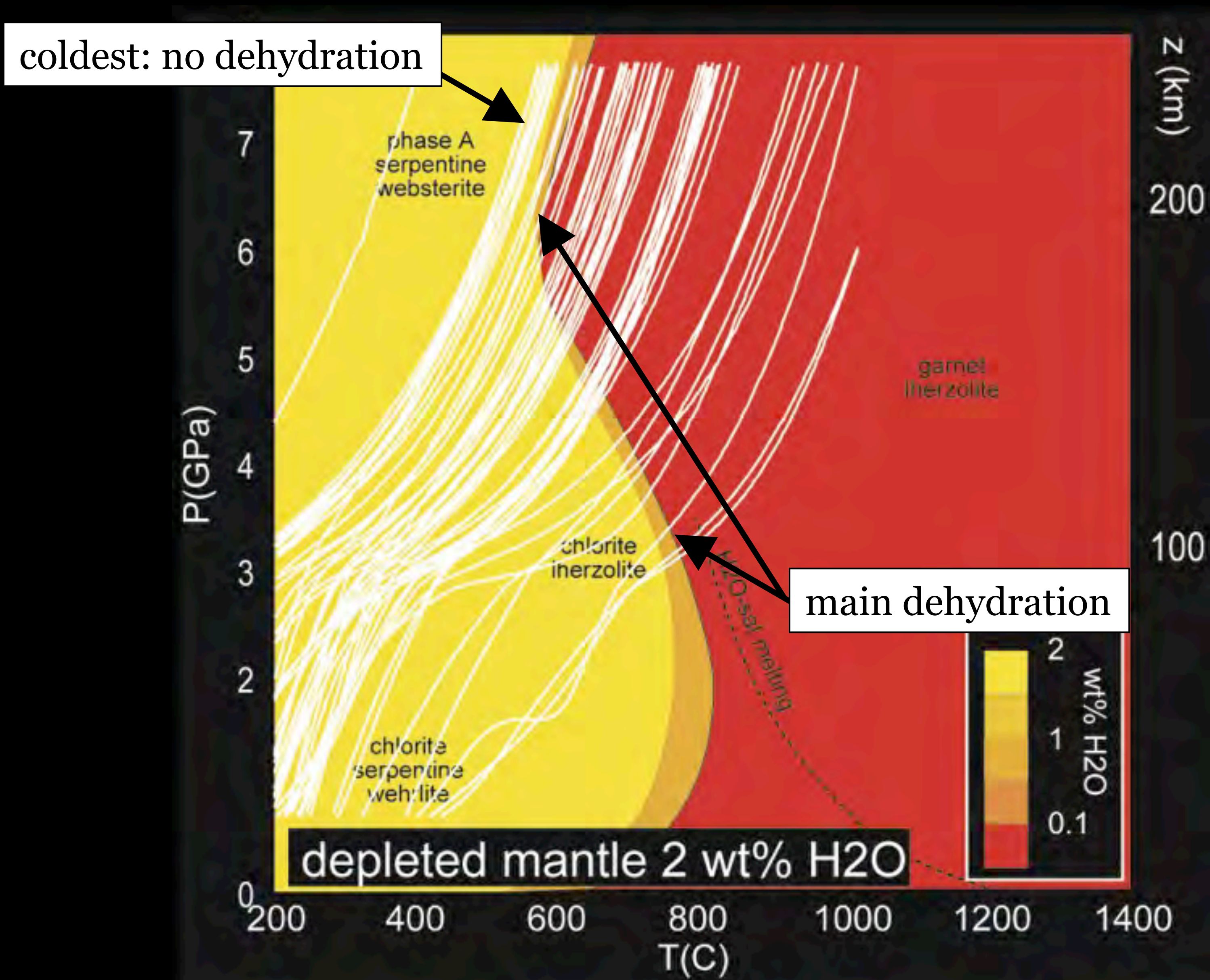
Lower Igneous Crust



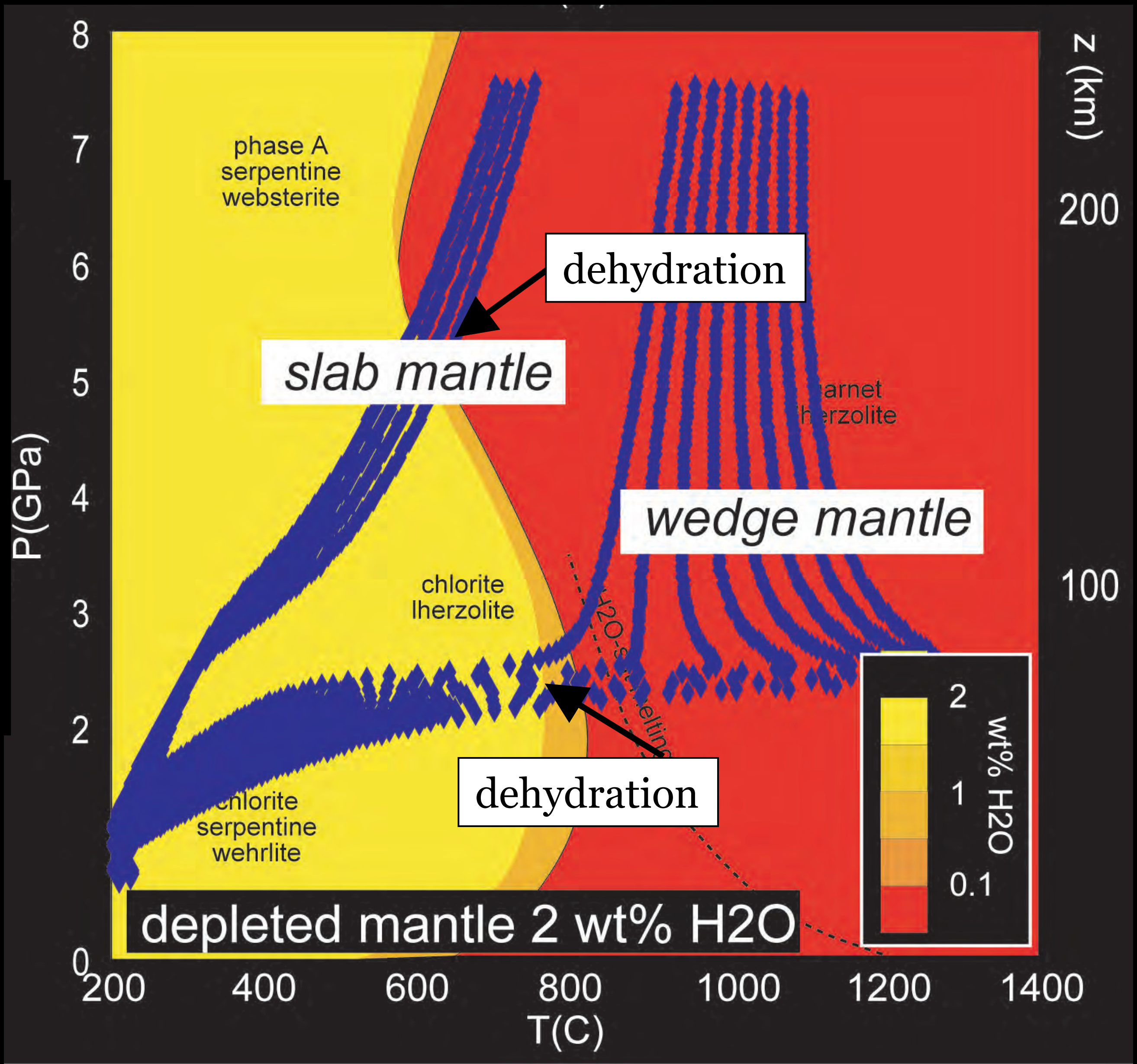
Lower Igneous Crust, NZ



Slab Uppermost Mantle

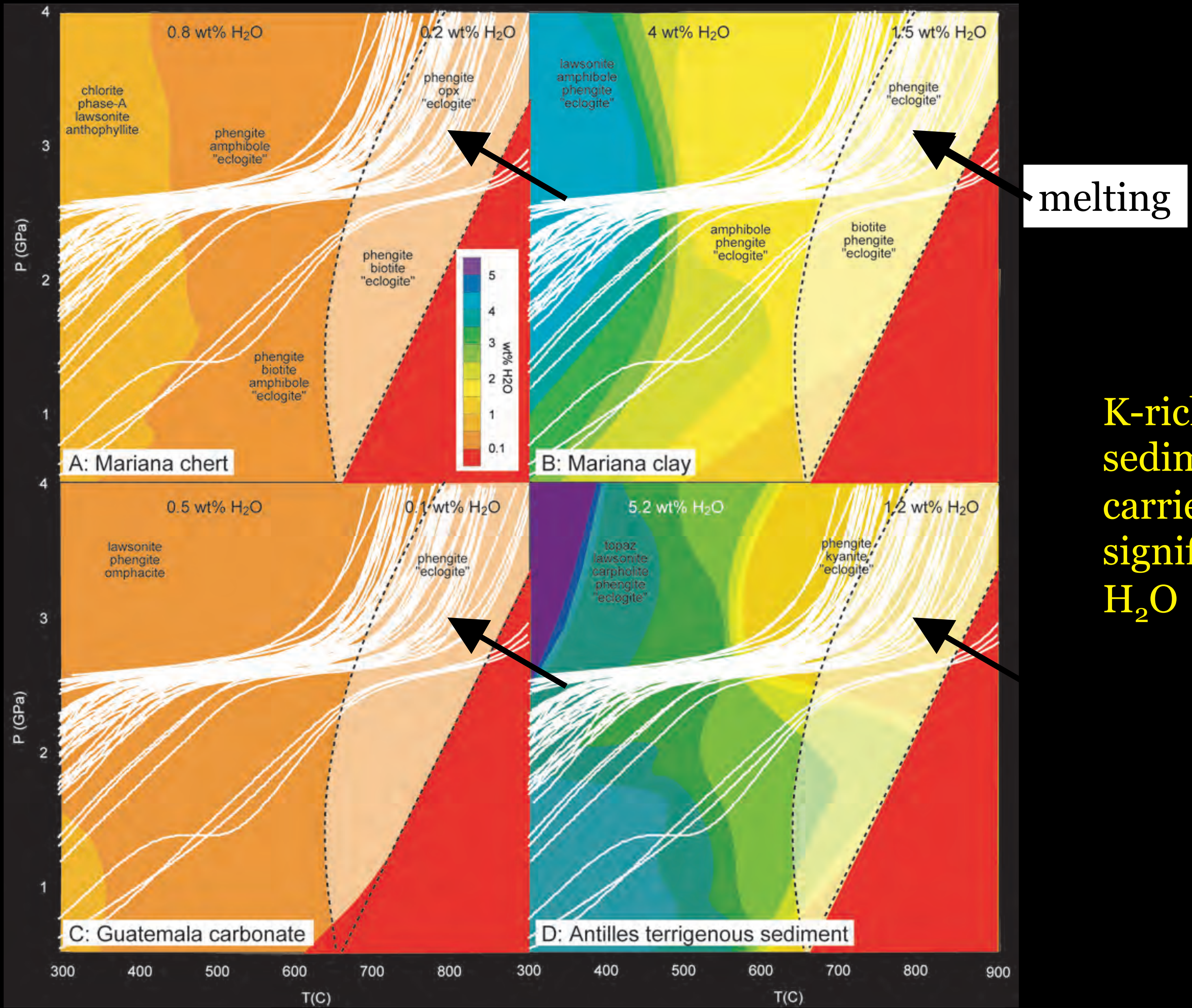


Slab & Wedge Mantle, NZ



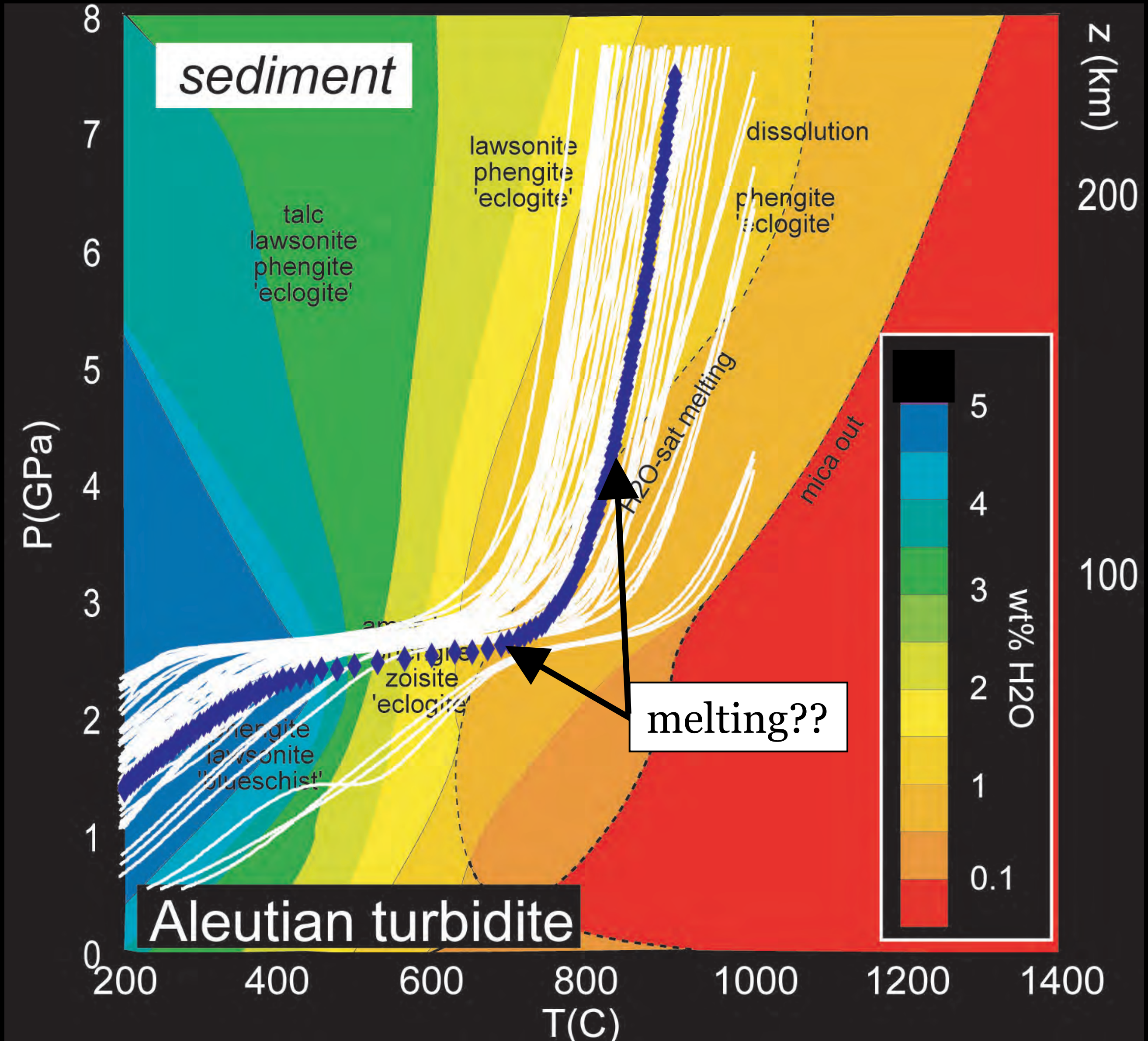
Oceanic Sediment

chert & carbonate carry little H_2O



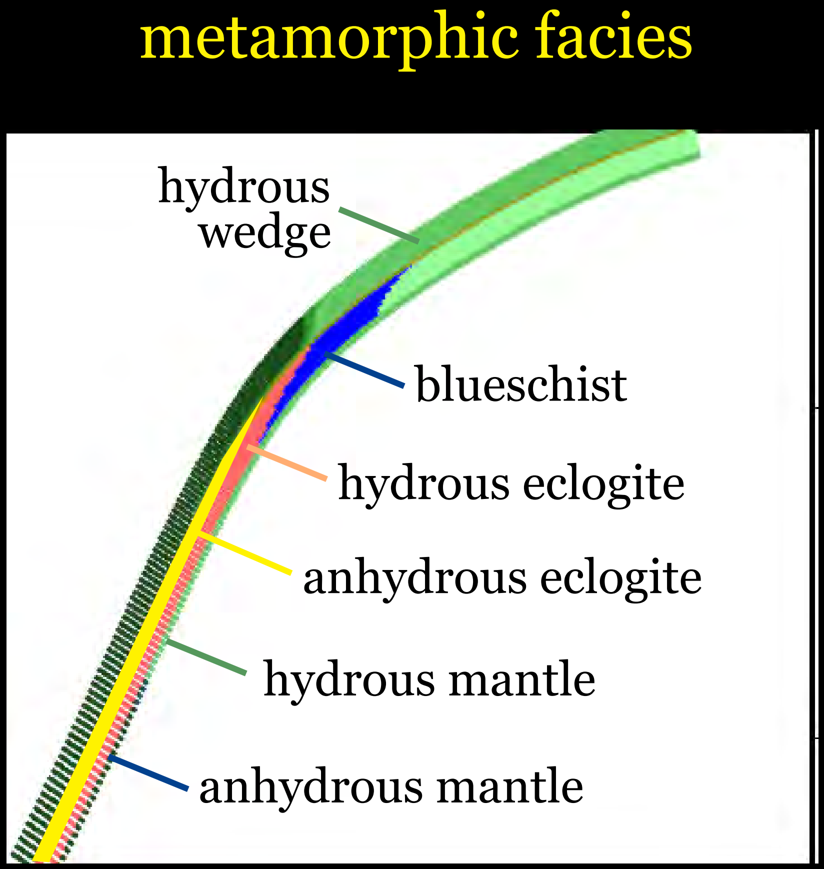
K-rich sediment carries significant H_2O

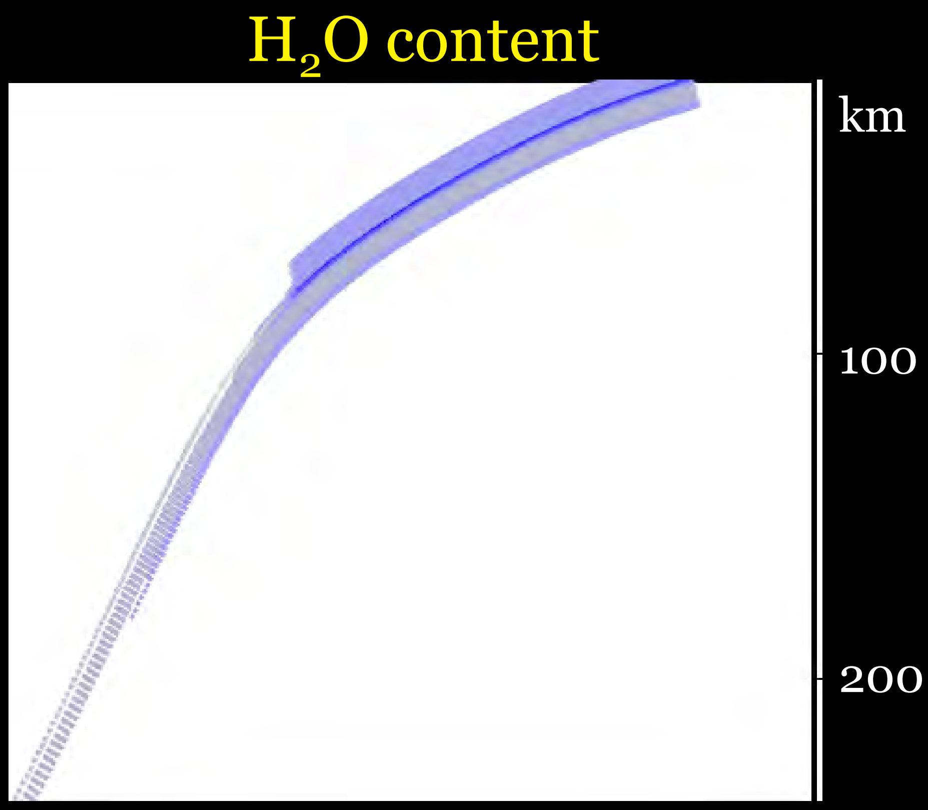
Sediment, NZ



sediment
talc
lawsonite
phengite
'eclogite'
lawsonite
phengite
'eclogite'
dissolution
phengite
'eclogite'
H2O-sat melting
mica out
zoisite
'eclogite'
phengite
lawsonite
'blueschist'
melting??
Aleutian turbidite
P(GPa)
T(C)
z (km)
wt% H2O
200
400
600
800
1000
1200
1400
0
1
2
3
4
5
6
7
8
100
200
0.1

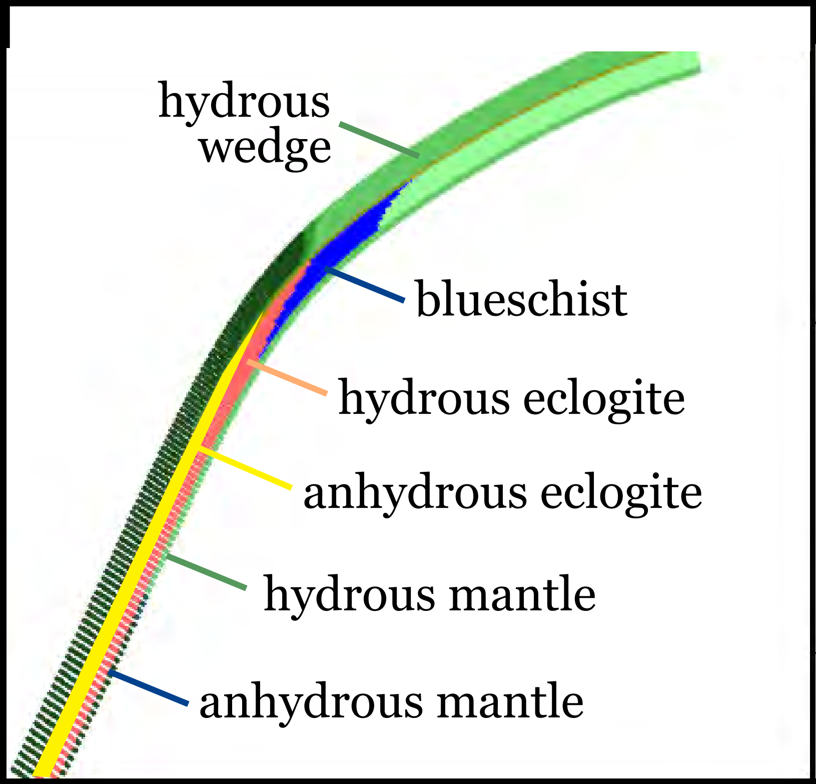
NZ Facies & H_2O

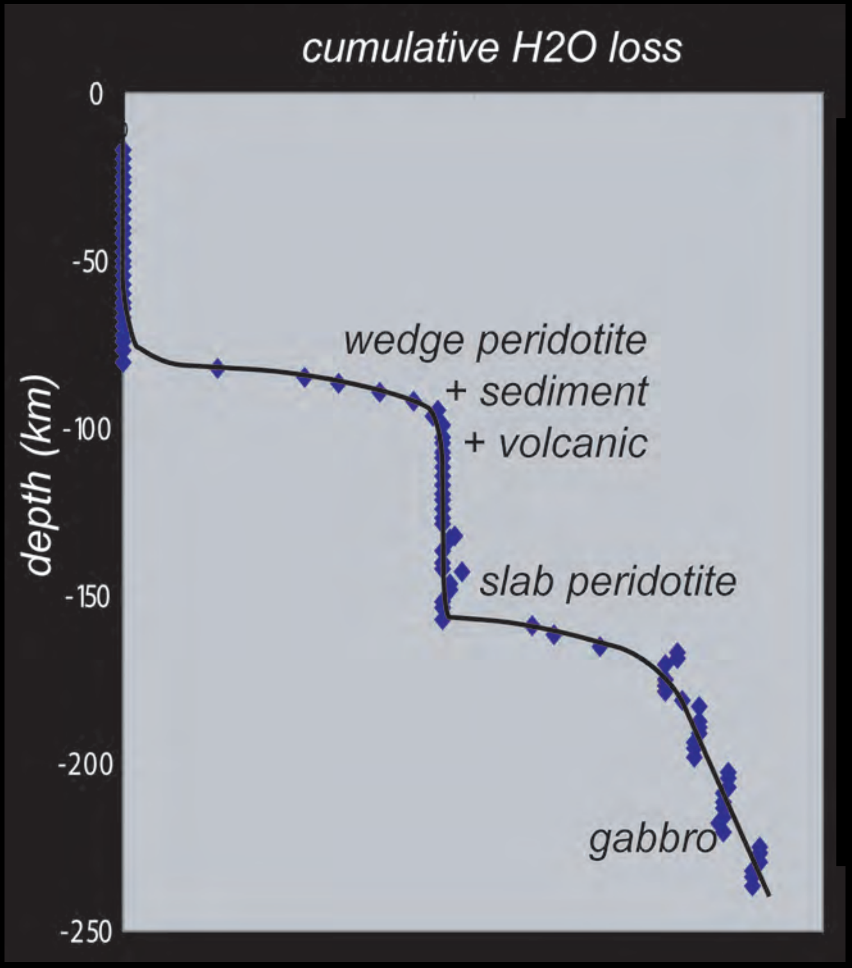




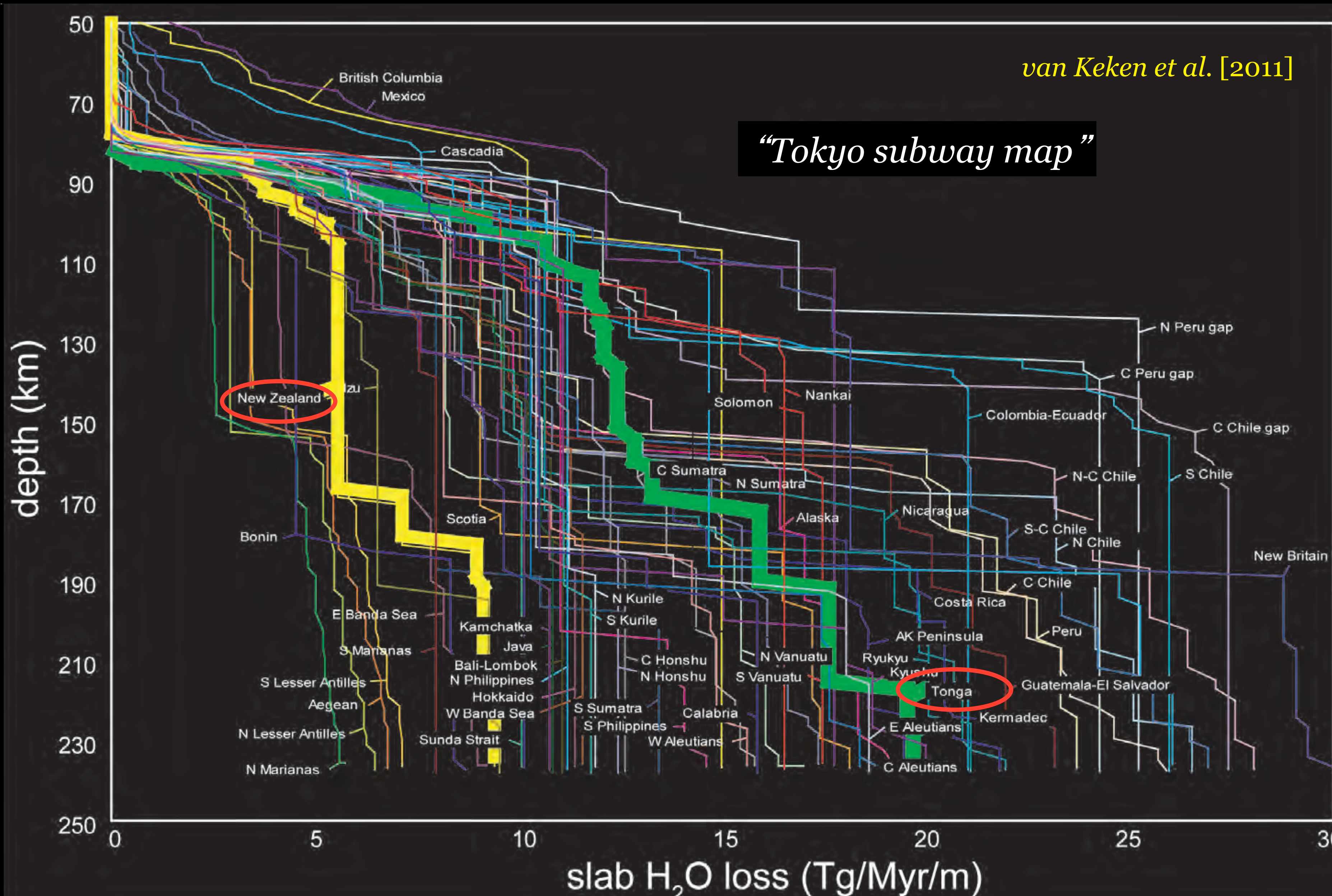
NZ Facies & H_2O Loss

metamorphic facies

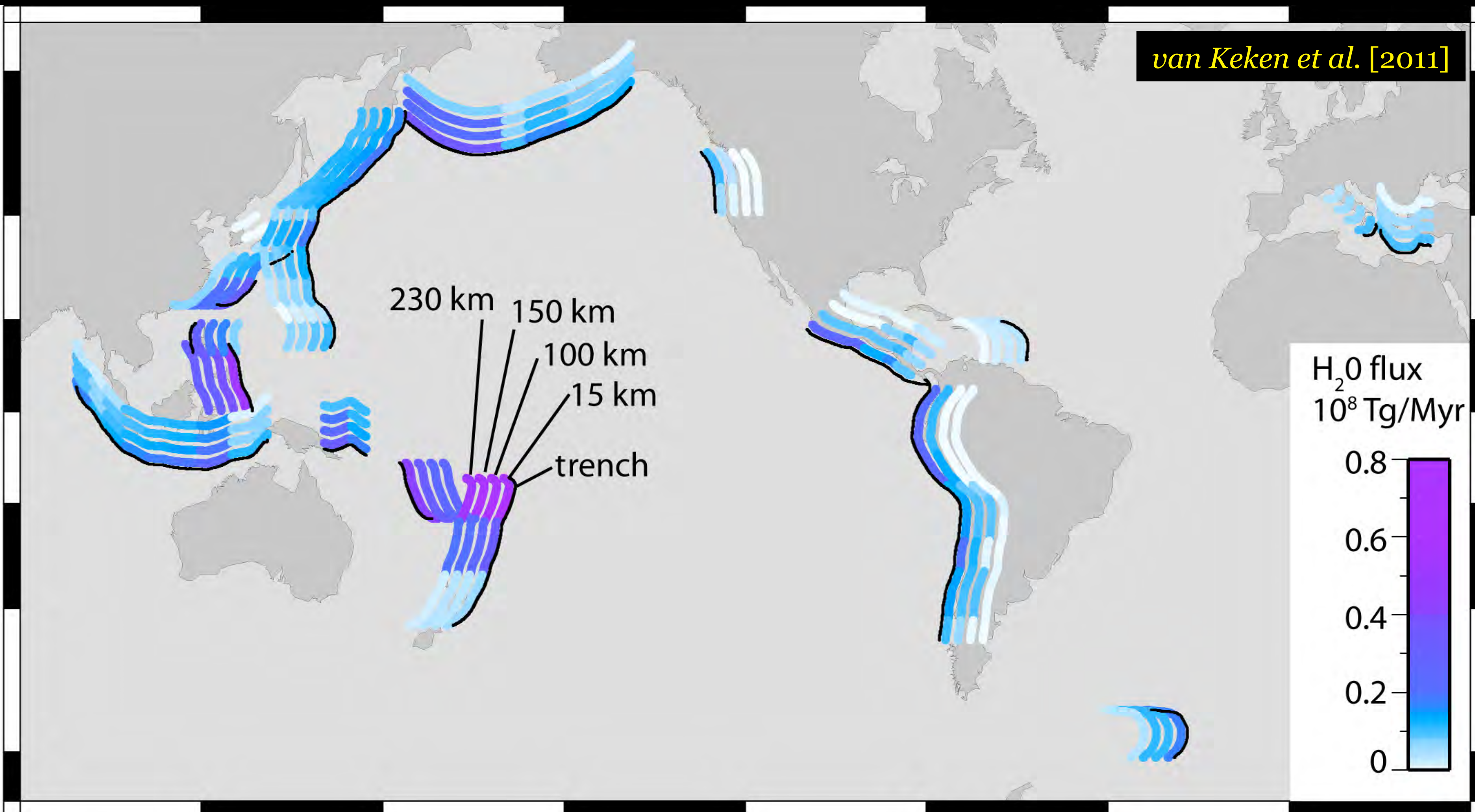




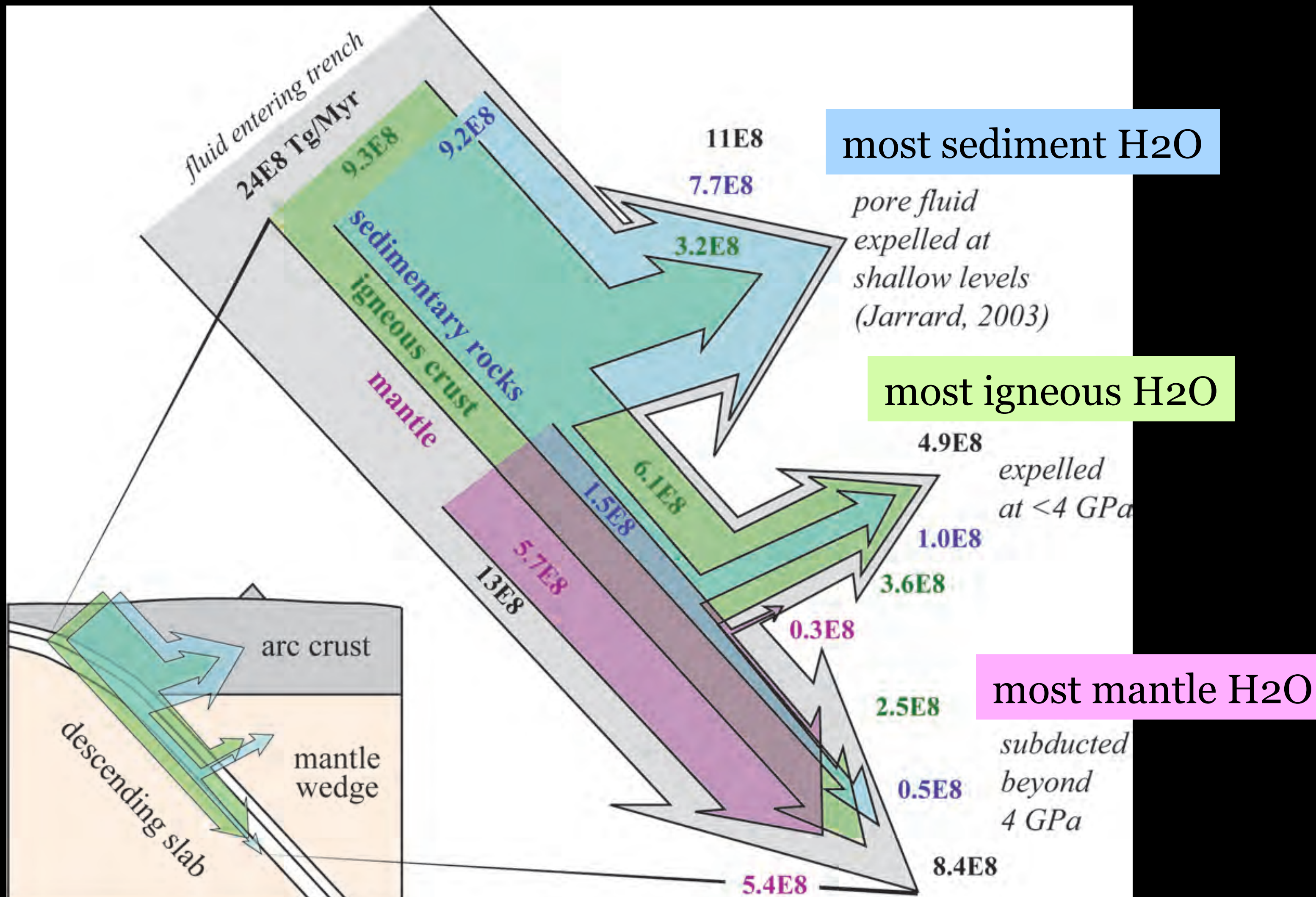
Global H_2O Loss with Depth



Global H_2O Loss with Depth

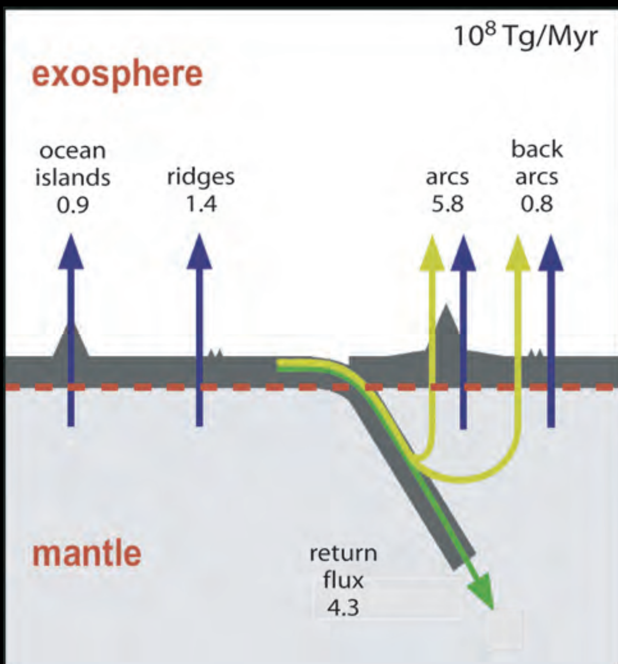


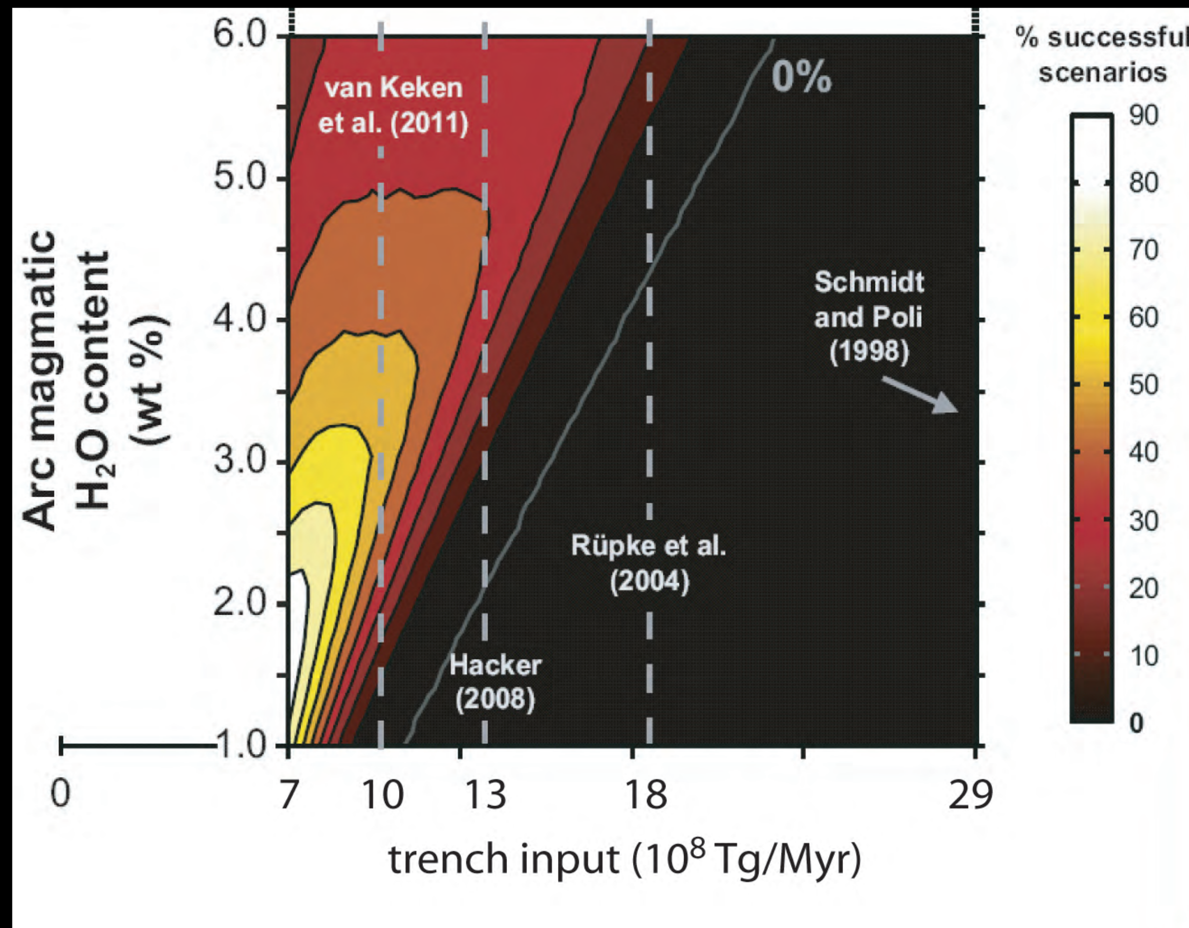
Summary: Global Slab H_2O Flux



Hacker [2008]

Overestimate of Trench Input?

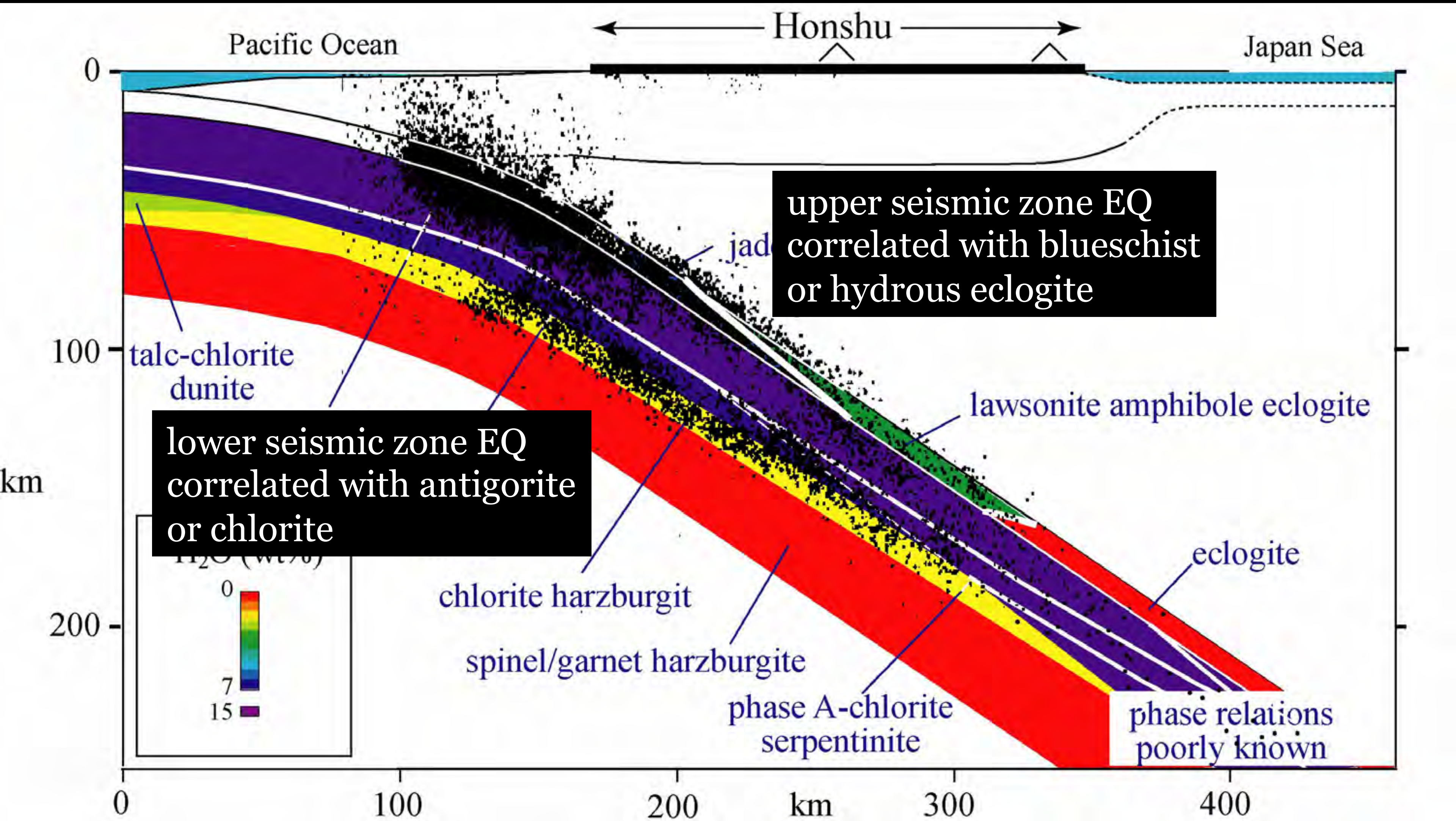




assuming steady-state ocean [*Paral & Mukhopadhyay*, 2012] suggests overestimate; perhaps less serpentinite?

(De)Hydration & Seismicity

classic double seismic zone

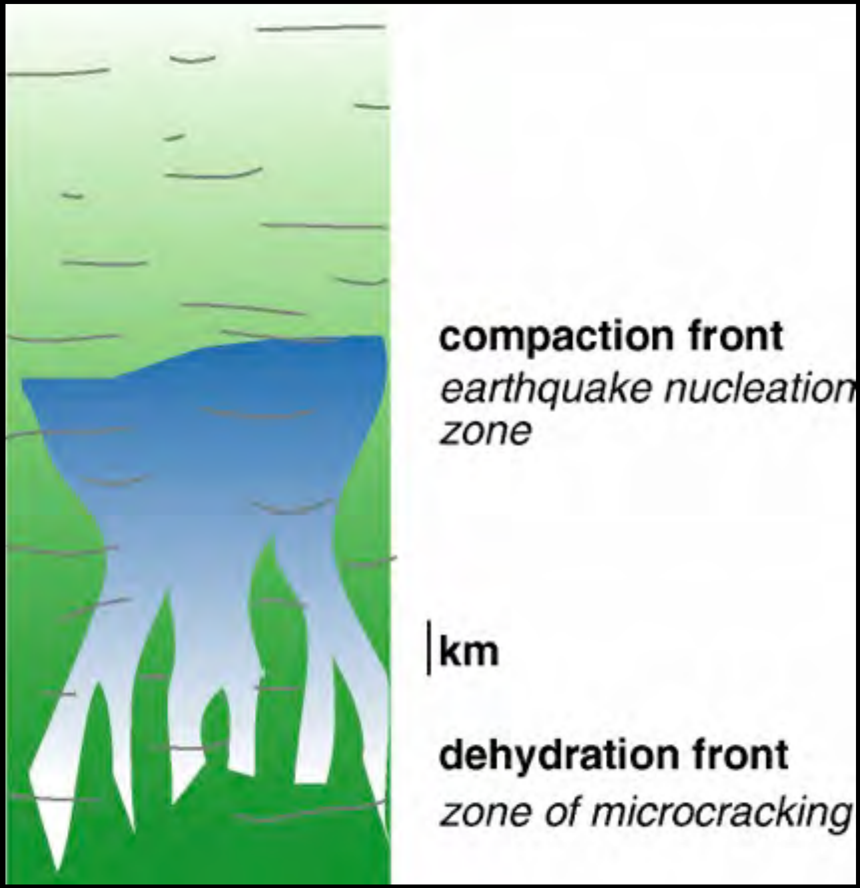


Hacker et al. [2003]

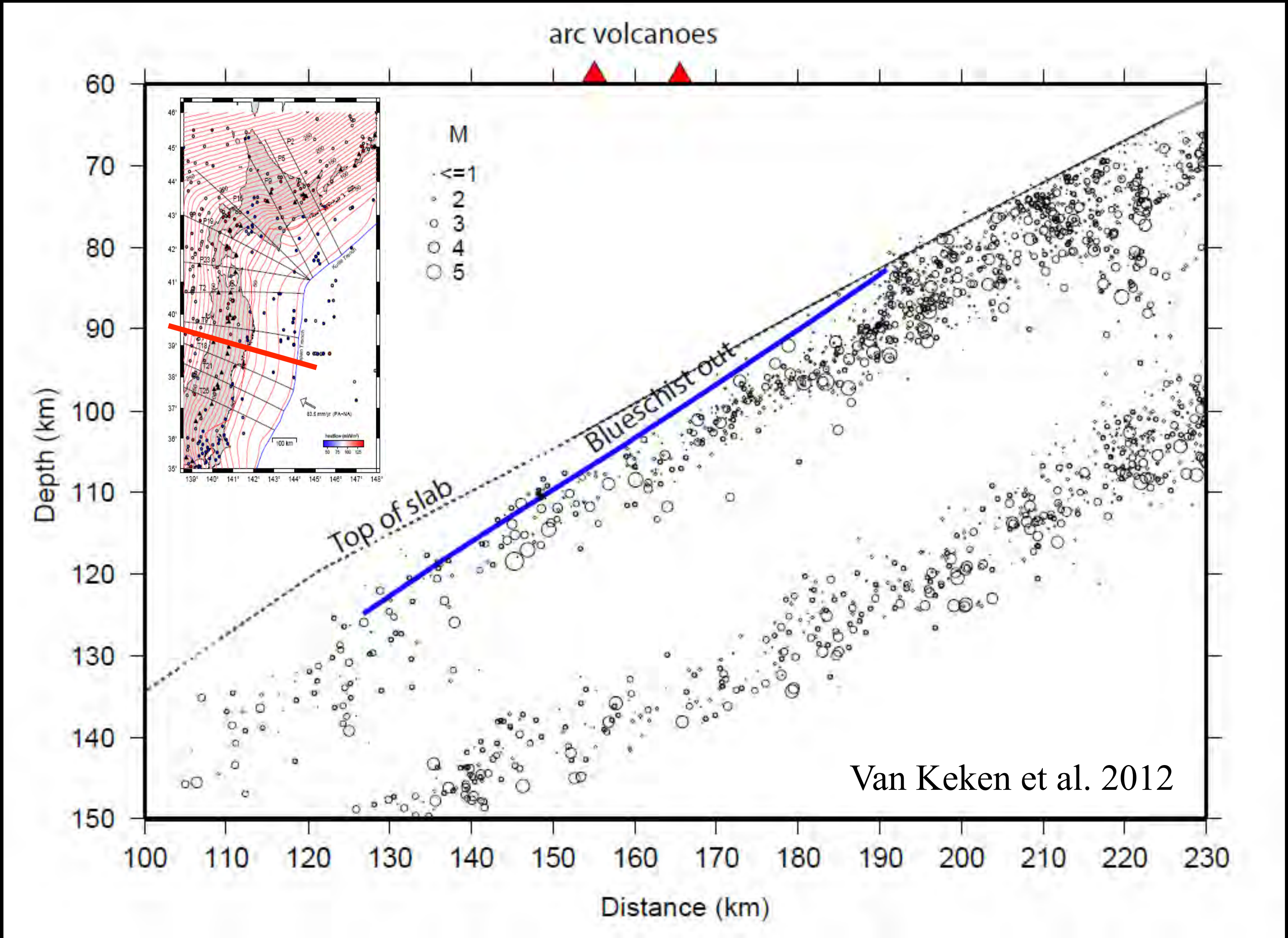
Hydration–Seismicity Hypothesis

presence of fluid *permits* intermediate-depth earthquakes

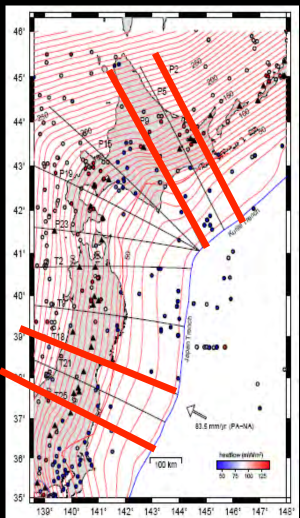
not dehydration embrittlement

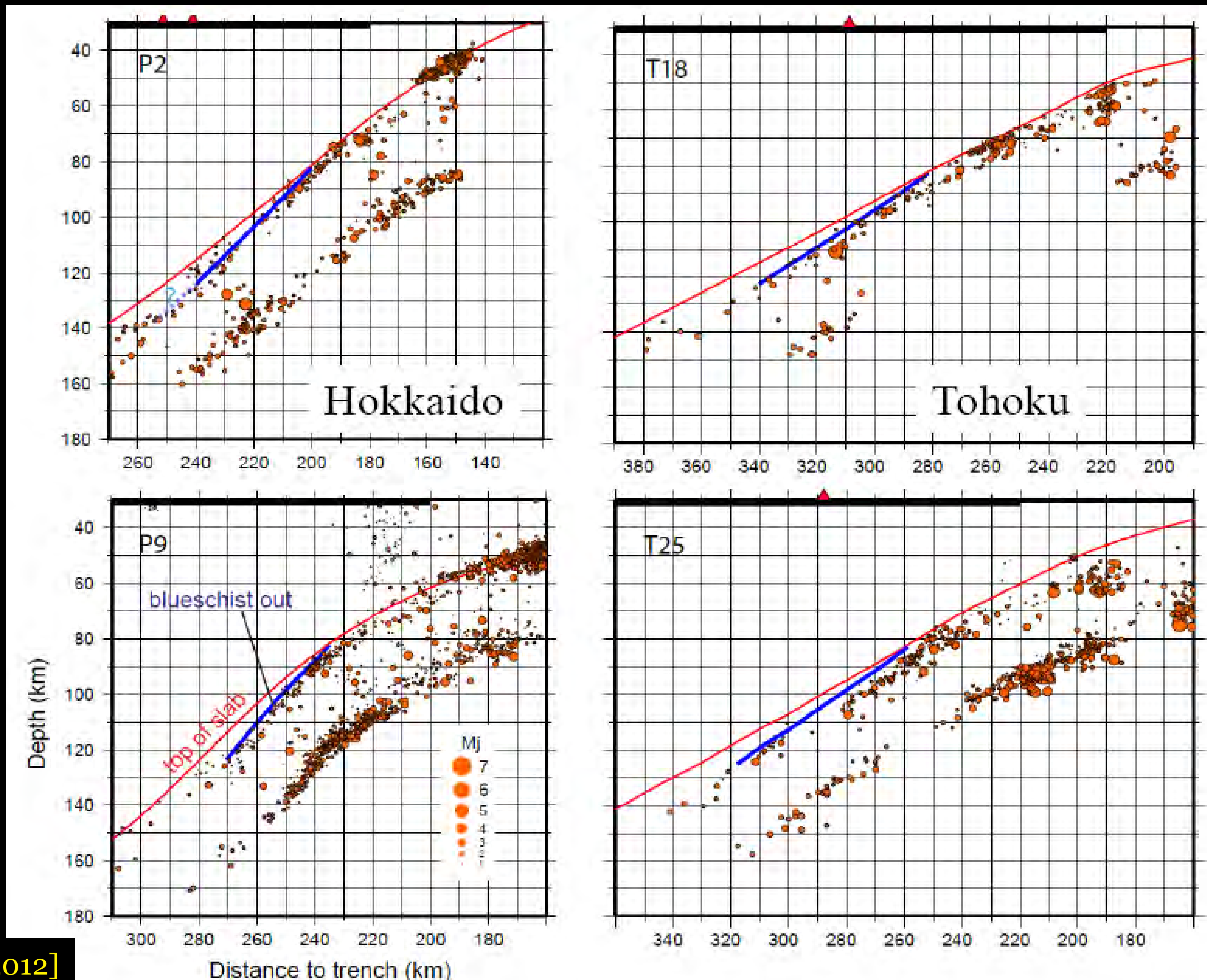


Blueschist-Out Limits Upper Seismic Zone



Blueschist-Out Limits Upper Seismic Zone

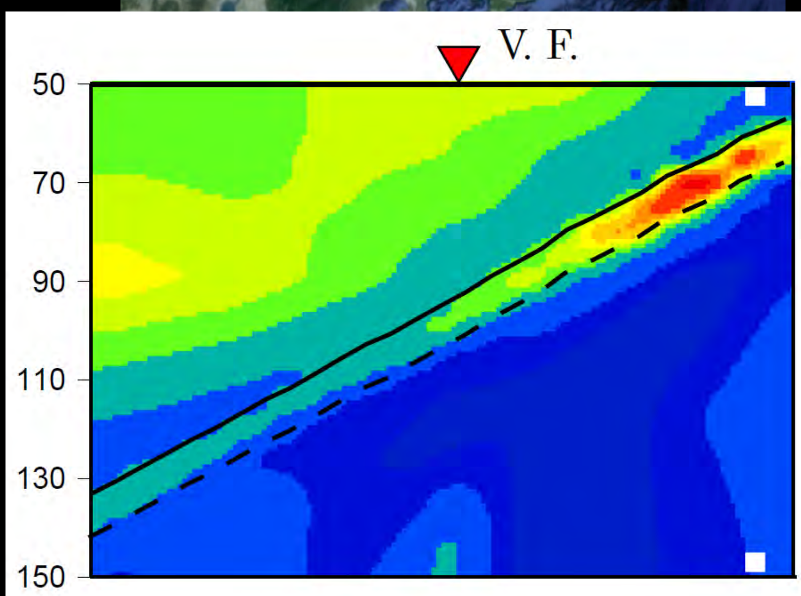


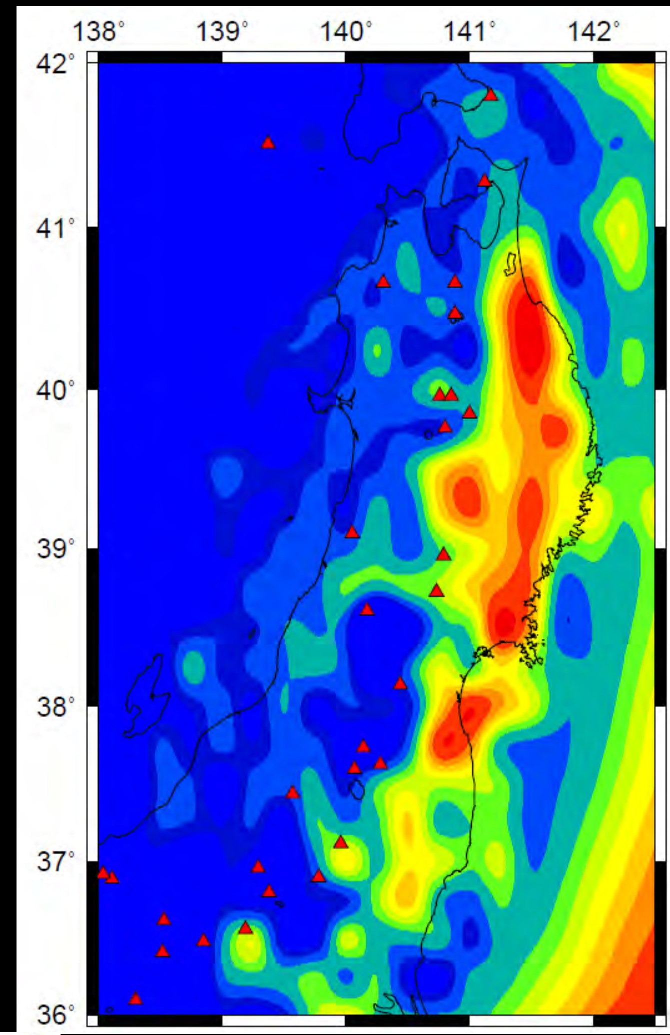


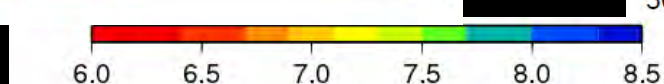
van Keken et al. [2012]

Dehydration = Slow & Seismic

V_P < 7.2 km/s
suggests fluid



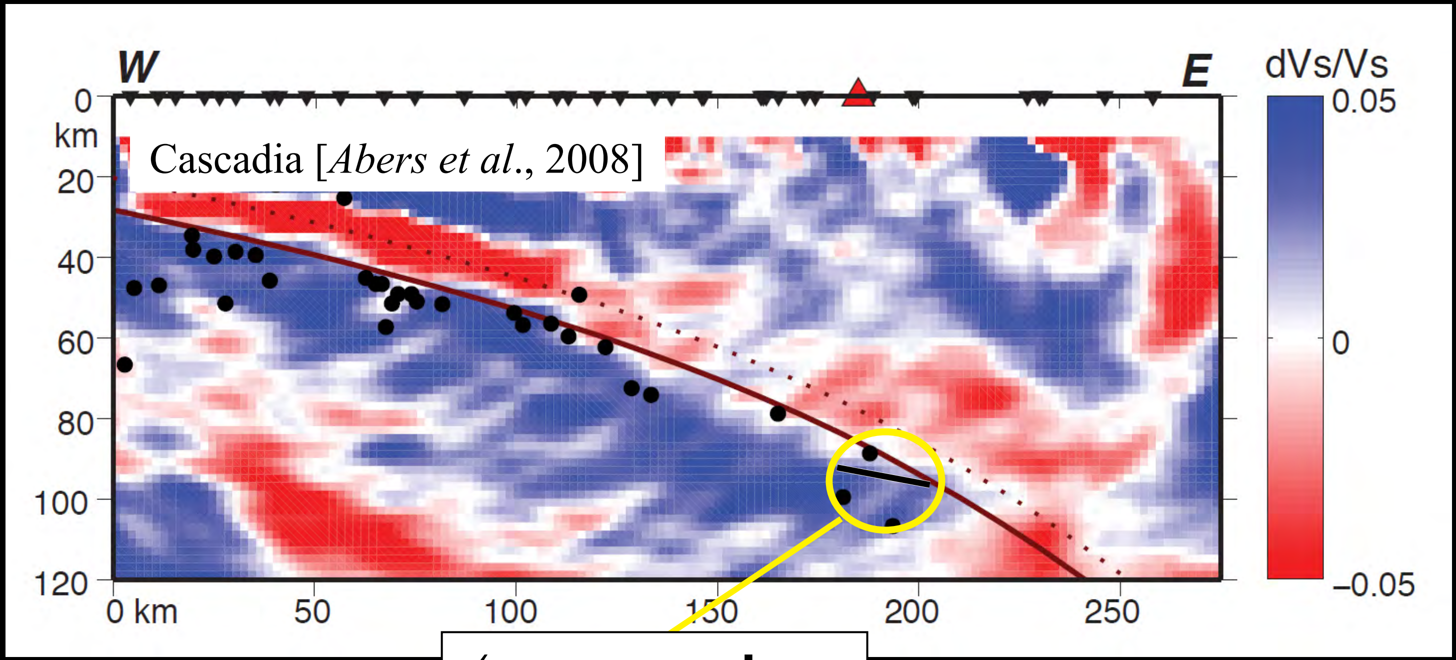




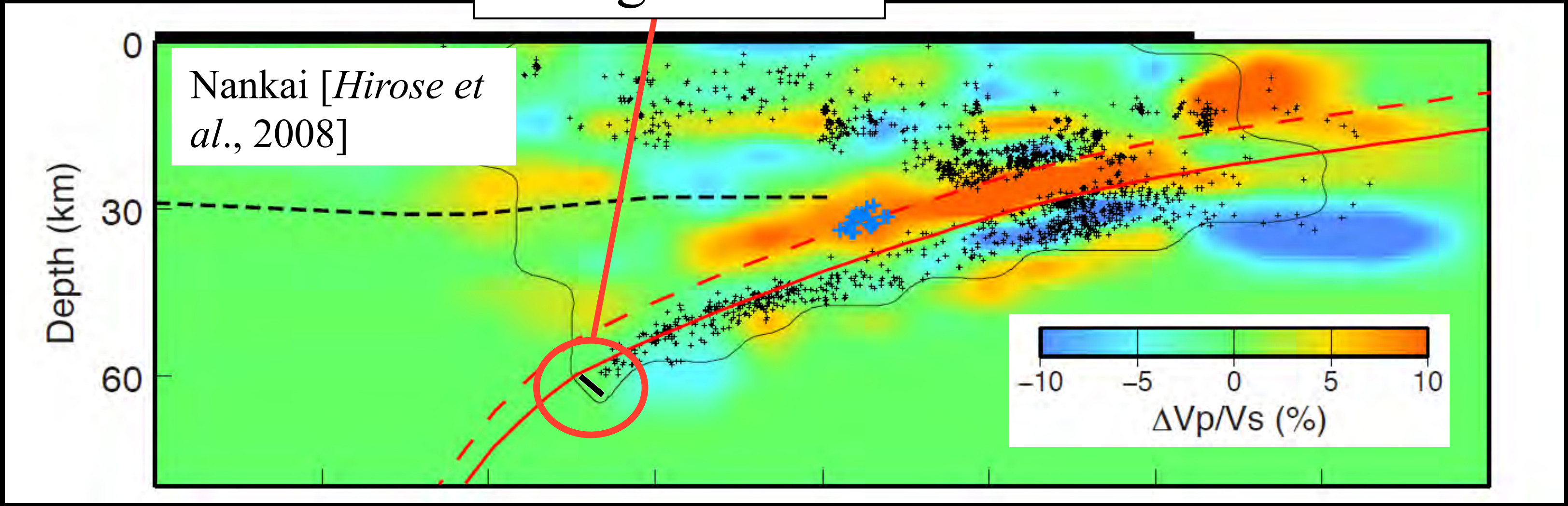
Vp [km/s]

Shina et al. [2012]

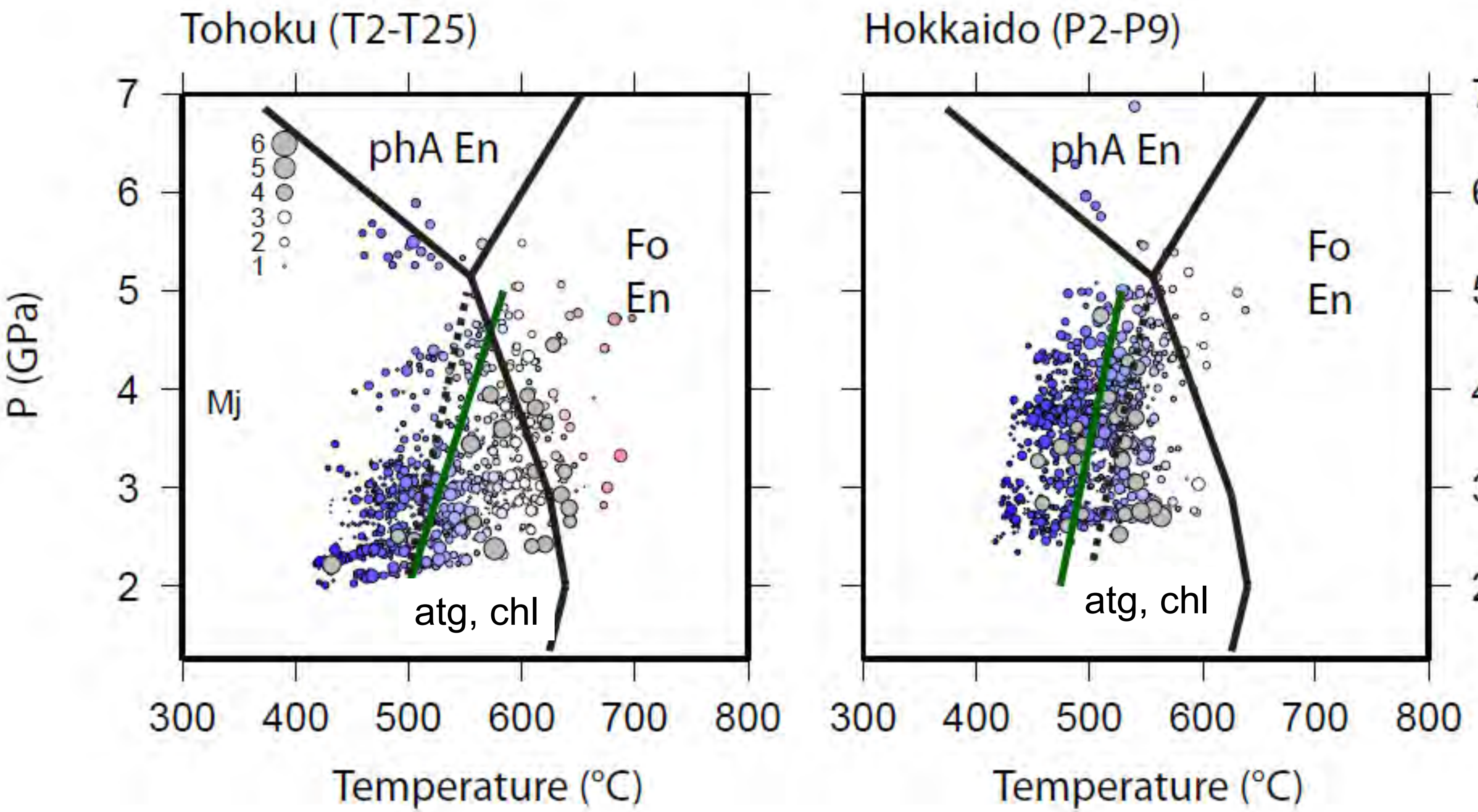
‘Serpentine’ -Out Limits Lower Seismic Zone



‘antigorite’ out

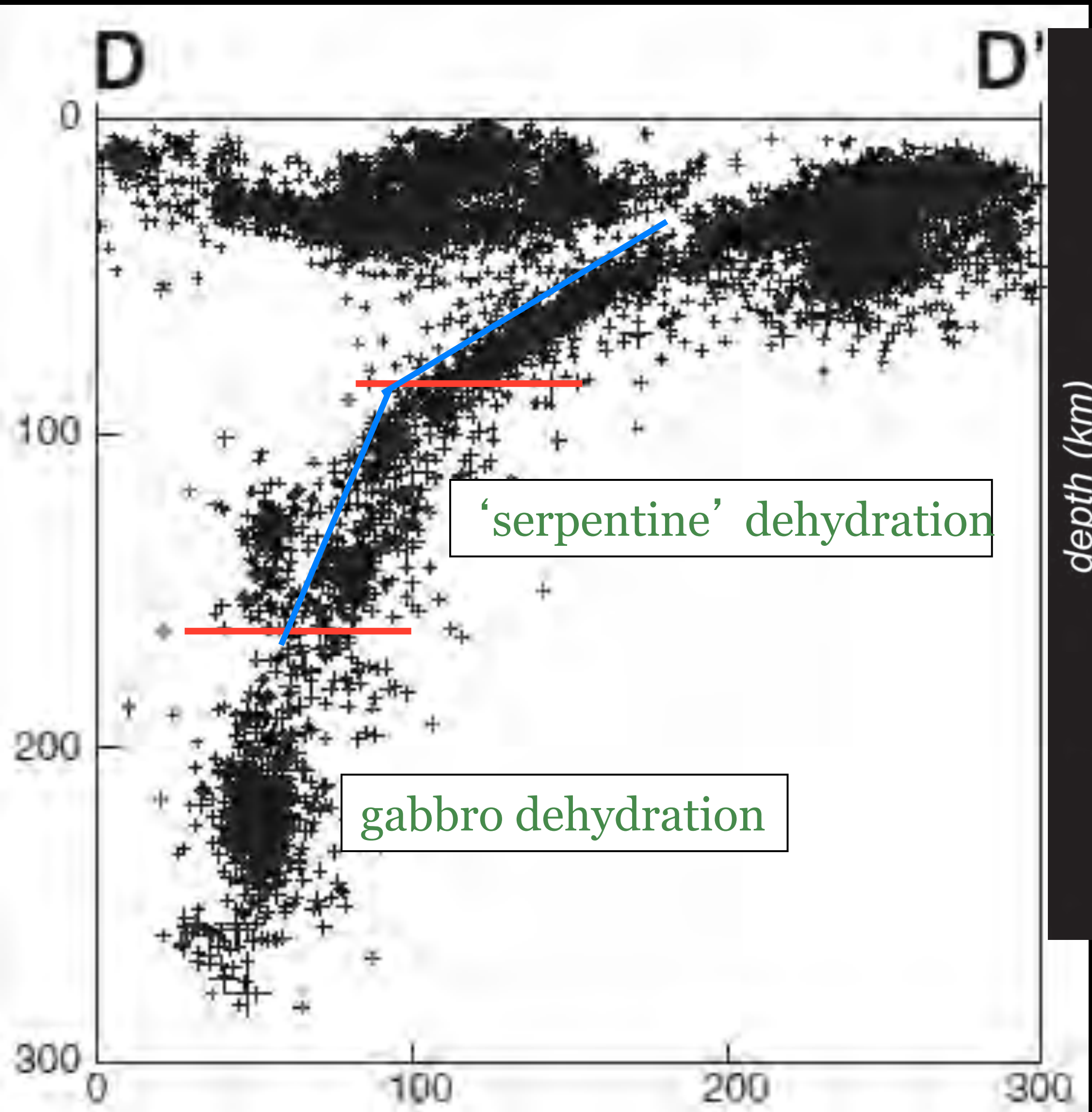


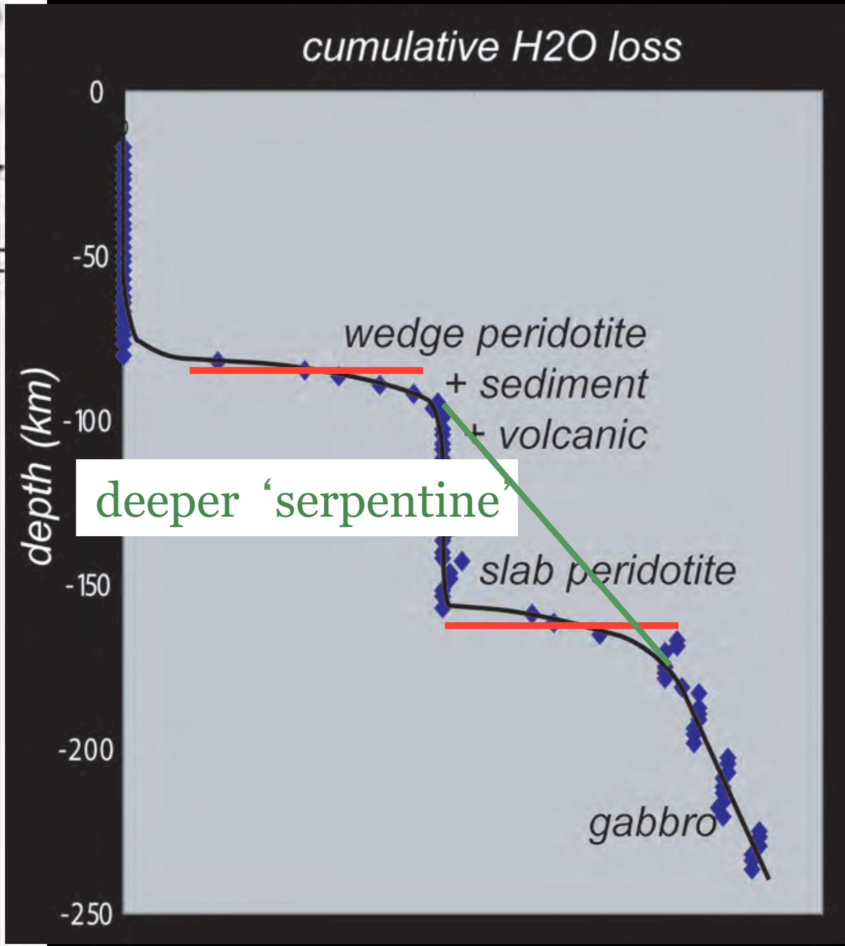
‘Serpentine’ -Out Limits Lower Seismic Zone



van Keken et al. [2013 EGU]

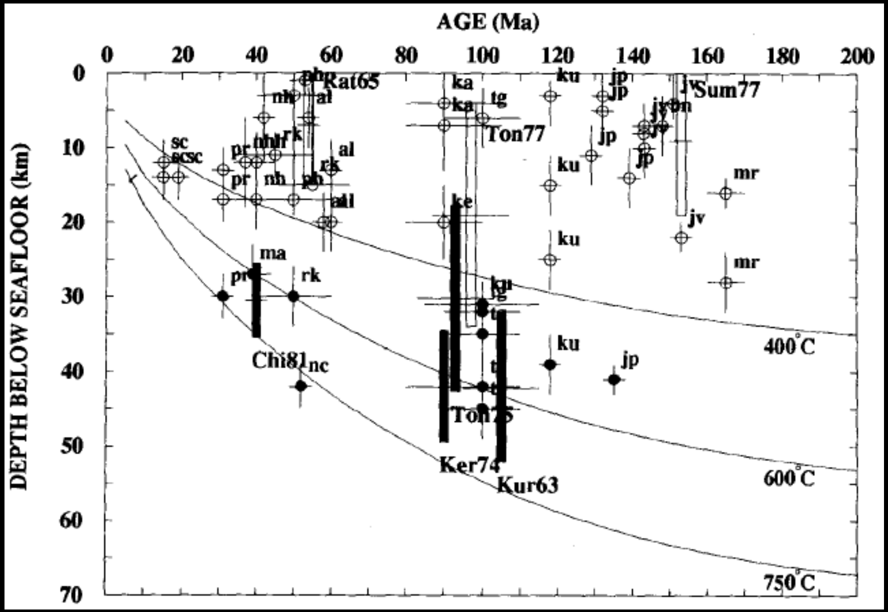
NZ Seismicity & Calculated Dehydration



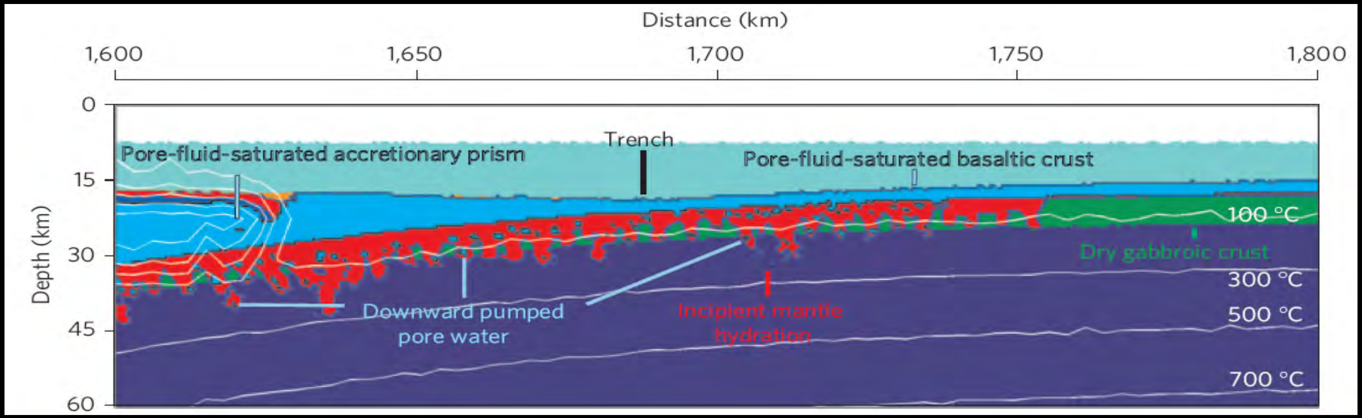


Reyners et al. [2011]

How Does Lower Seismic Zone Hydrate?

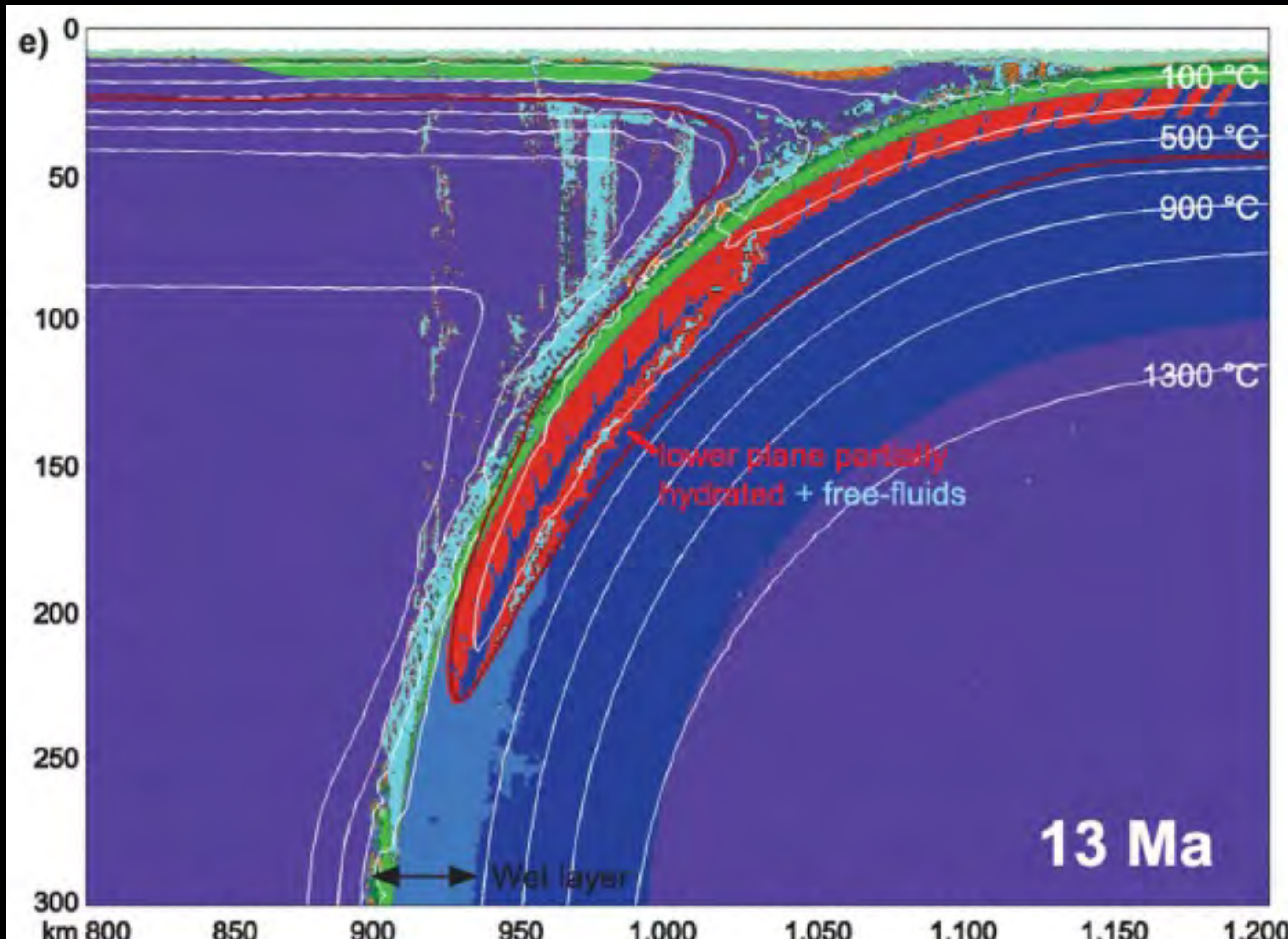


outer rise quakes [*Seno & Yamanaka*, 1996]



bending at outer rise pumps fluid downward [*Faccenda et al.*, 2009]

How Does Lower Seismic Zone Hydrate?

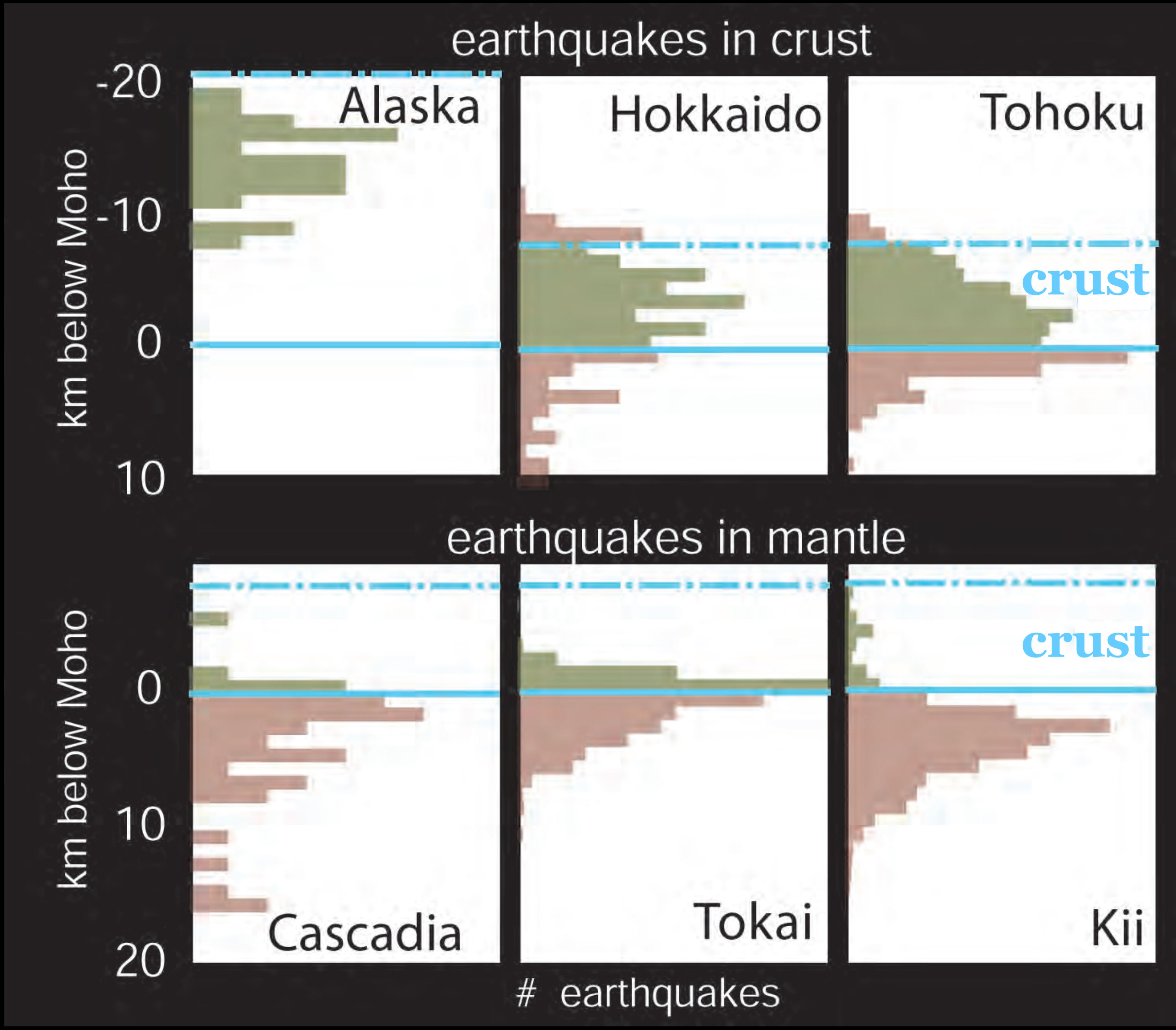


unbending stresses drive fluid into slab core [*Faccenda et al.*, 2012]

Hot & Cold Slab Seismicity Different

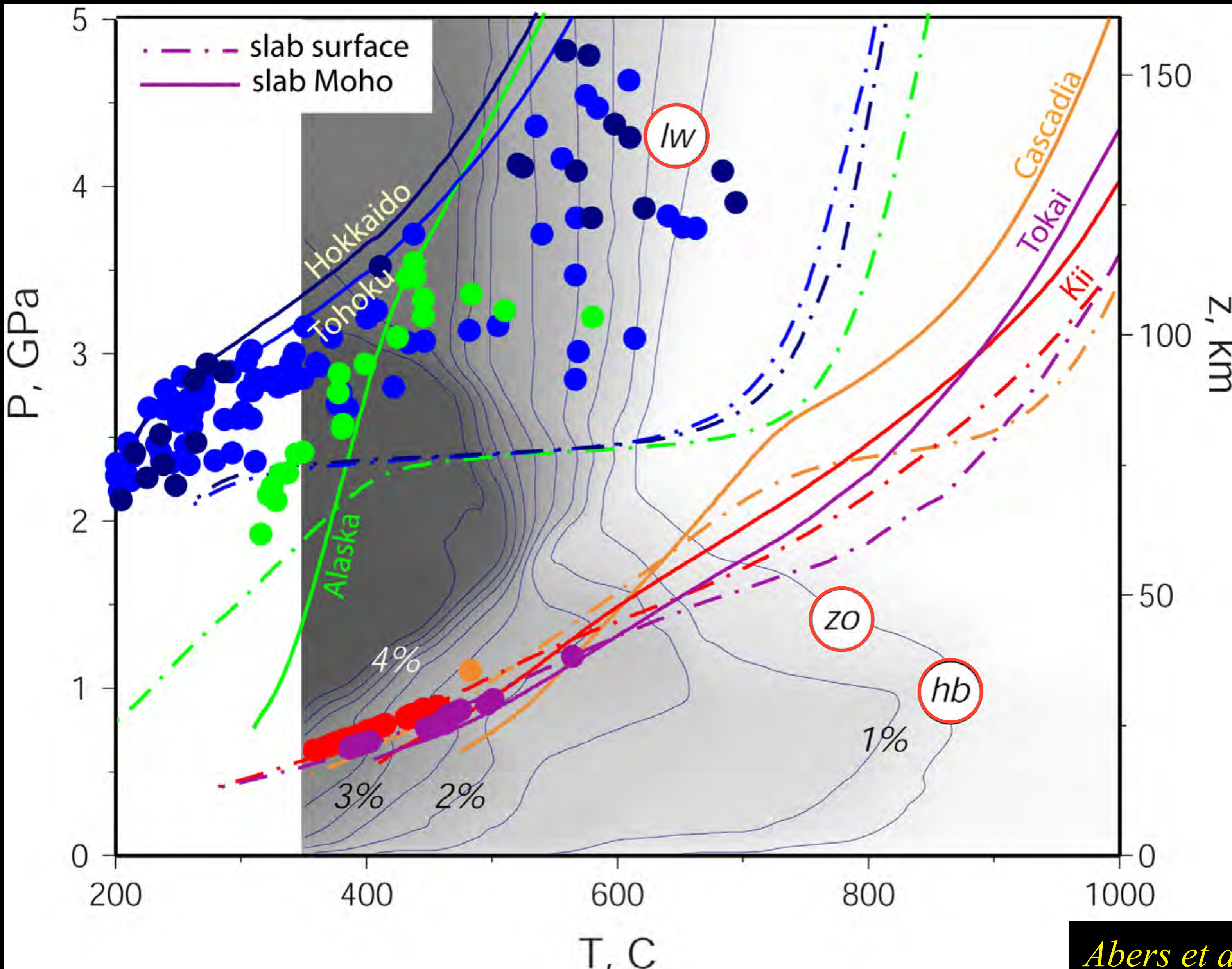
most cold slabs:
upper zone EQs
in crust

hot slab:
EQs in mantle



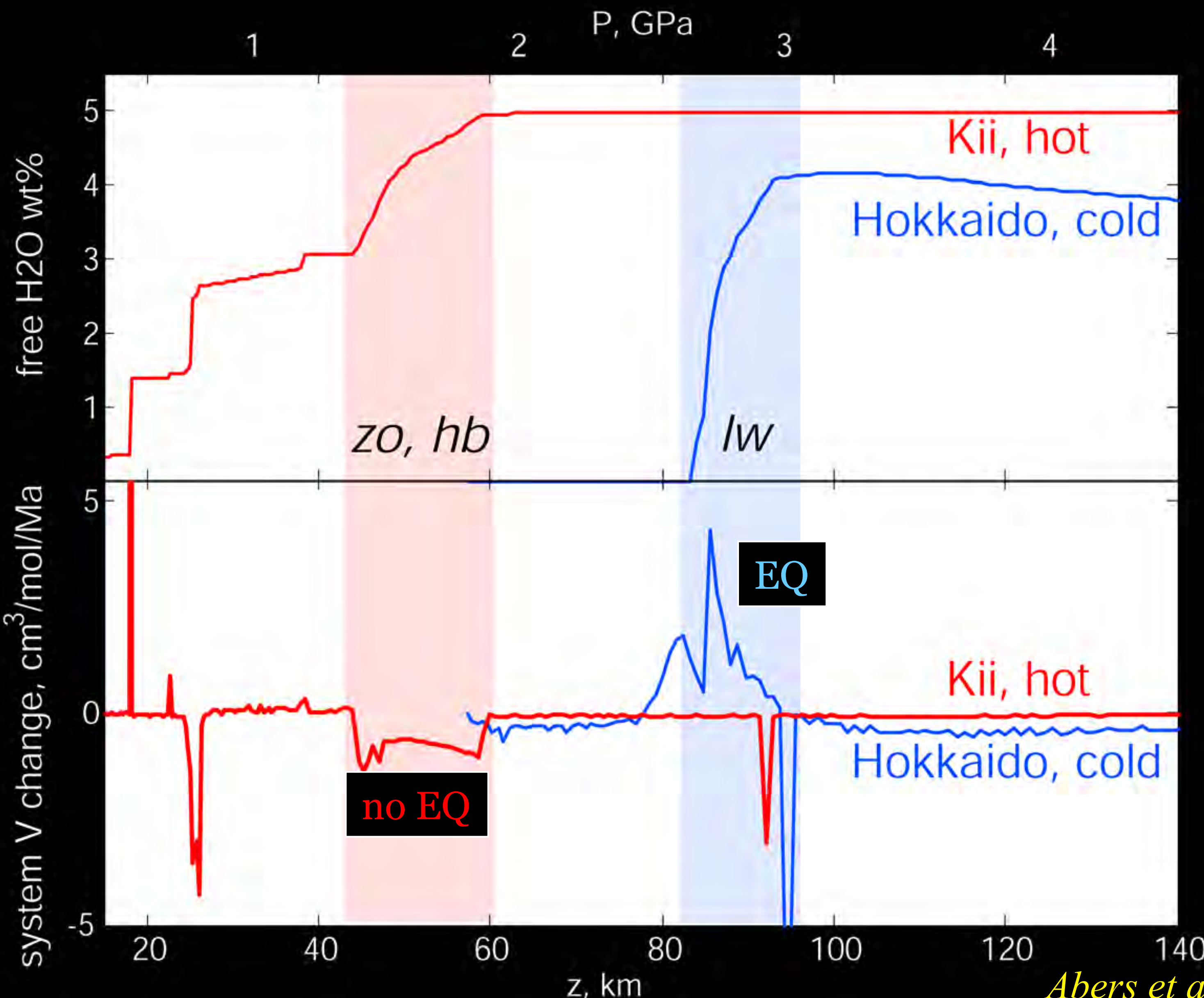
Abers et al. [2013]

EQ Where Clapeyron Slope > 0



Abers et al. [2013]

EQ if Fluid >Porosity



Abers et al. [2013]

Summary: Slab H_2O Cycle

- hotter zones have sediment dehydration melting
- most slabs *may* have hydrous melting
  - depends on fluid flow
- slab mantle dehydrates at lowest T (~600°C)
  - hydration state & fluid flow critical
- most sediment/igneous/mantle H_2O expelled beneath forearc/arc/backarc
- large along-strike change in “NZ” zone

Summary: Seismicity & H_2O

- seismicity generally in hydrated material

- seismicity in crust/mantle limited by blueschist/ ‘antigorite’

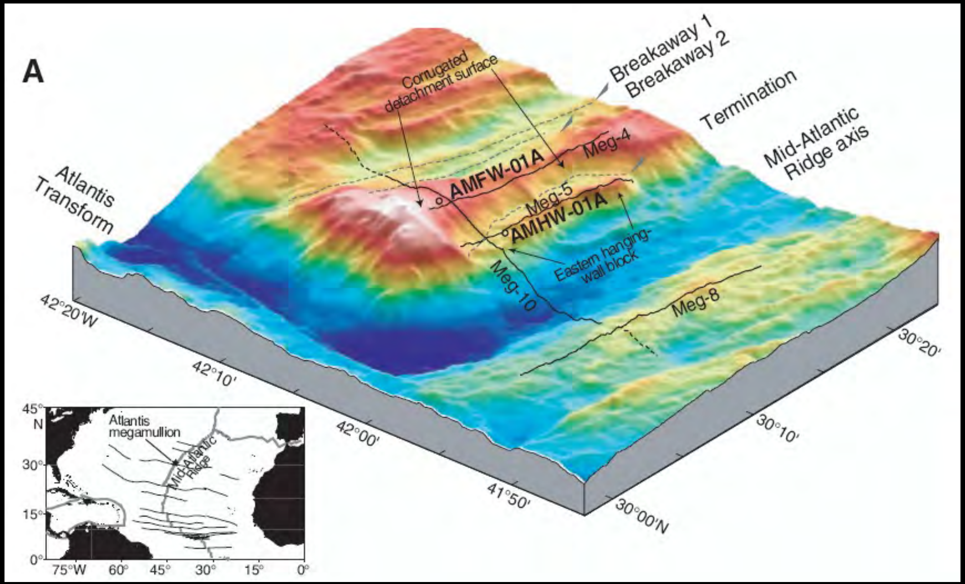
- lower plane may hydrate at outer rise or in slab

- hot/cold zones upper plane EQs in mantle/crust

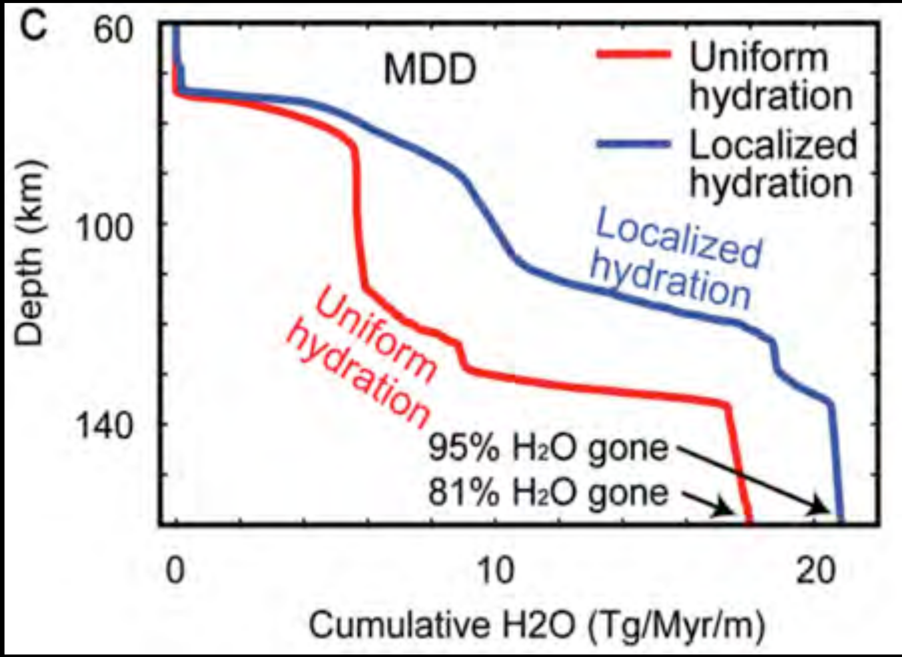
- negative Clapeyron slopes control seismicity??

4 Key Questions to Address

Slab Heterogeneity

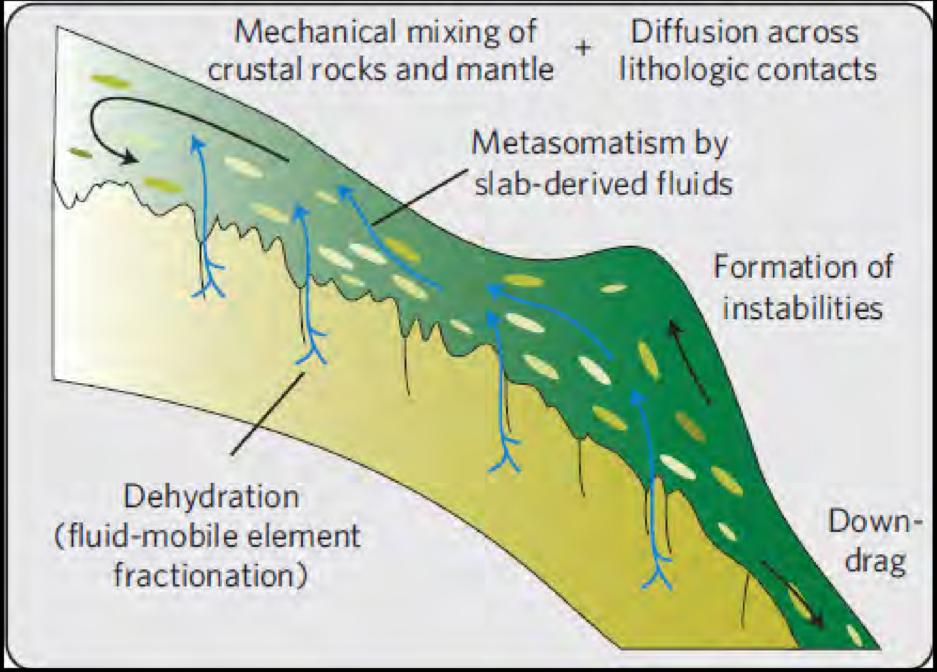


Blackman et al. [2003]



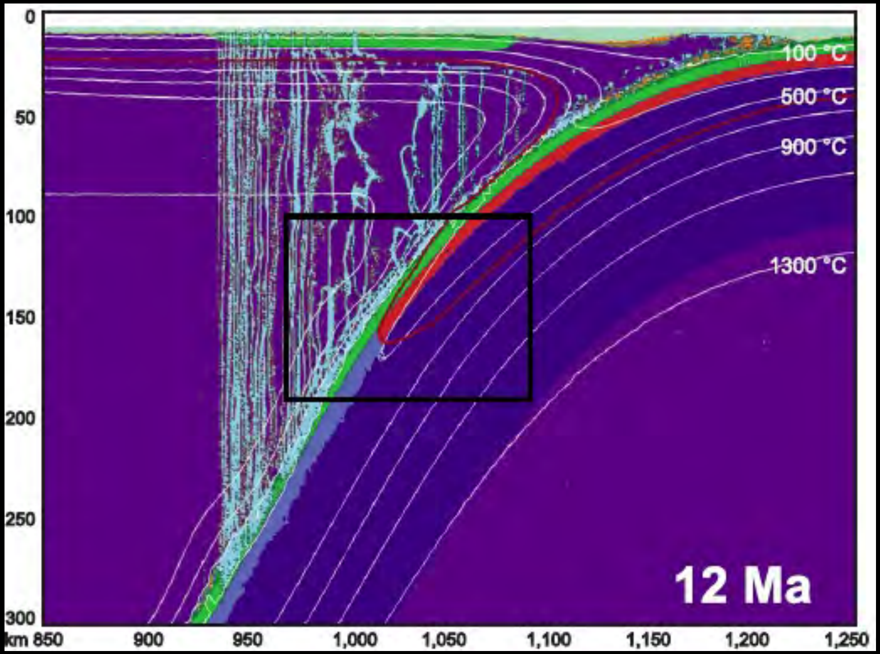
local hydration carries more H_2O to depth [*Wada et al.*, 2012]

Metasomatic Bulk Compositions

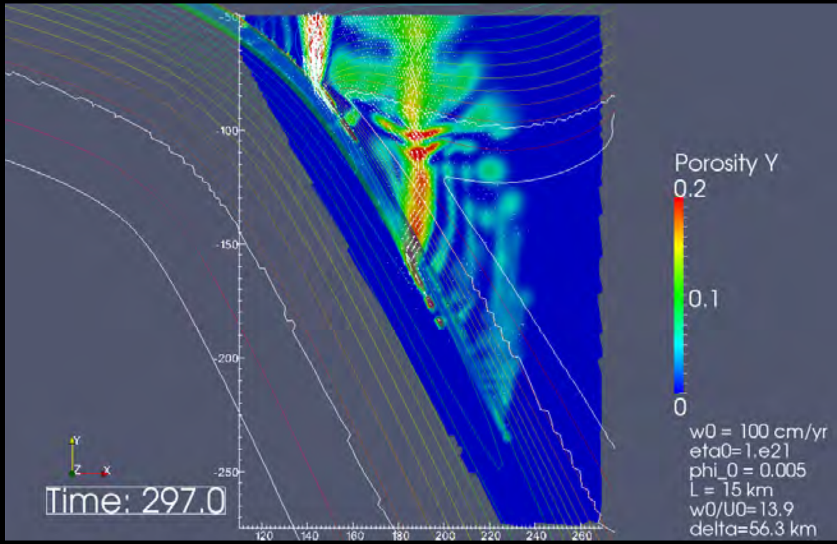


Marschall & Schumacher [2012]

Fluid Flow, Including Rehydration

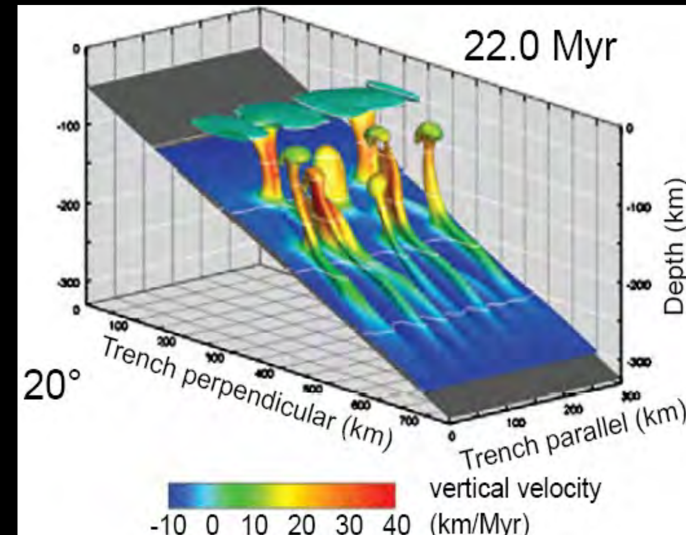


Faccenda et al. [2012]

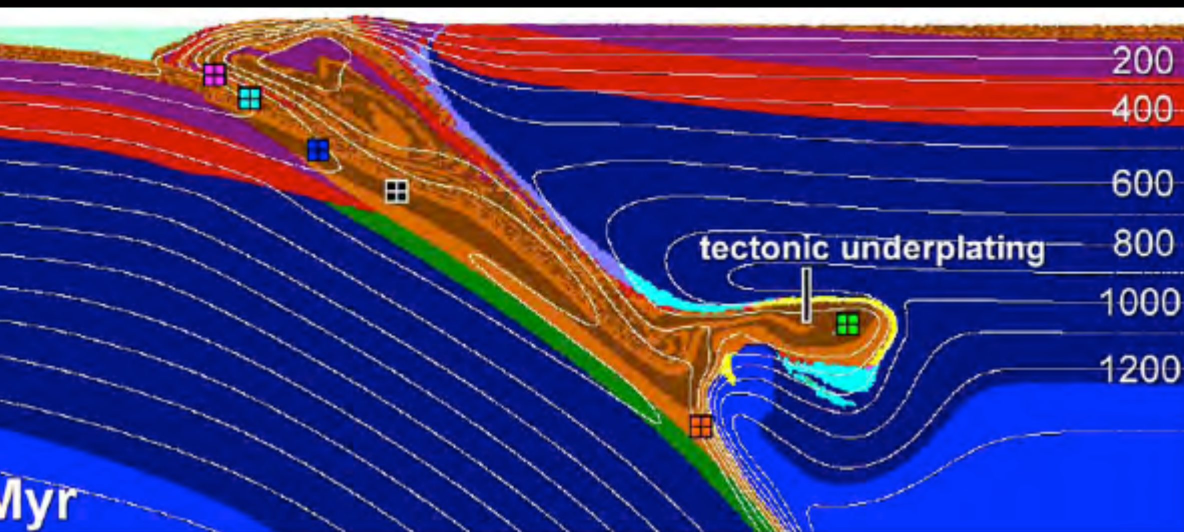


M Spiegelman, AGU 2012

Non-H_2O Mass Flow



Hassenclever et al. [2011]



Gerya et al. [2007]

Warren et al. [2008]