

From thermodynamics to geodynamics: An overview of the geophysical thermodynamics of phase relations

Craig R. Bina



Dept. of Earth and Planetary Sciences
Northwestern University
Evanston, Illinois, U.S.A.

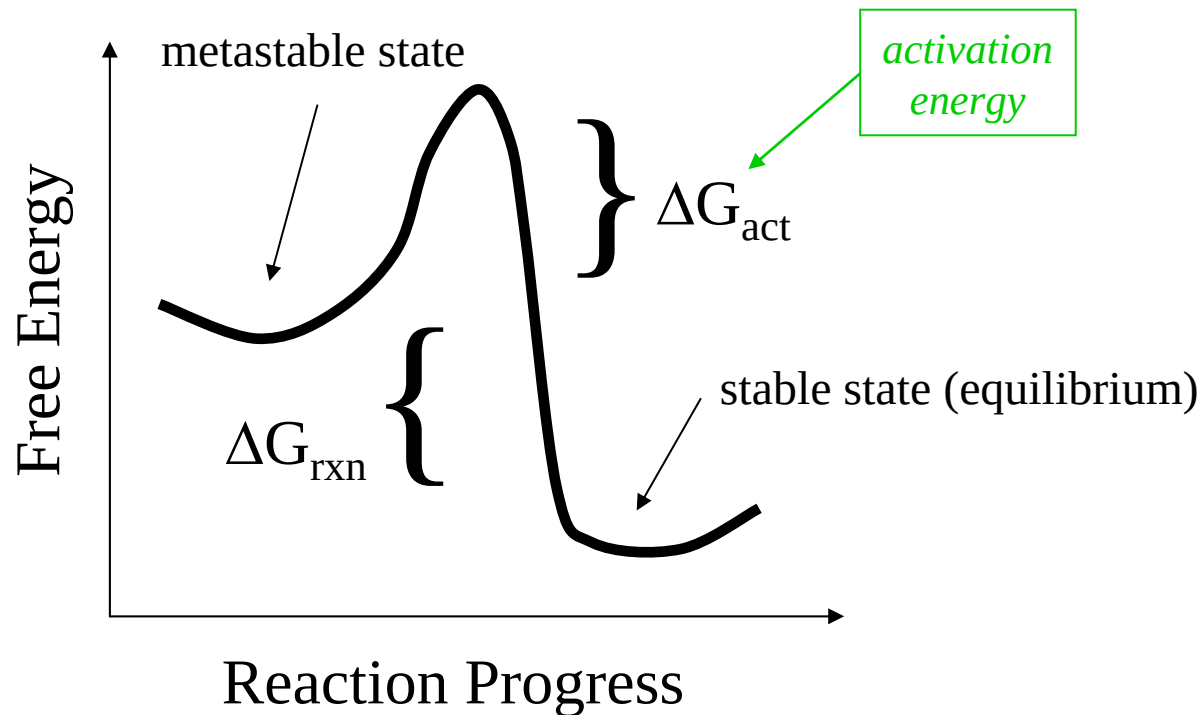


*Katedra geofyziky
Matematicko-fyzikální fakulta
Univerzita Karlova v Praze*

*přednášky na podzim 2011
6. lekce 16.11.*

Thus far, we have considered only equilibrium phase relations.
However, we should also consider the possibility of:

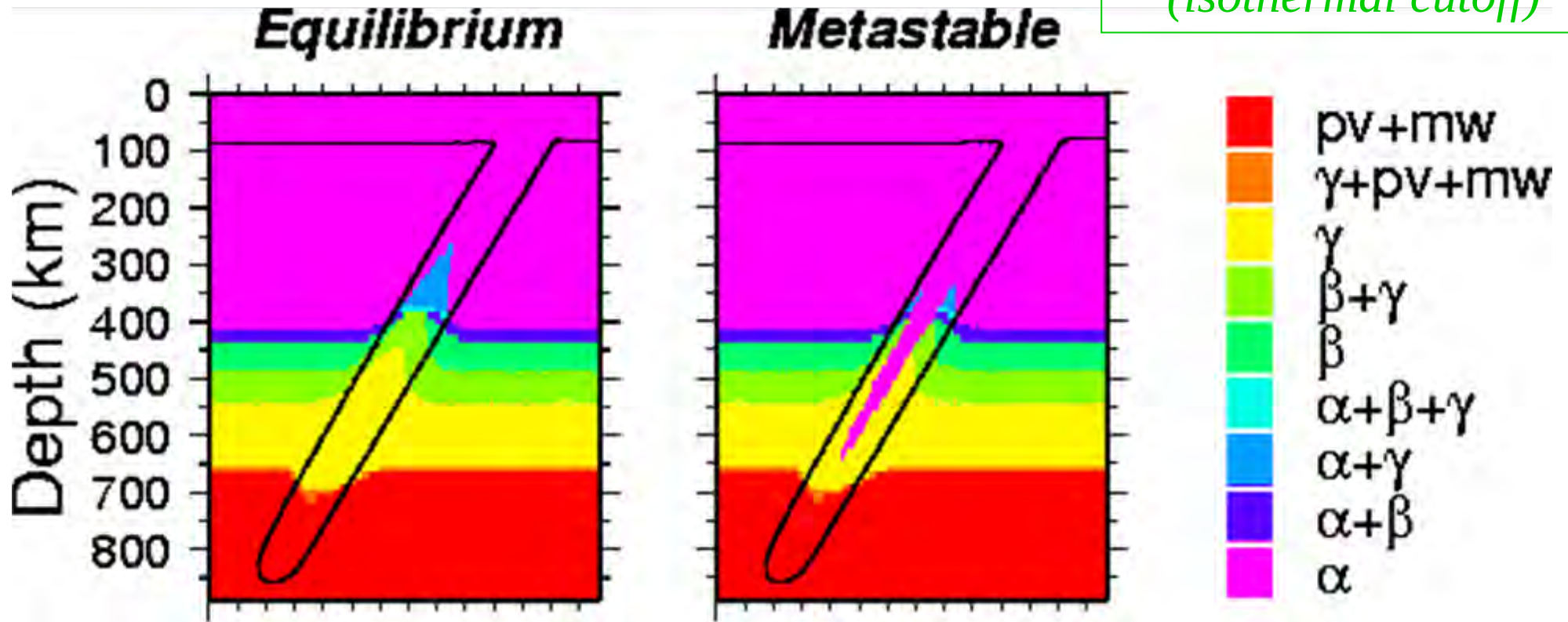
Metastability



It is more difficult to overcome ΔG_{act} at low temperatures, so some phases may persist metastably beyond their stability fields.

Metastability: Olivine as an Example

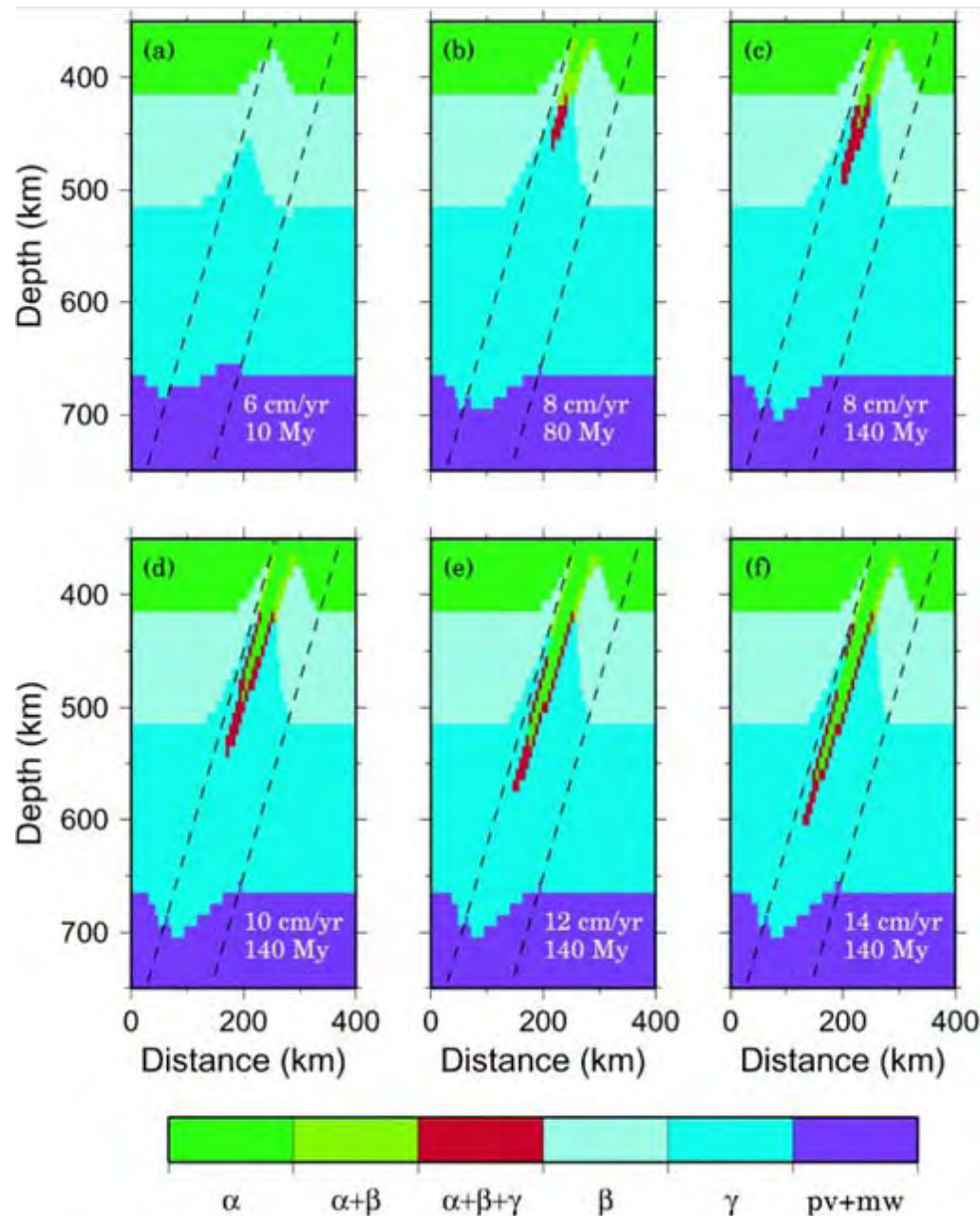
*approximate kinetics
(isothermal cutoff)*



A model of metastable persistence of α olivine at $T < 1000$ K

(from Figure 4 of Bina et al. [2001])

Olivine Metastability



(Figure 5 of Mosenfelder et al., *PEPI*, 2001)

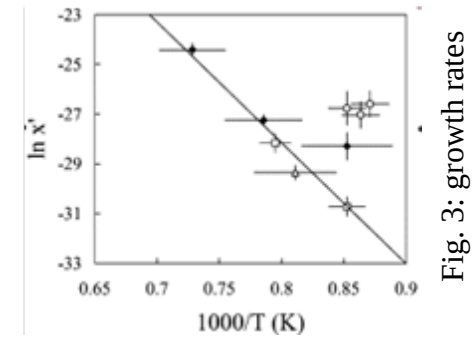


Fig. 3: growth rates

measured kinetics

Fig. 5. Thermo-kinetic model results for slabs with varying convergence rates and ages, as shown on the figure. Colors represent phase fields for olivine (α), wadsleyite (β), ringwoodite (γ), and (Mg, Fe)SiO₃ perovskite + magnesiowüstite (pv+mw). All of these models were calculated using the growth rate parameters of kinetic model 1 (see Table 2), (a) Young, warm slab ($\varphi=520$ km) in which growth rates are fast enough for transformation to occur close to the equilibrium phase boundary; (b–f) successively colder slabs ($\varphi=5543, 9699, 12124, 14549$, and 16974 km, respectively) showing increasingly greater depth of olivine metastability. Parts (c) and (f) show slabs with parameters corresponding to slabs C and D, respectively, of Kirby et al. (1996), as discussed in the text.

Olivine Metastability

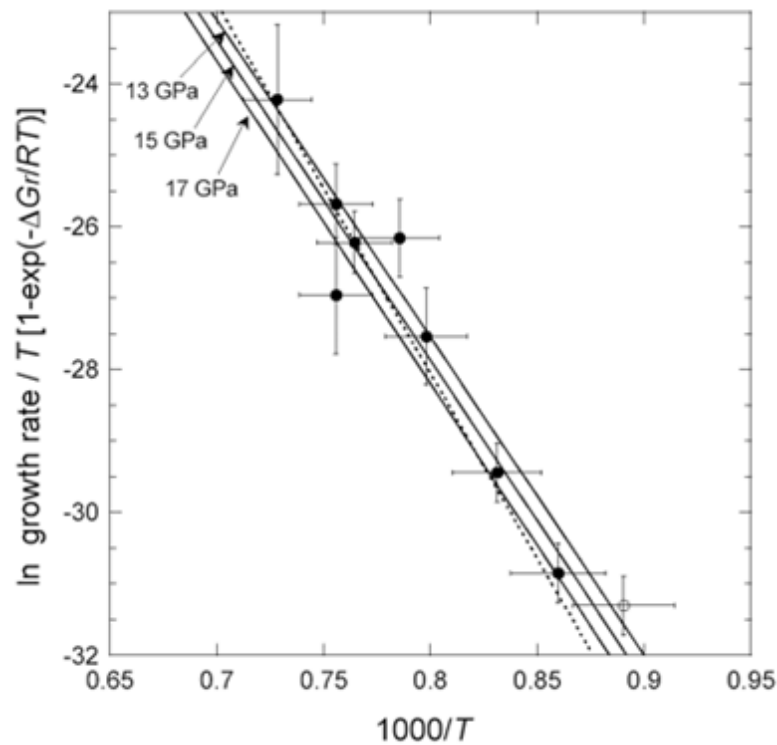
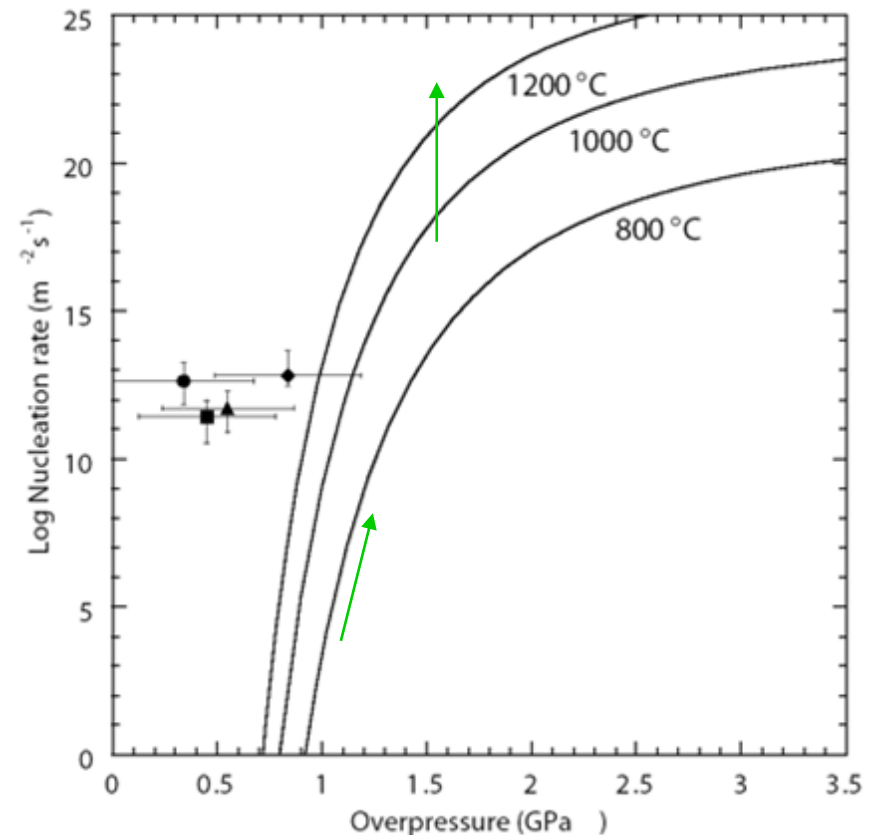


FIGURE 8. Pressure and temperature dependencies of the growth rate. A least-squares fit (straight line) using growth-rate Equation 4 to the obtained data (solid circles) gives an activation energy of 348 (137) kJ/mol and an activation volume of 1.7 (4.5) cm³/mol. The growth rate of run S220 (open circle) was excluded from fitting (see text). The dotted line shows temperature dependence of the growth rate at 15 GPa from model 1 in Mosenfelder et al. (2001).

kinetic dependence upon T and ΔP

FIGURE 9. Plots of the nucleation rates as a function of over-pressure. The nucleation rate curves estimated using kinetic parameters of Rubie and Ross (1994) are also shown (solid lines). Symbols are: circle = 13.6 GPa and 1100 °C; square = 13.5 GPa and 1050 °C; triangle = 13.4 GPa and 980 °C; diamond = 13.9 GPa and 1050 °C.



(Figures 8 and 9 of Kubo et al., *Amer. Mineral.*, 2004)

Olivine Metastability

kinetic dependence upon T , P , and X_{H_2O}

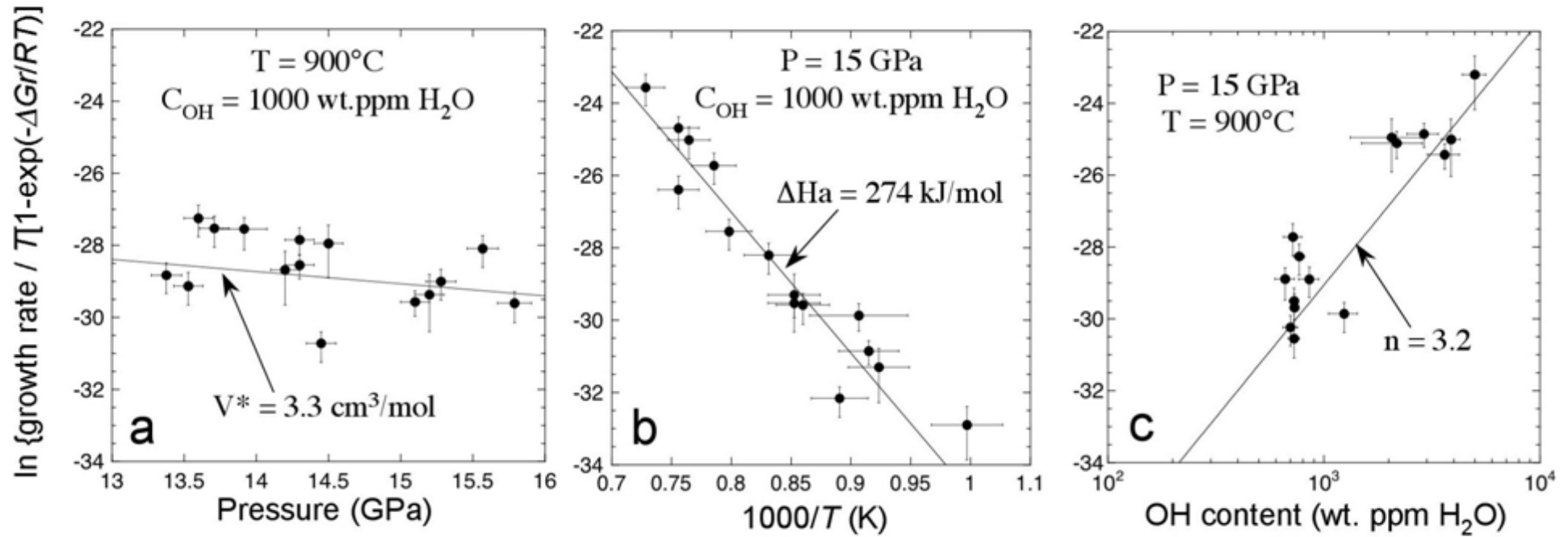
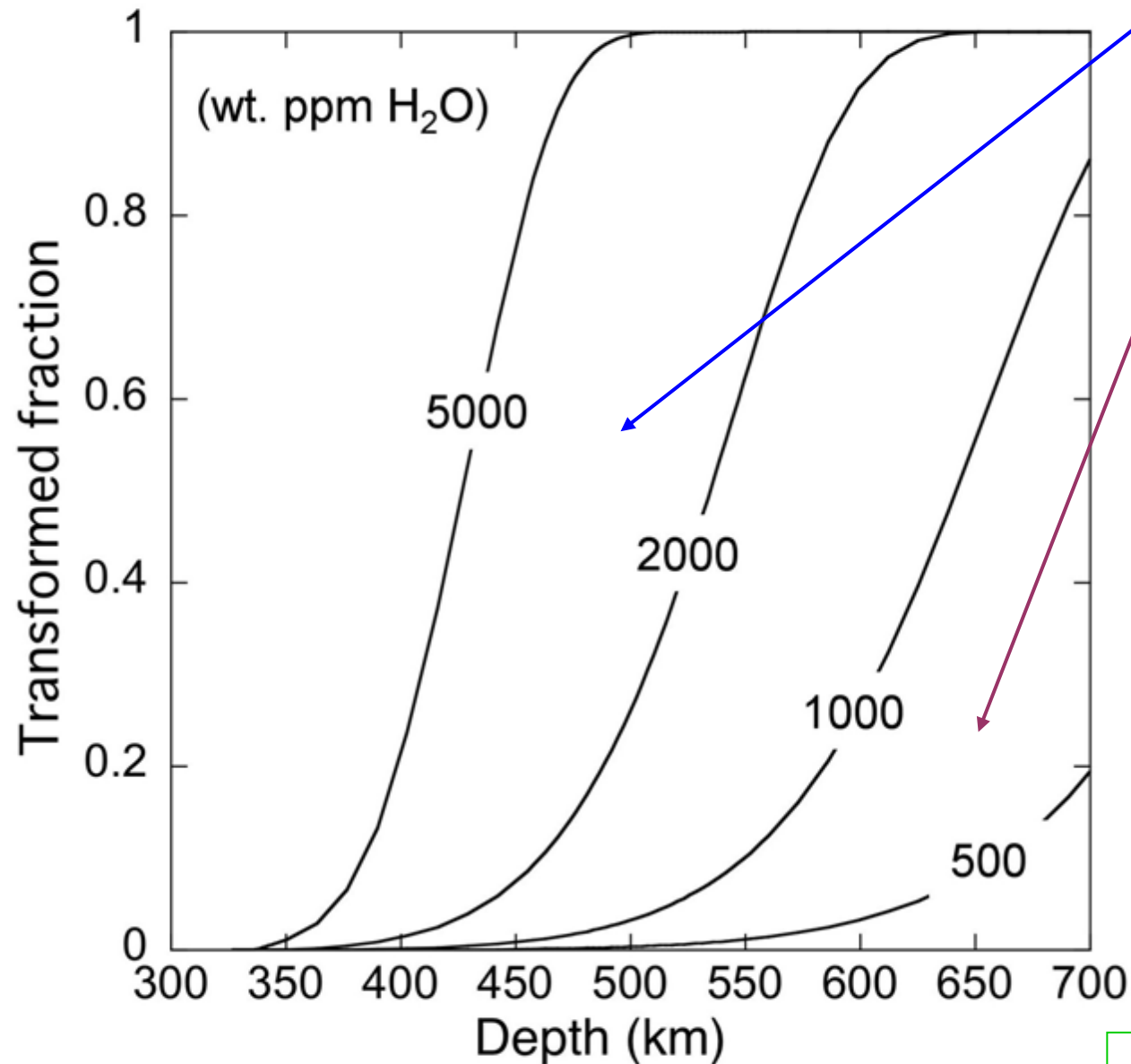


Figure 2. (a) Pressure, (b) temperature, and (c) OH content dependences of the growth rate obtained in the present study and Kubo et al. [2004b]. For plotting purposes, the growth rate data are plotted after corrections to given P , T , and OH content conditions using kinetic parameters determined in this study.

(Figure 2 of Hosoya et al., *GRL*, 2005)

Olivine Metastability



wetter slabs → shallower transformation

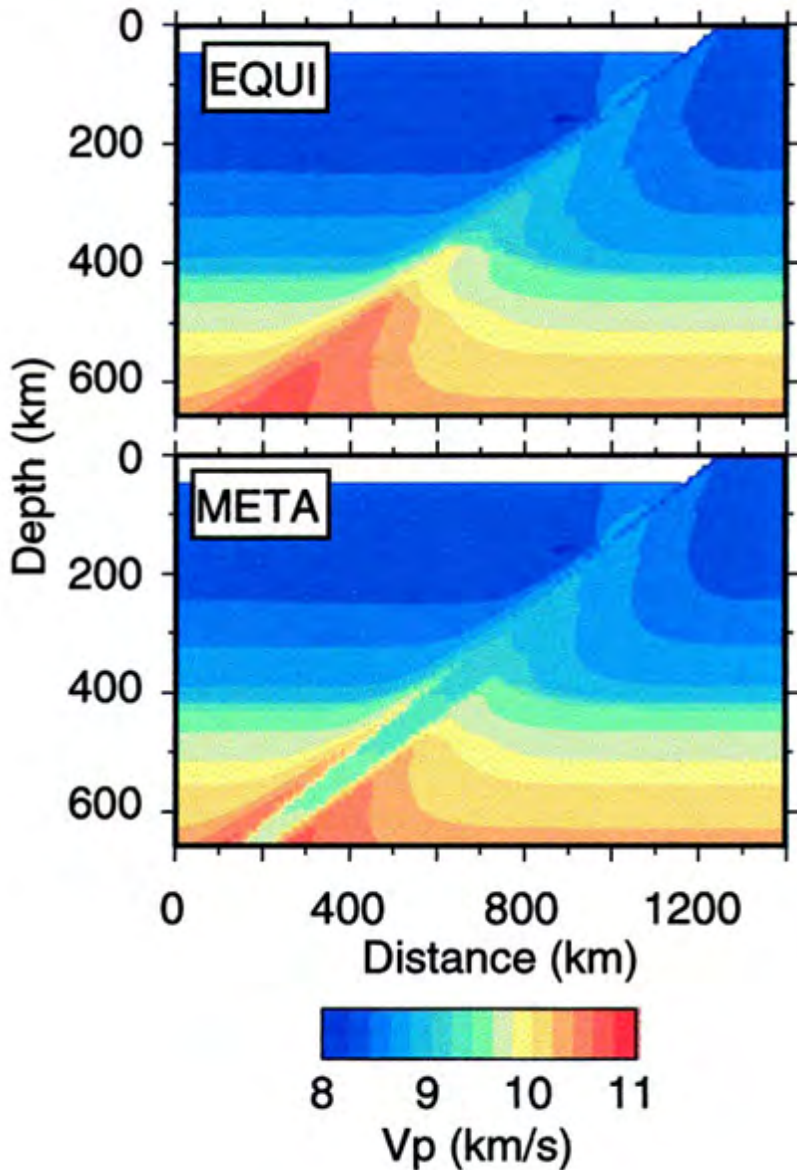
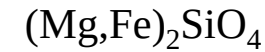
drier slabs → deeper transformation

Figure 3. Depths of the olivine transformation with water contents in the cold slab. The temperature at 660 km of 873 K, the thermal gradient of 0.6 K/km, and the vertical subduction speed of 12 cm/year are used as the pressure-temperature-time path of the cold slab.

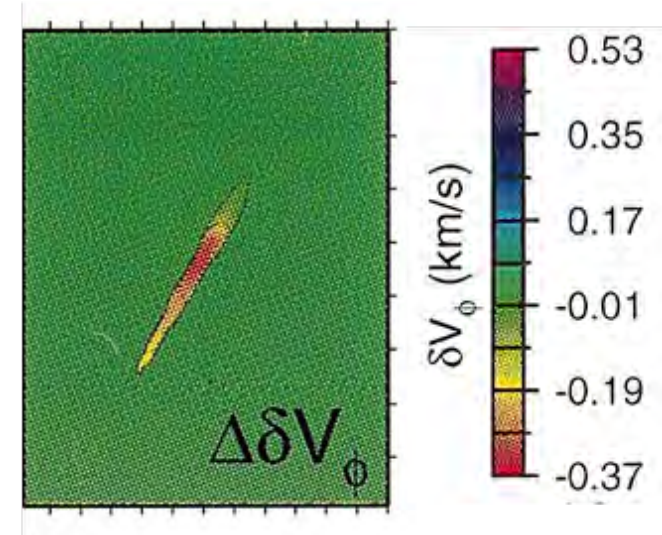
(Figure 3 of Hosoya et al., *GRL*, 2005)

kinetic dependence upon T , P , and X_{H_2O}

Seismic Velocity Signature of Metastable Olivine



(Figure 3 of Vacher et al., 1999)

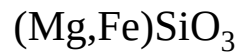


Residual bulk sound velocity anomalies ($\Delta \delta V_\phi$) for case of metastable α -olivine, after subtraction of anomalies for equilibrium case.

(from Plate 1 of Bina, 1997)

Computed P-wave velocities for the equilibrium model (top) and metastable model (bottom).

Metastable Pyroxene



kinetic barrier to $\text{cpx} \rightarrow \text{ilm}$

kinetic barrier to $\text{cpx} \rightarrow \beta + \text{st}$

kinetic barrier to $\alpha \rightarrow \beta$

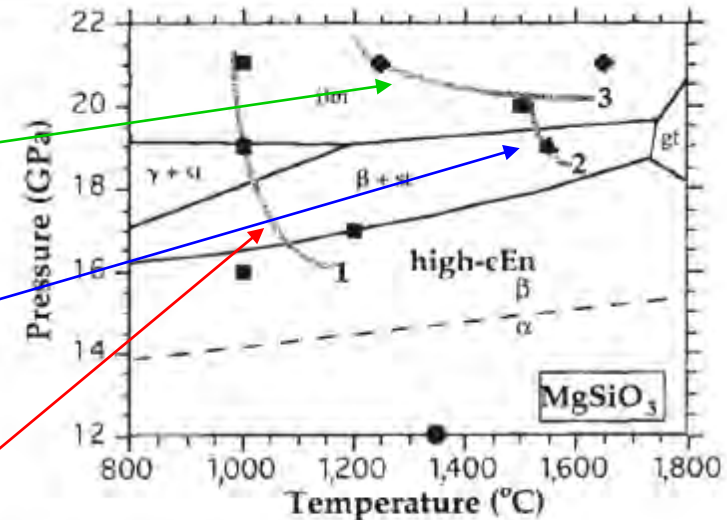
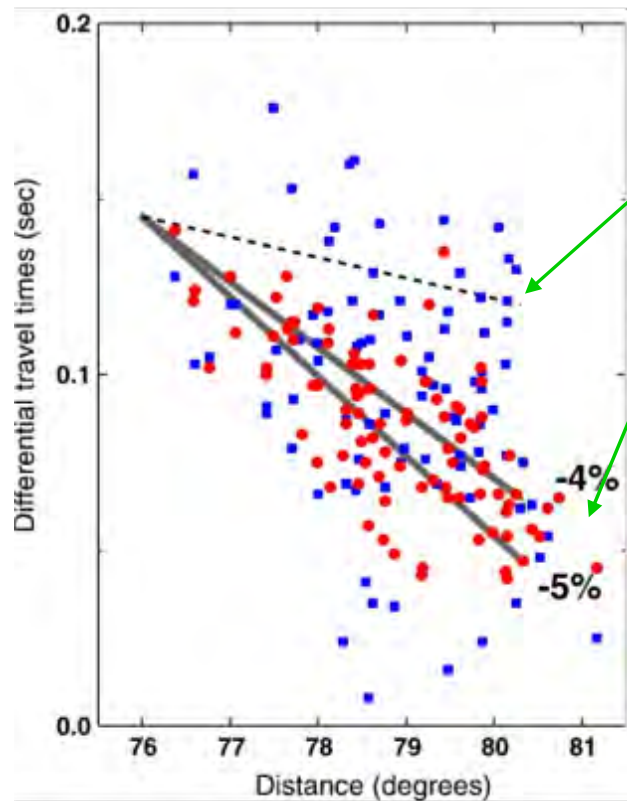


FIG. 1 MgSiO_3 phase diagram (after ref. 34) showing the conditions of the high-pressure experiments. The Mg_2SiO_4 α - β phase boundary is also shown (dashed line). Abbreviations are defined in Table 1. Circle, conditions used for hot pressing the forsterite + enstatite starting material; squares, no transformation of enstatite; triangle, very minor transformation of enstatite to β -phase + stishovite; diamonds, complete transformation of enstatite to ilmenite. The three curved shaded lines are semi-schematic kinetic boundaries showing approximate P - T conditions required for (1) the transformation of forsterite to β - or γ -phase in <1 h, (2) the initiation of the enstatite to β -phase + stishovite transformation after 30 h, and (3) complete transformation of enstatite to ilmenite after ~ 3 h. These curves emphasize semiquantitatively the difference in kinetics of the respective transformations of forsterite and enstatite. Note that on a geological timescale these kinetic boundaries move to considerably lower temperatures—it is estimated, for example, that $\sim 600^\circ\text{C}$ is required for the $(\text{Mg,Fe})_2\text{SiO}_4$ α - γ transformation to occur in subducting slabs¹⁴. Discrepancies between observed phases (Table 1) and this phase diagram may either be the result of uncertainties in the exact locations of the MgSiO_3 phase boundaries (refs 5, 33 and 34) or may result from the nucleation and growth of metastable phases²¹.

(Hogrefe et al., 1994)

Seismological Observations of Metastability



Cold slab material should be seismically fast, but ... observed travel times indicate the presence of some slow material.

Fig. 4. Observed differential travel times of B1 (red) and B2 (blue) relative to A1 for the UW array as a function of epicentral distance. Differential P wave travel times are calculated by subtracting the picked times of the first upswing peaks of P wave for the reference event (A1) from those for B1 and B2 at each station. The differential times are corrected for the difference in the origin times, such that they match at 81° the averaged residual time at western US stations from 82° to 85° in the relocation (~ 0.02 s). Solid lines indicate the synthetic differential travel times of the first P wave upswing picked on the finite-difference seismograms from the low velocity wedge model with 4% and 5% anomalies. Dashed line indicates the prediction due to the differences in distance and focal depth between B1 and A1 based on IASP91.

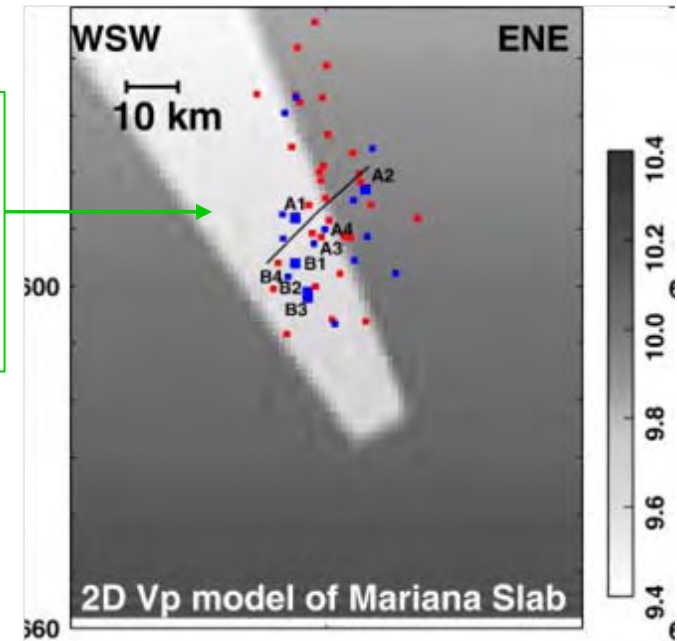
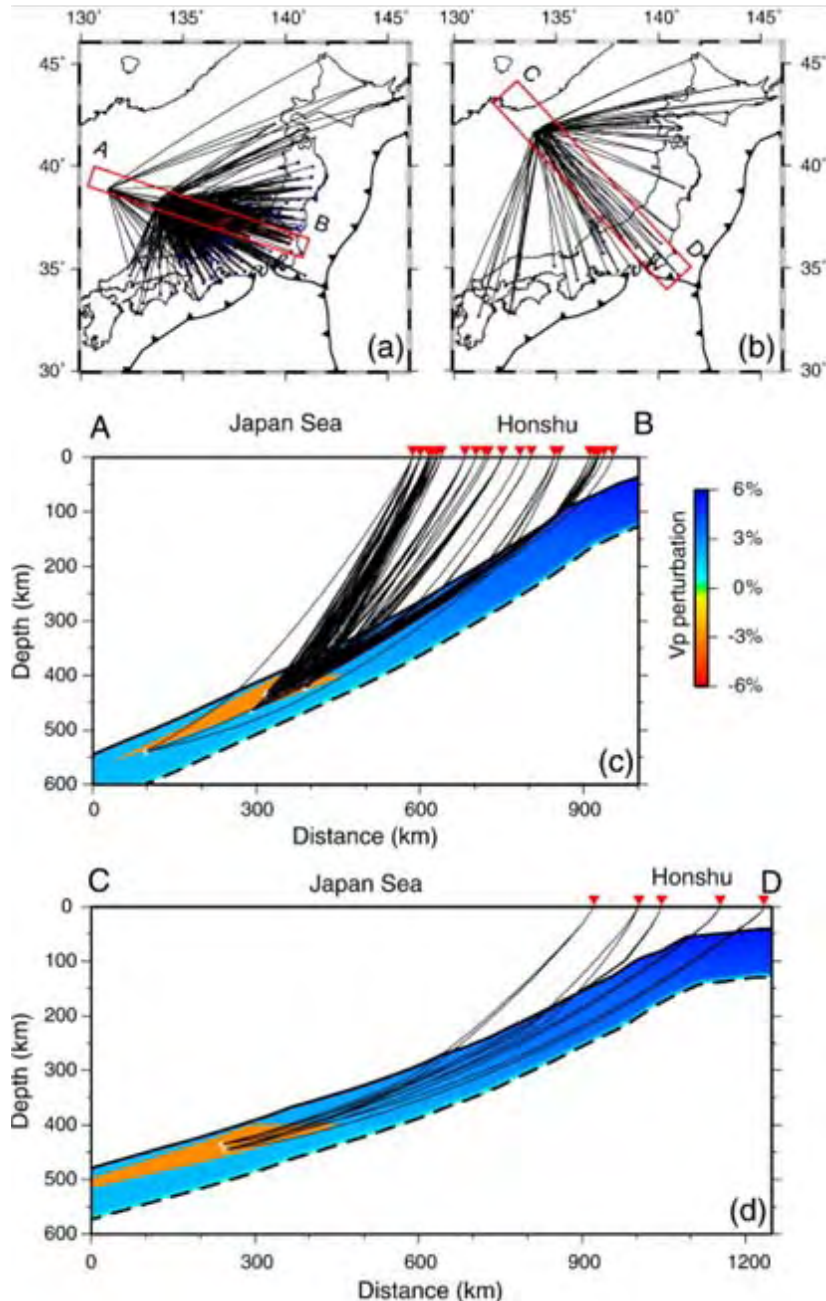


Fig. 5. ENE-WSW vertical cross section of the 2D Vp model for the interior of the Mariana slab (solid box in the inset of Fig. 1b) with the master event hypocenters relative to A1 of the events (blue squares for 1995 aftershocks, red for others). Shown for B1, B2, B3, and A2 are the refined hypocenters by the waveform analyses. The location of the wedge also is determined relative to A1. Vp (in km/s) is shown with a grey scale. Vs has the same fractional anomaly as Vp. Thick solid line indicates the projection of the rupture fault of the large event at 7:6:3, Aug. 23, 1995 [30], which initiated from outside the wedge near A2. The boundaries of the low velocity wedge shallower than about 580 km are not constrained by the data, but represent nothing but simple continuations of the deeper structure.

(Figures 4 and 5 of Kaneshima et al., *EPSL*, 2007)

Seismological Observations of Metastability

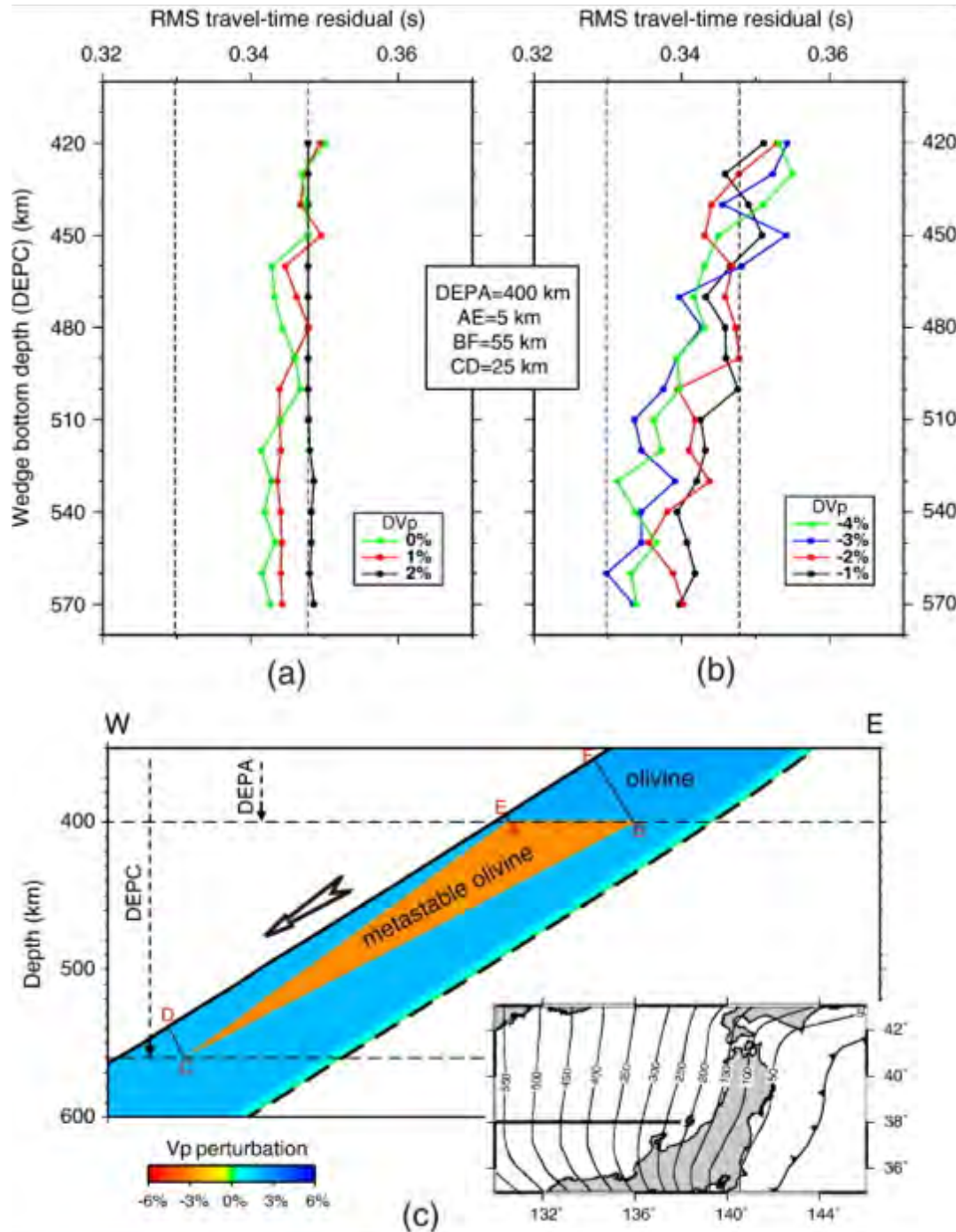


Are seismic waves propagating from earthquakes in the slab delayed by passage through slow material?

Fig. 3. Examples of seismic ray-tracing. (a, b) The plane views of ray paths from the earthquakes to seismic stations. (c, d) The cross-sectional views of ray paths within the red boxes in (a) and (b), respectively. The white dots and red triangles denote the hypocenters and seismic stations, respectively. The thick black line and dashed line indicate the upper and lower boundaries of the subducting Pacific slab, respectively. The P-wave velocity perturbations relative to the JB-model are shown by the color scale beside (c).

(Figure 3 of Jiang et al., *EPSL*, 2008)

Seismological Observations of Metastability

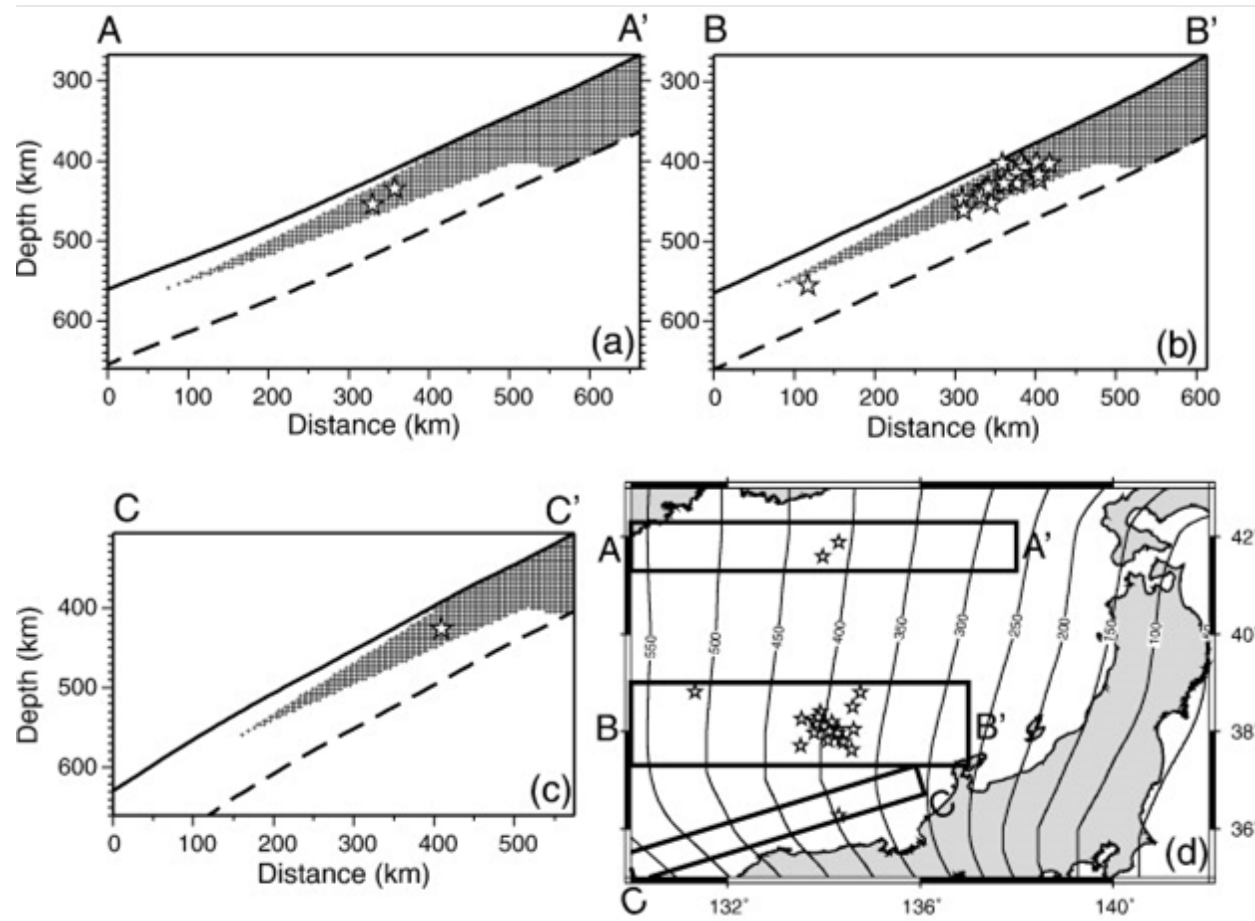


Use observed delays to constrain the spatial extent of any slow material.

Fig. 4. (a) Changes in the RMS travel-time residual with DEPC (bottom depth of the metastable olivine wedge in the Pacific slab). The black, red and green curved lines represent the corresponding RMS values obtained for the velocity anomaly of the olivine wedge as 0%, 1% and 2% (relative to the JB model), respectively. Other parameters used (depicted in Fig. 4c) are indicated in the insert box. (b) The same as (a), but the velocity anomalies of the olivine wedge are -1%, -2%, -3%, and -4%, respectively. The two vertical dashed lines denote RMS values of 0.329 s and 0.347 s, for references. (c) The cross-sectional view of the slab model with a metastable olivine wedge (see the insert map for the location of the cross-section). DEPA and DEPC represent the depths of top (AB) and bottom (C) of the metastable olivine wedge. AE, BF and CD indicate the distances of the three corners of the olivine wedge away from the upper boundary of Pacific slab, respectively. The blue area above 400 km depth and orange area represent the olivine and metastable olivine minerals, respectively. The hollow arrow shows the subduction direction of the Pacific slab. The thick solid and dashed lines denote the upper and lower boundaries of the Pacific slab, respectively.

(Figure 4 of Jiang et al., *EPSL*, 2008)

Seismological Observations of Metastability

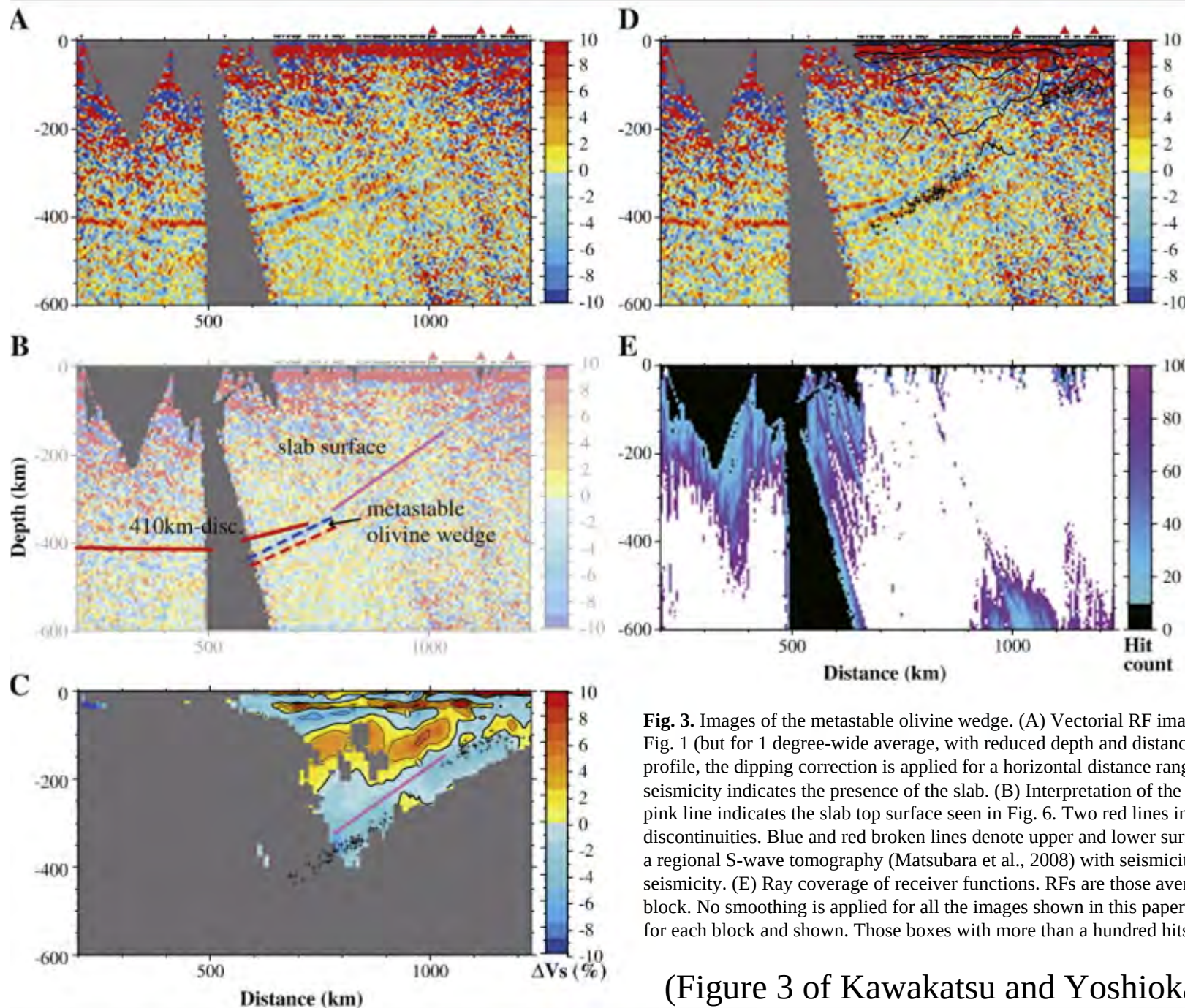


Wedges of slow material
are present along various
cross-sections.

Fig. 5. (a–c) Vertical cross-sectional views of relocated hypocenters (star symbols) along lines AA', BB' and CC', respectively. The hatched areas denote olivine and metastable olivine wedge. (d) Locations of the profiles in (a–c). Star symbols denote the epicenters of the 23 deep earthquakes used. Curved lines show the depth contours of the upper boundary of the subducting Pacific slab.

(Figure 5 of Jiang et al., *EPSL*, 2008)

Seismological Observations of Metastability



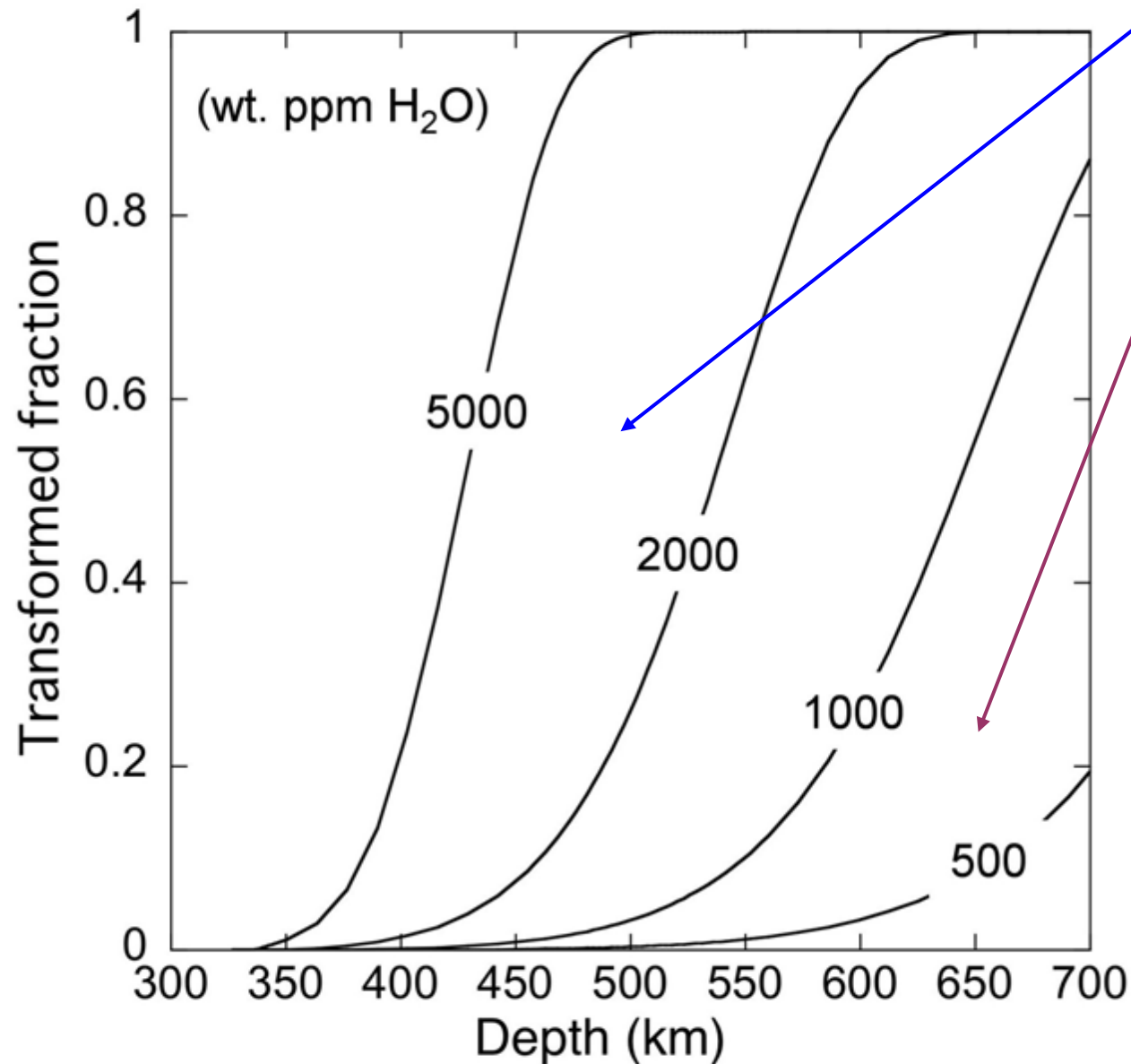
wedge imaged
at ~330-450 km

Fig. 3. Images of the metastable olivine wedge. (A) Vectorial RF image along the same profile with Fig. 1 (but for 1 degree-wide average, with reduced depth and distance ranges). In this particular profile, the dipping correction is applied for a horizontal distance range exceeding ~ 500 km where the seismicity indicates the presence of the slab. (B) Interpretation of the image is overlaid on top. The pink line indicates the slab top surface seen in Fig. 6. Two red lines indicate flat and elevated 410 km discontinuities. Blue and red broken lines denote upper and lower surfaces of the MOW. (C) Image of a regional S-wave tomography (Matsubara et al., 2008) with seismicity. (D) Same as (A) with seismicity. (E) Ray coverage of receiver functions. RFs are those averaged for every 5 km-square block. No smoothing is applied for all the images shown in this paper. The number of rays are counted for each block and shown. Those boxes with more than a hundred hits are shown by white.

(Figure 3 of Kawakatsu and Yoshioka, *EPSL*, 2011)

(C.Bina, 9/2011)

Olivine Metastability



wetter slabs → shallower transformation

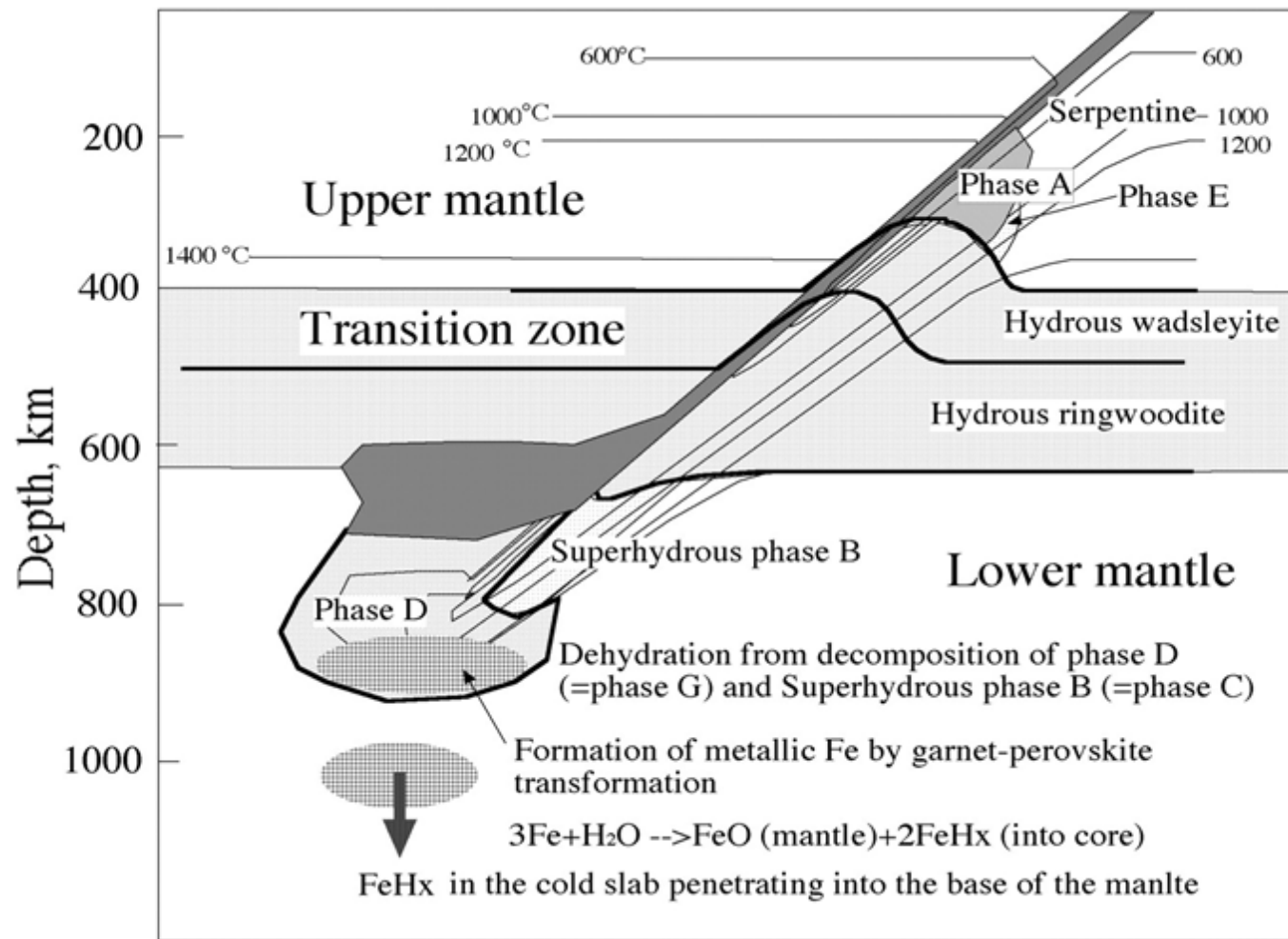
drier slabs → deeper transformation

Figure 3. Depths of the olivine transformation with water contents in the cold slab. The temperature at 660 km of 873 K, the thermal gradient of 0.6 K/km, and the vertical subduction speed of 12 cm/year are used as the pressure-temperature-time path of the cold slab.

Does the presence of metastable material indicate dry material?

(Figure 3 of Hosoya et al., *GRL*, 2005)

Seismological Observations of Metastability: Implications?



The “dry slab” view (Green et al., 2010) conflicts with the “wet slab” view (e.g., Ohtani, 2005).

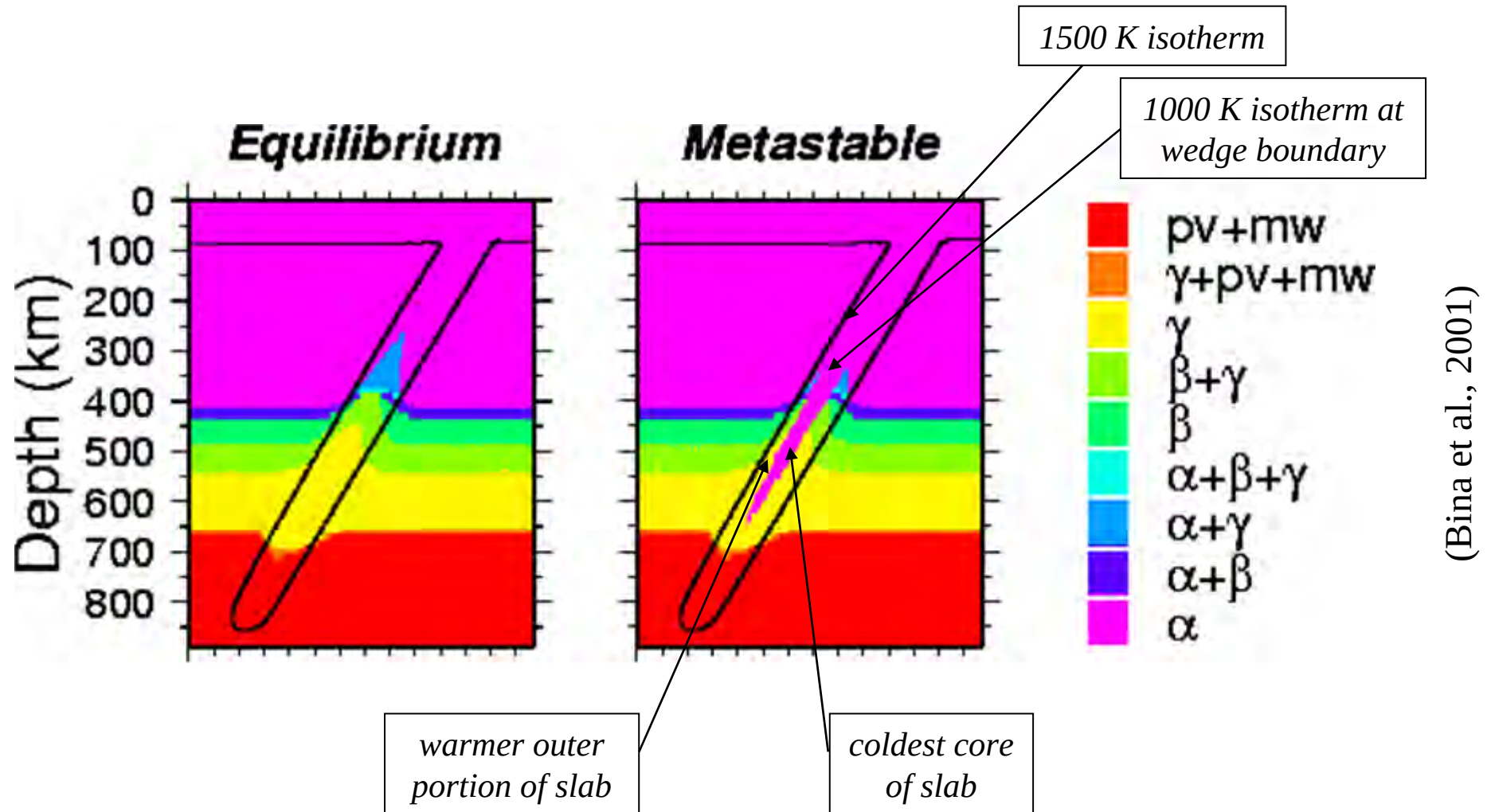
Can these two end-member models of water transport in the mantle be reconciled?

FIGURE 5. The process in the slabs subducting into the lower mantle. Water can be generated by dehydration from decomposition of superhydrous phase B and phase D. Metallic iron can be generated associated with the garnet-perovskite transformation (Miyajima et al. 1999; Frost et al. 2004). Metallic iron and water react to form iron oxide and iron hydride in the lower mantle. The model provides a possible mechanism of hydrogen transport into the base of lower mantle.

(Figure 5 of Ohtani, *Elements*, 2005)

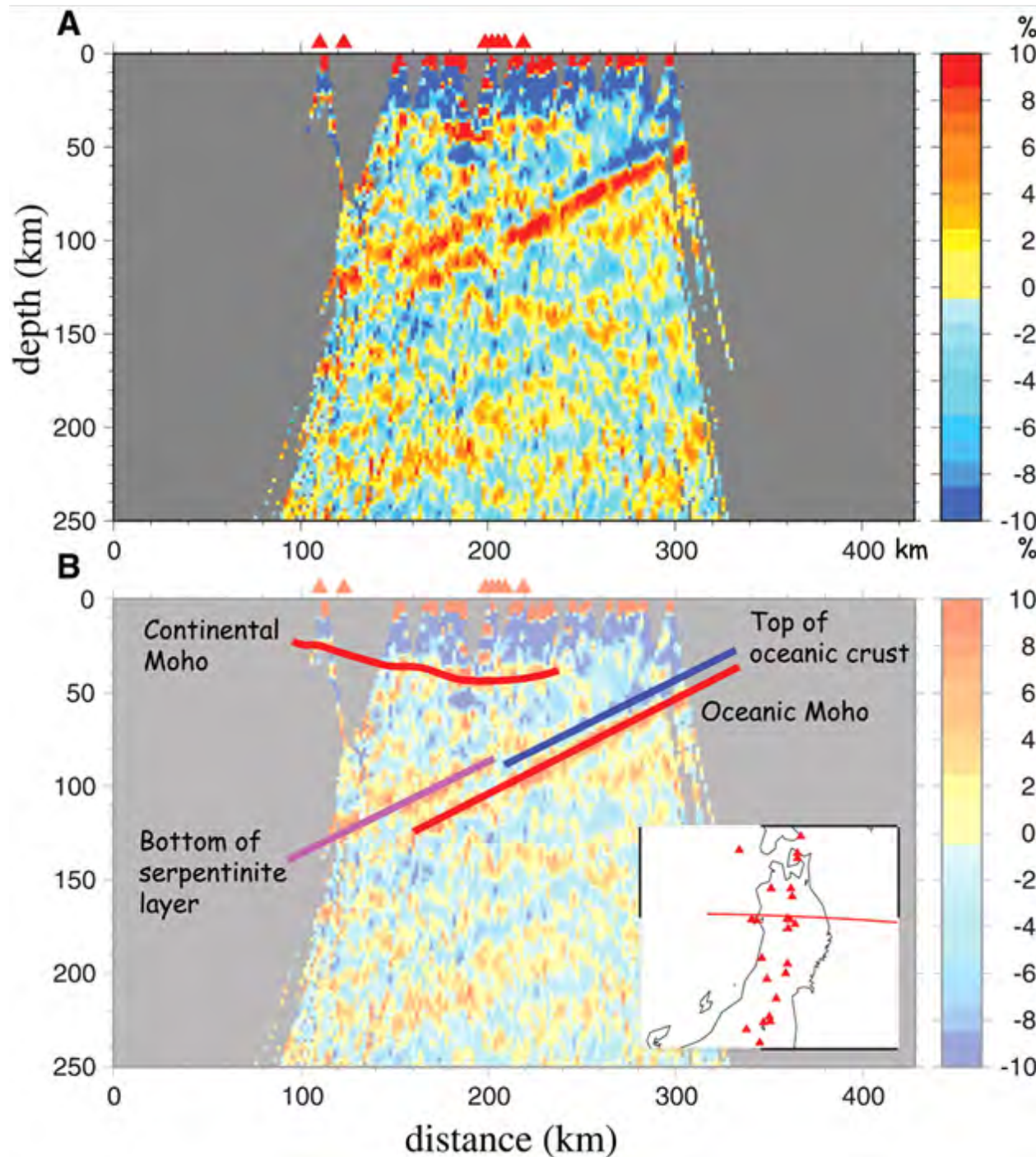
(C.Bina, 9/2011)

Seismological Observations of Metastability: Implications?



Even if a lack of water is required to sustain metastability, this only applies to the coldest core of the slab. Water may still be transported in the warmer outer portions of the slab, which are more likely to have been hydrothermally hydrated anyway.

Seismological Observations of Metastability: Implications?

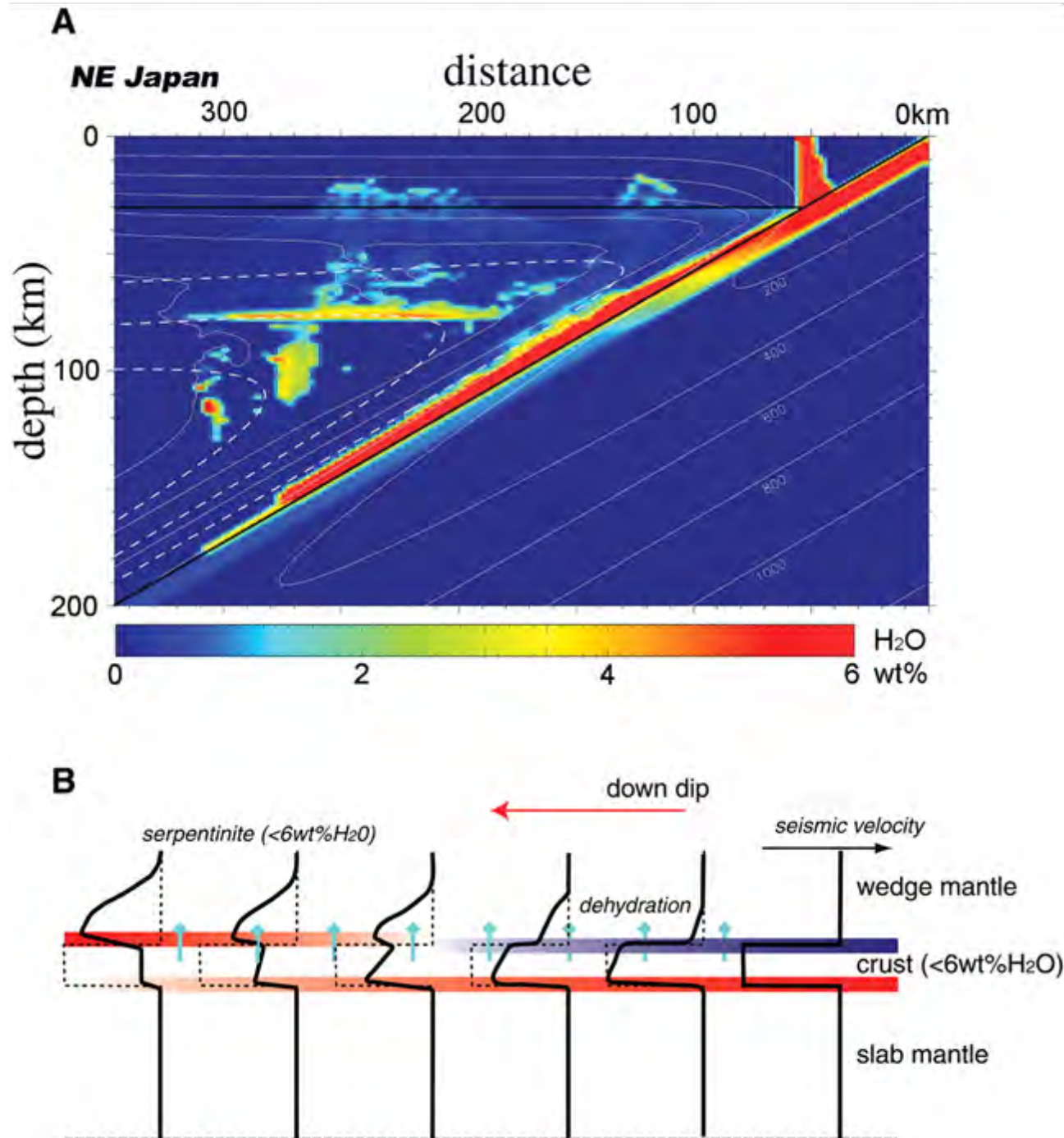


*imaging of deep water transport:
dehydration of upper slab surface*

Fig. 1. The reflectivity profile beneath northeast Japan. **(A)** Reflectivities given by RFs are measures of local S-wave velocity jumps, because a P-to-S seismic wave conversion is sensitive to the S-wave velocity change. Red and blue colors correspond to velocity increase and decrease with depth, respectively. The color scale is given in terms of an equivalent S-wave velocity change (in percent) at a first-order discontinuity. **(B)** Interpretation of the image is overlaid on top of the reflectivity profile in (A). The continental Moho is not imaged well because of the frequency range used for the analysis. (Inset) A map of northeast Japan. The red line delineates where the 100-km-wide cross section is made. Red triangles indicate volcanoes active in the past 10,000 years (Smithsonian Institution, Global Volcanism Program) and are also plotted on the top of the cross sections.

(Figure 1 of Kawakatsu and Watada, *Science*, 2007)

Seismological Observations of Metastability: Implications?



*imaging of deep water transport:
hydration of mantle wedge base*

Fig. 3. Interpretation of the reflectivity profile in terms of the water transportation in the mantle wedge. **(A)** A numerical simulation of the water transportation beneath northeast Japan (4). Bright colors indicate a high concentration of water. The water in the hydrated oceanic crust [shallow (<50 km) dipping red layer] is expelled to serpentinize the mantle wedge, which is dragged downward on top of the subducting plate to form a serpentinite layer (deeper dipping red layer). **(B)** A schematic model for the effect of crustal dehydration on the seismic velocity near the top of the subducting plate. Seismic-velocity profiles (black lines) perpendicular to the slab surface are given at different down-dip distances. Red and blue colors show the expected reflectivities in a manner similar to that for the reflectivity profile (Fig. 1). Light blue arrows indicate the dehydration process. The slab surface is rotated to become horizontal.

(Figure 3 of Kawakatsu and Watada, *Science*, 2007)

Seismological Observations of Metastability: Implications?

imaging of deep water transport

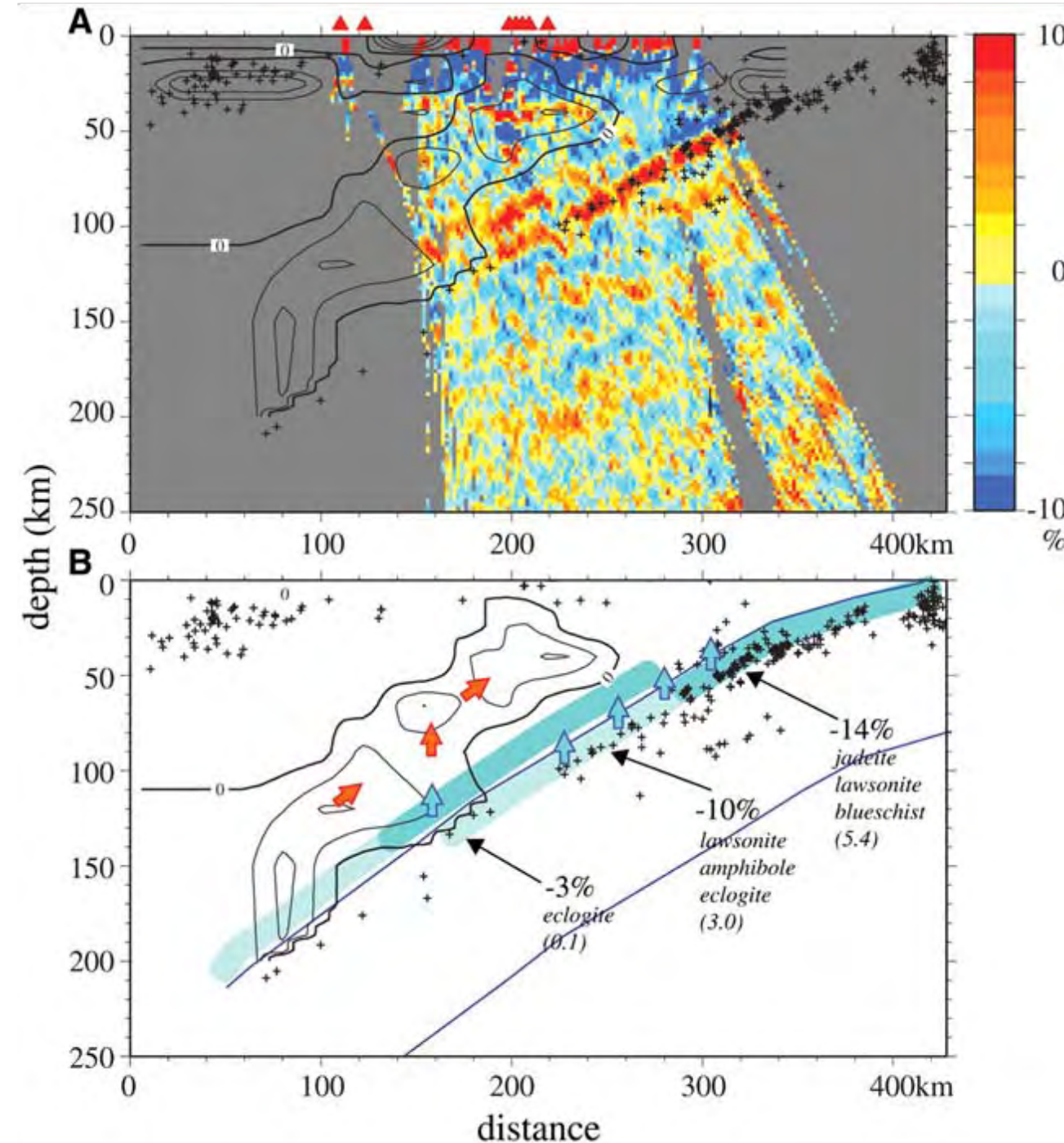


Fig. 4. Integrated seismic images beneath the Tohoku subduction zone and a schematic model for the water transportation. **(A)** The dip-corrected reflectivity image of Fig. 1A is compared with the tomographic image (7) and the seismicity (magnitude larger than 3) reported by the Japan Meteorological Agency. The S-wave tomographic image above the subducting slab is given by contours with 3% velocity-change intervals. The thick solid contours give the average velocity. Thin contours in the mantle wedge correspond to the low-velocity regions. Plus signs indicate earthquakes. Red triangles are the same as in Fig. 1. **(B)** The pathway of water transportation postulated by Iwamori [(4); see also (30)] is schematically illustrated by light blue and red colors for nonmagmatic and magmatic paths, respectively. Negative percentages give the S-wave velocities of fully hydrated oceanic crust relative to those of the slab-mantle estimated by Hacker and Abers (29) (also given are the names of the stable crustal rock facies, and wt % H₂O in parentheses). The plate boundaries of the subducting slab are shown schematically as blue lines. Earthquakes and contours of the low-velocity region in the mantle wedge of Fig. 4A are also shown.

(Figure 4 of Kawakatsu and Watada, *Science*, 2007) (C.Bina, 9/2011)

Metastability: Disequilibrium Latent Heat Release

Adiabatic temperature change across a phase boundary:

$$\Delta T \approx -\Delta H / C_p = - (T\Delta S + \Delta G) / C_p$$

$$\Delta S \geq \int (\delta q / T)$$

Equilibrium: $0 = \Delta G = \Delta H - T\Delta S$

$$\Delta S_{rev} = \int (\delta q / T)$$

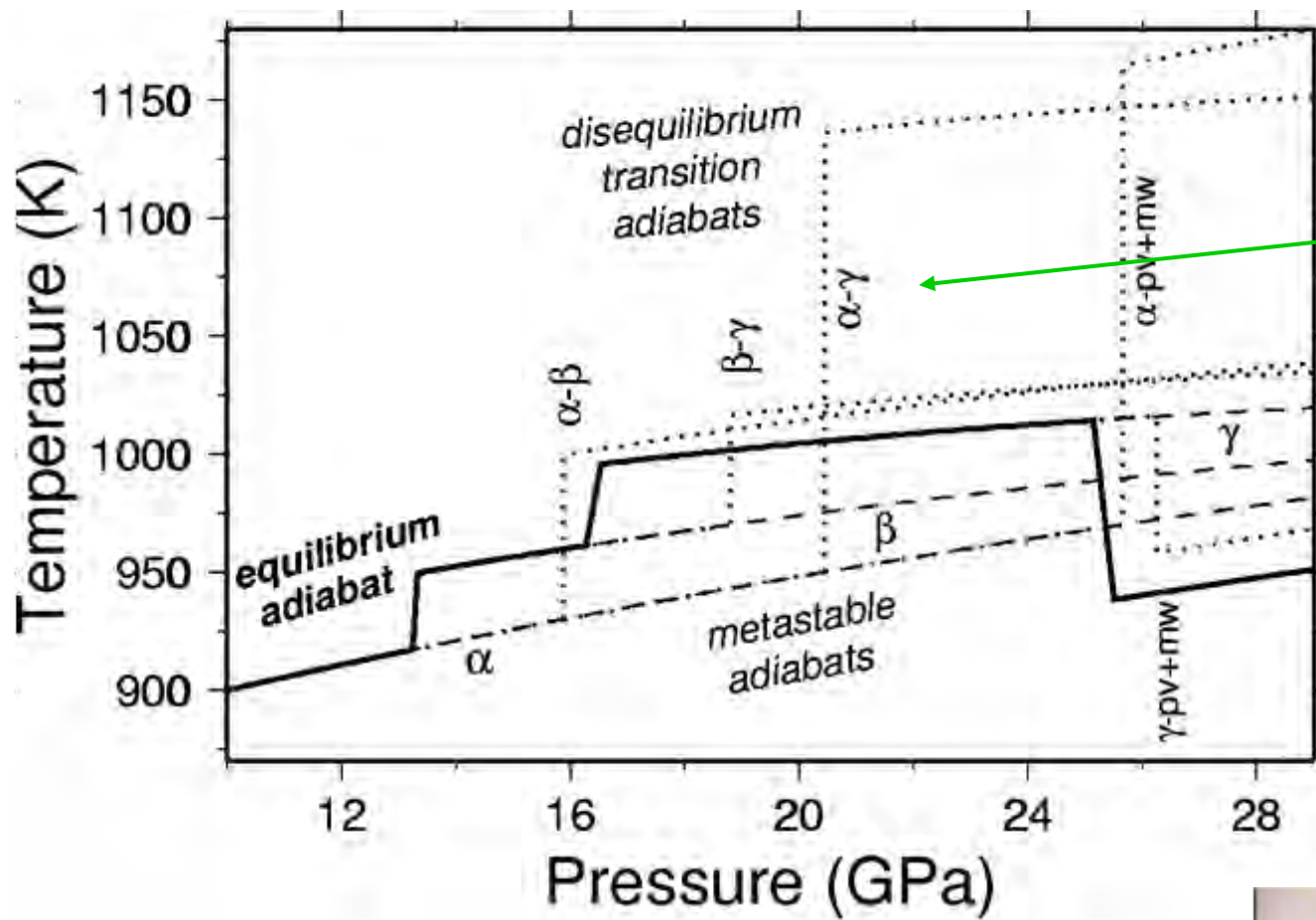
adiabat ($\delta q = 0$) $\leftrightarrow$ isentrope ($\Delta S = 0$)

Disequilibrium: $0 > \Delta G = \Delta H - T\Delta S$

$$\Delta S_{irrev} > \int (\delta q / T)$$

adiabat ($\delta q = 0$) $\neq$ isentrope ($\Delta S = 0$)

$$\Delta T_{diseq} > \Delta T_{eq}$$



superheating
(possible trigger for seismicity?)

[Bina (1998)]

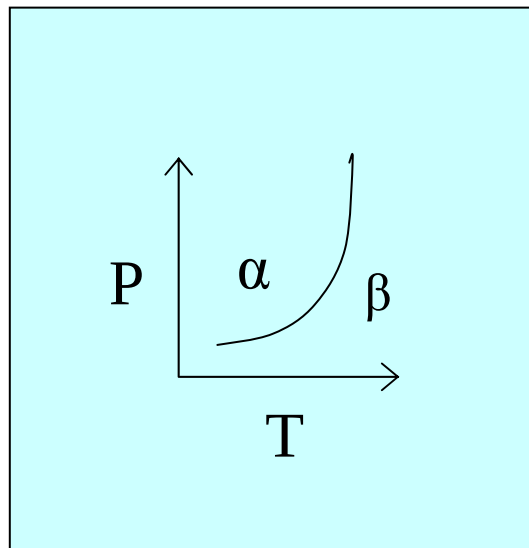
Instant Handwarmer:
(supersaturated sodium acetate solution)
[photo by Univ. of Maryland Physics Dept.]



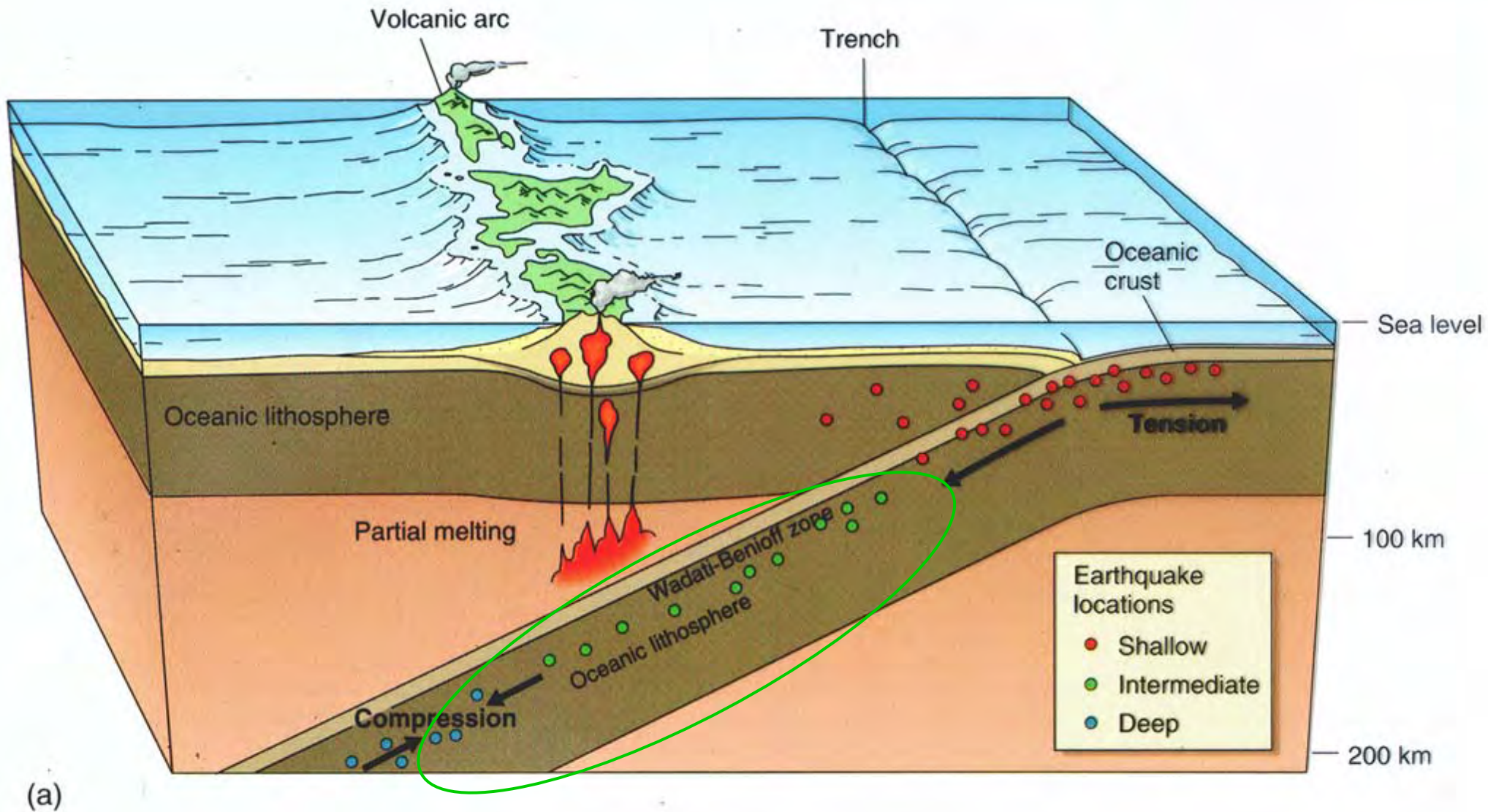
Dehydration: Seismogenesis and Magmagenesis

Dehydration: promotes faulting and intermediate-depth *seismicity* (because of positive volume change?).

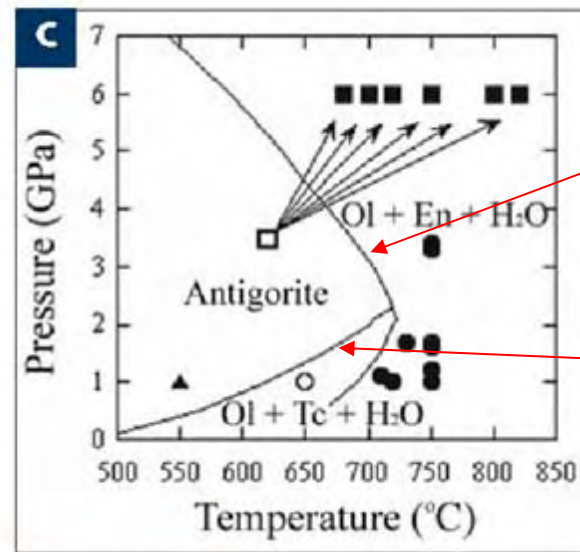
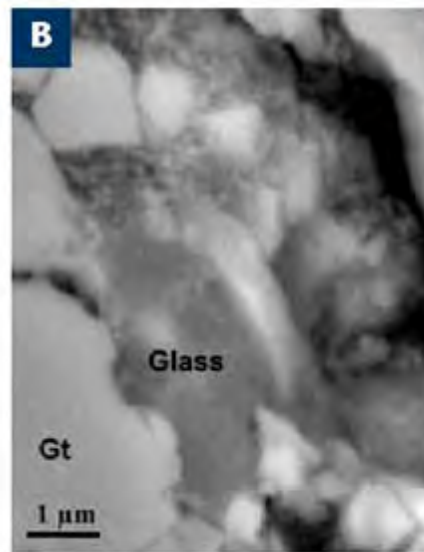
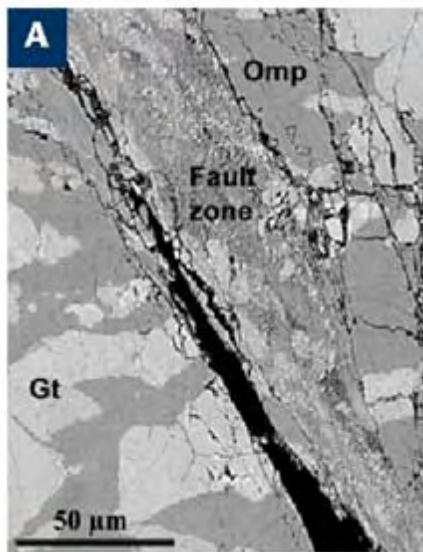
Dehydration: promotes melting and convergent-margin *magmatism* (because of melting point depression?).



SUBDUCTION ZONE SEISMICITY



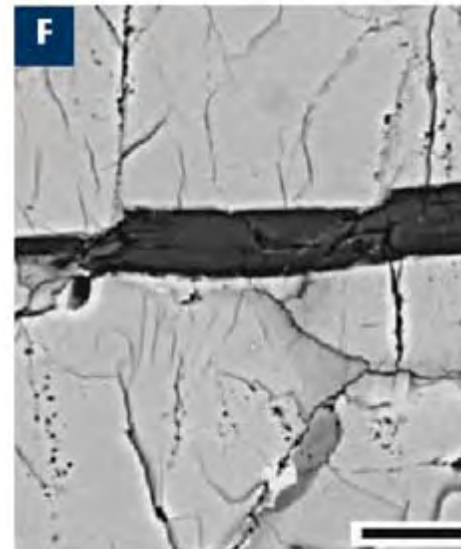
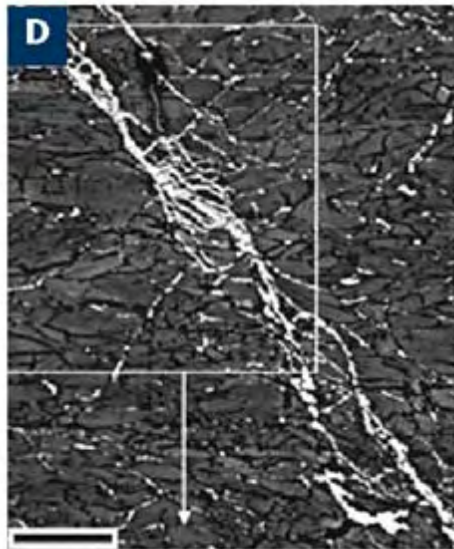
(Figure 9-4a from Davidson, Reed, and Davis [1997])



$\Delta V < 0$

$\Delta V > 0$

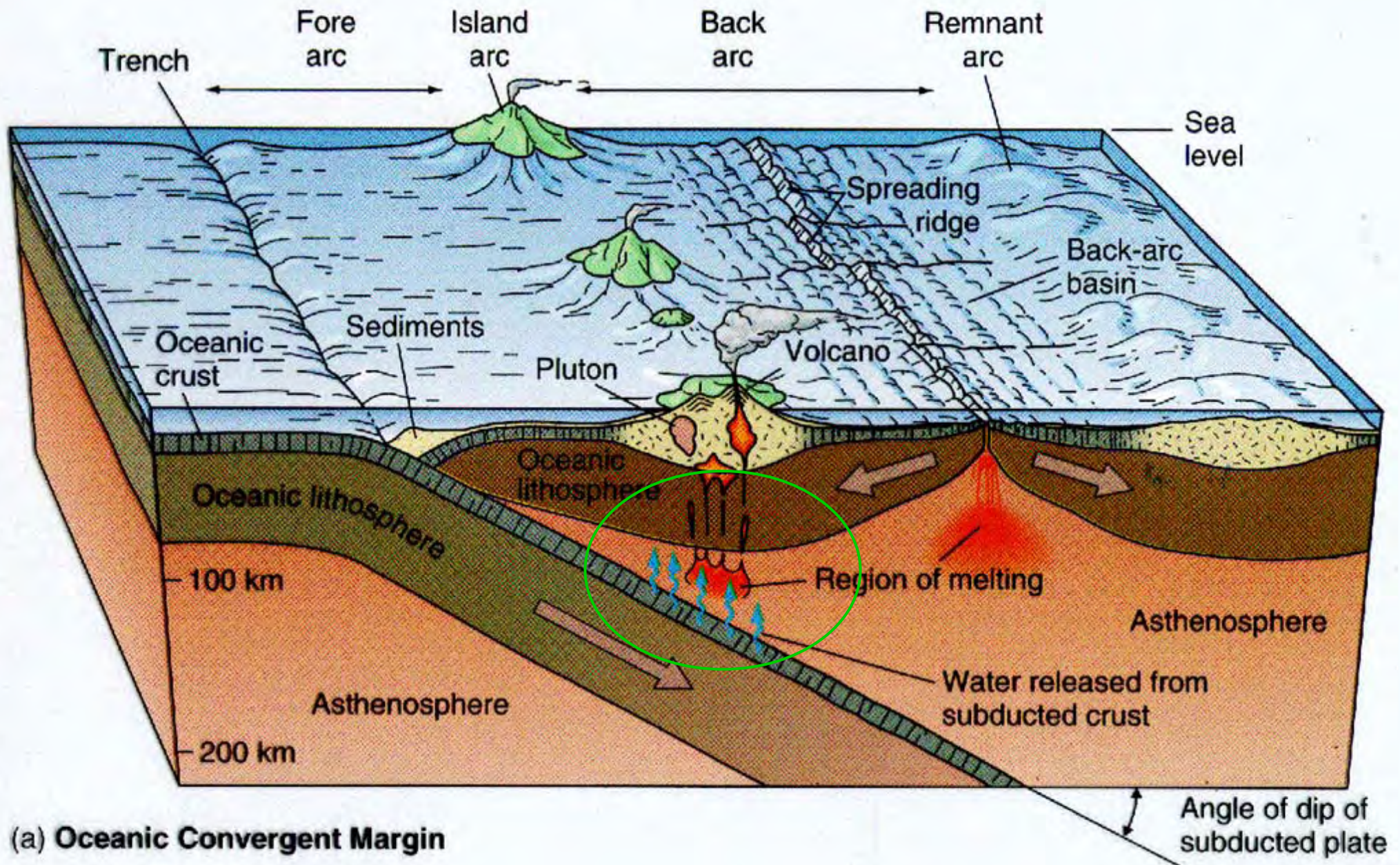
*faulting by
“dehydration
embrittlement”*



(Figure 1 of Green and Jung, 2005)

Dehydration Faulting. Back-scattered electron images of a fault zone in eclogite **A.** and detail of fault gouge **B.** Gt = garnet; Omp = omphacite (modified after Zhang et al. 2004). **C.** Phase relations for antigorite (Ulmer and Trommsdorff 1995) and experimental conditions after Jung et al. 2004. Ol = olivine; En = enstatite; Tc = talc. Open symbols represent conditions where specimens were annealed but not deformed; circles are conditions of experiments conducted in a modified Griggs apparatus; squares denote final conditions of experiments pressurized along arrow paths in a multi-anvil device; triangle represents specimen stressed to the breaking point without dehydration. **D.** Scanning electron micrograph in back-scatter mode showing a fault system generated at 6 GPa. Dark phase is antigorite; bright material is solid reaction products. **E.** Sketch clarifying features in **D.** **F.** Optical micrograph of relict olivine (white) and a single antigorite crystal (black) accompanied by numerous microcracks and fluid inclusion arrays aligned parallel to α_1 . Scale bars of D to F = 20 μm.

SUBDUCTION ZONE VOLCANISM



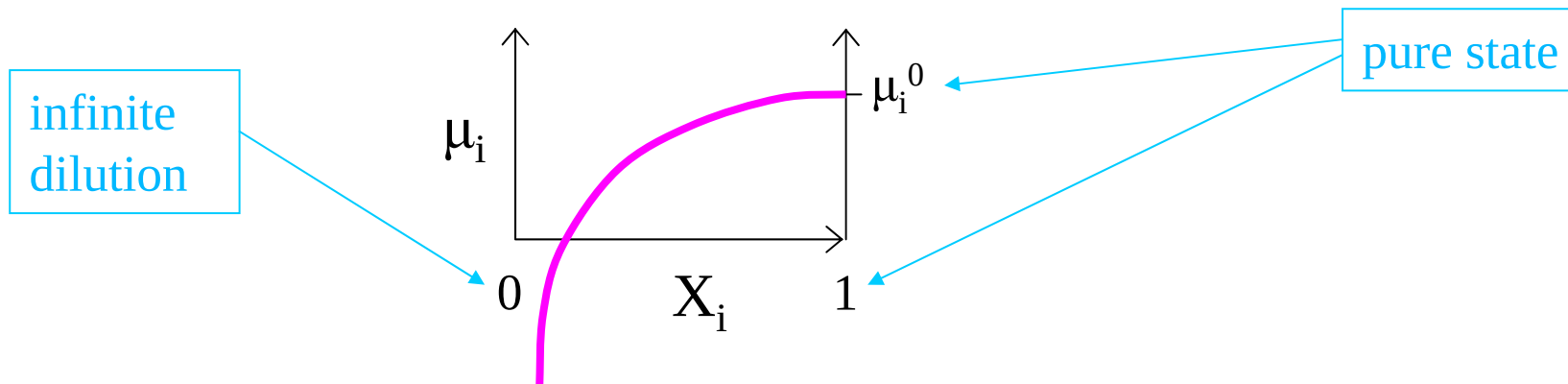
(Figure 9.1a from Davidson, Reed, and Davis [1997])

Melting-Point Depression

Compositional (Concentration) Dependence of $\mu_i(P,T,X)$:

$$\mu_i = \mu_i^0 + nRT \ln a_i$$

$$a_i \leq 1 \rightarrow RT \ln a_i \leq 0$$



Dilute solutions have lower chemical potentials (lower free energies) than pure end-members.

Complex solutions have expanded stability fields.

$$(\partial\mu_i^0/\partial T)_P \sim -S_i^0$$

$$(\partial\mu_i/\partial T)_P \sim -S_i^0 + nR \ln a_i$$

entropy of mixing

Melting-Point Depression

For an ideal solution: $\mu_i^{solid} = \mu_i^{solution} = \mu_i^0 + RT \ln X_i$

$$d/dT [\ln X_i] = d/dT [(\mu_i^{solid} - \mu_i^0)/(RT)]$$

$$= [T(-s_i^{solid} + s_i^0) - (\mu_i^{solid} - \mu_i^0)]/(RT^2)$$

$$= [(\mu_i^0 + Ts_i^0) - (\mu_i^{solid} + Ts_i^{solid})]/(RT^2)$$

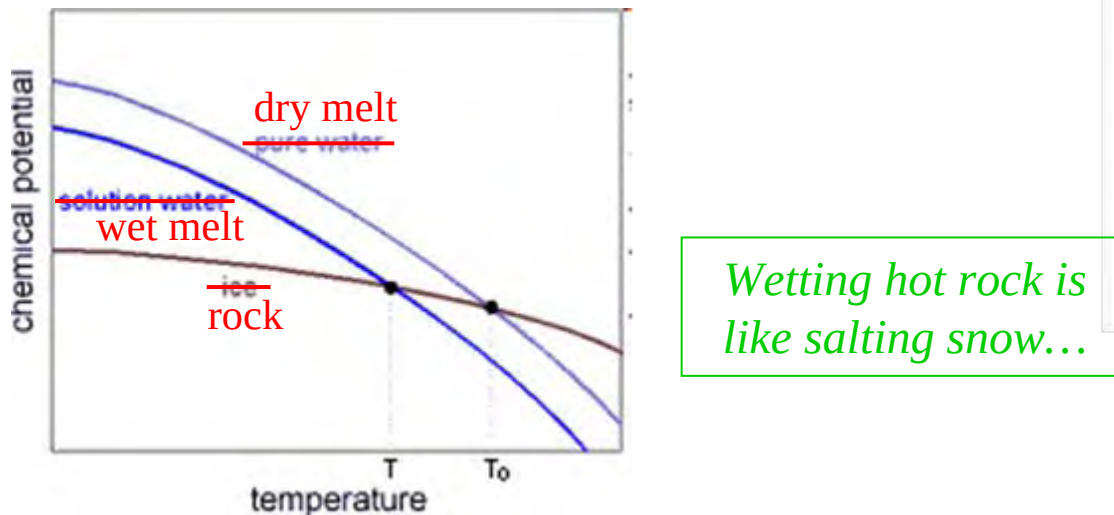
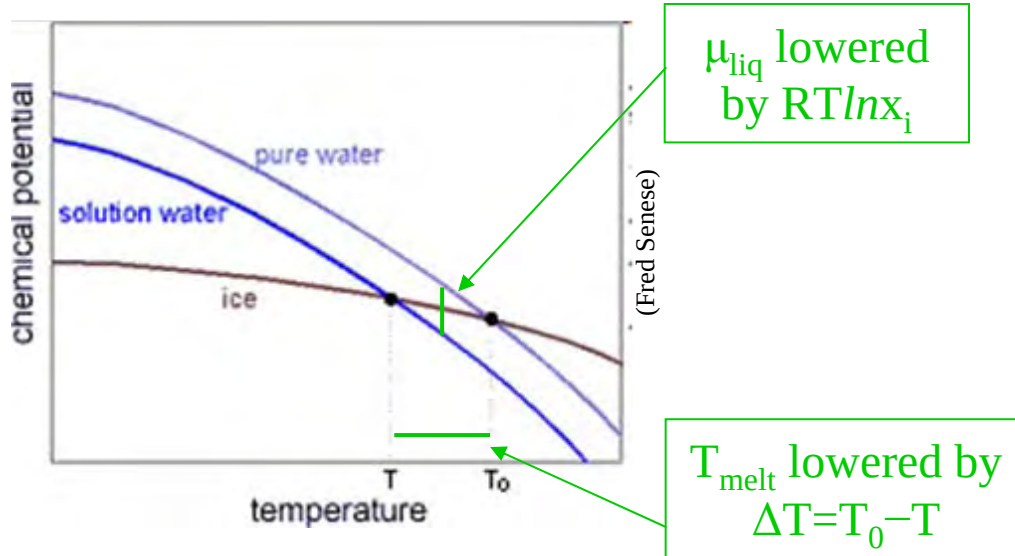
$$= (h_i^0 - h_i^{solid})/(RT^2)$$

$$\begin{aligned} (\partial G / \partial N_i)_{P,T,X_{j \neq i}} &= \mu_i \\ G &= H - TS \\ \mu_i &= h_i - Ts_i \end{aligned}$$

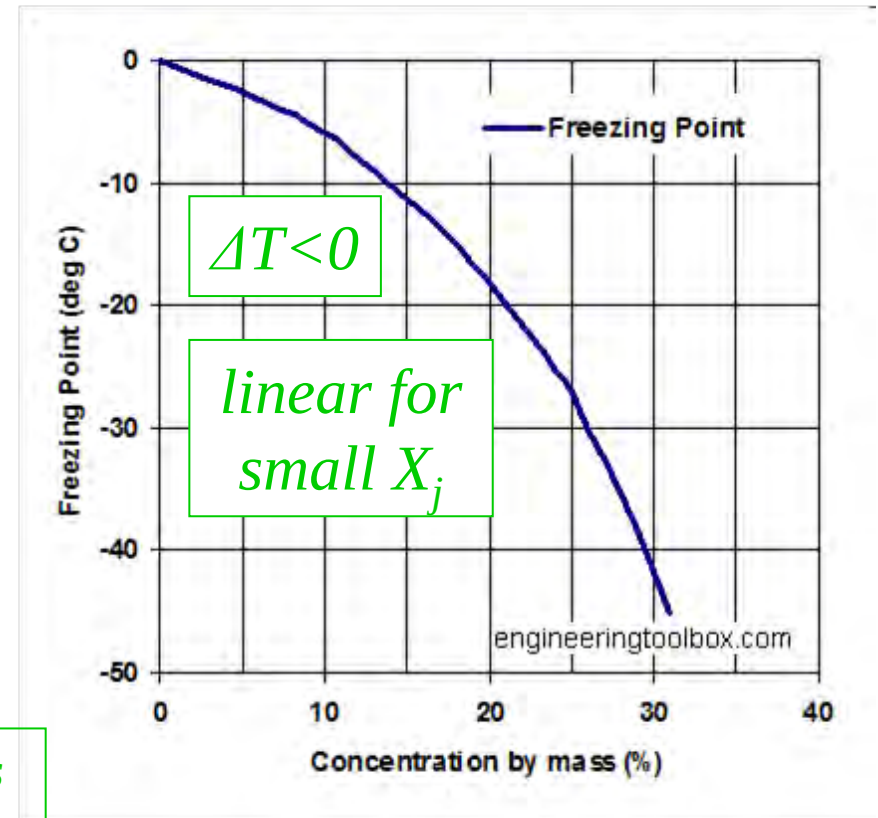
$$\Delta T \approx X_j \cdot RT^2 / (h_i^{solid} - h_i^0) \quad \{ \text{for } X_j \ll 1 \}$$

<0

Melting-Point Depression



calcium chloride - water coolant



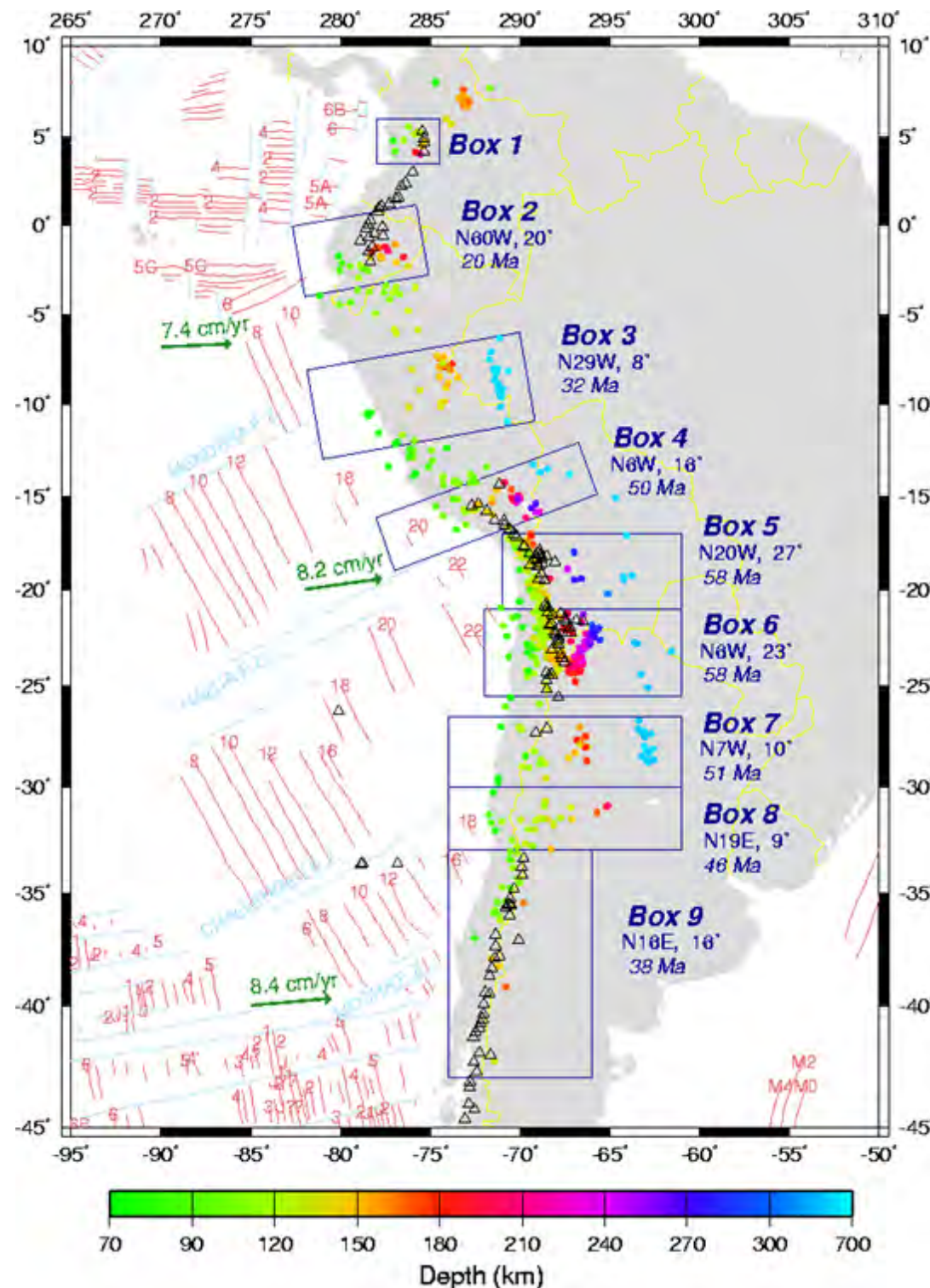
(Figure 1 from Chen, Bina, and Okal [2001])

Study Area

Partition of the study area into regional boxes. Dots, color-keyed for depth, show intermediate and deep earthquakes from the Harvard CMT catalogue. Open triangles indicate volcanoes active in the past 10,000 years. Note that both seismicity and volcanism exhibit along-strike variations. Labels for each box show slab strike and dip angles determined from this study and, in italics, the age of the oceanic lithosphere at the trench as inferred from magnetic anomalies, themselves shown as red lines on the ocean floor [Cande et al., 1989]. Green arrows indicate the motion of the Nazca plate relative to South America [DeMets et al., 1990].

Note variation across study area in seismicity, volcanism, and dip angle of subduction.

(C.Bina, 9/2011)



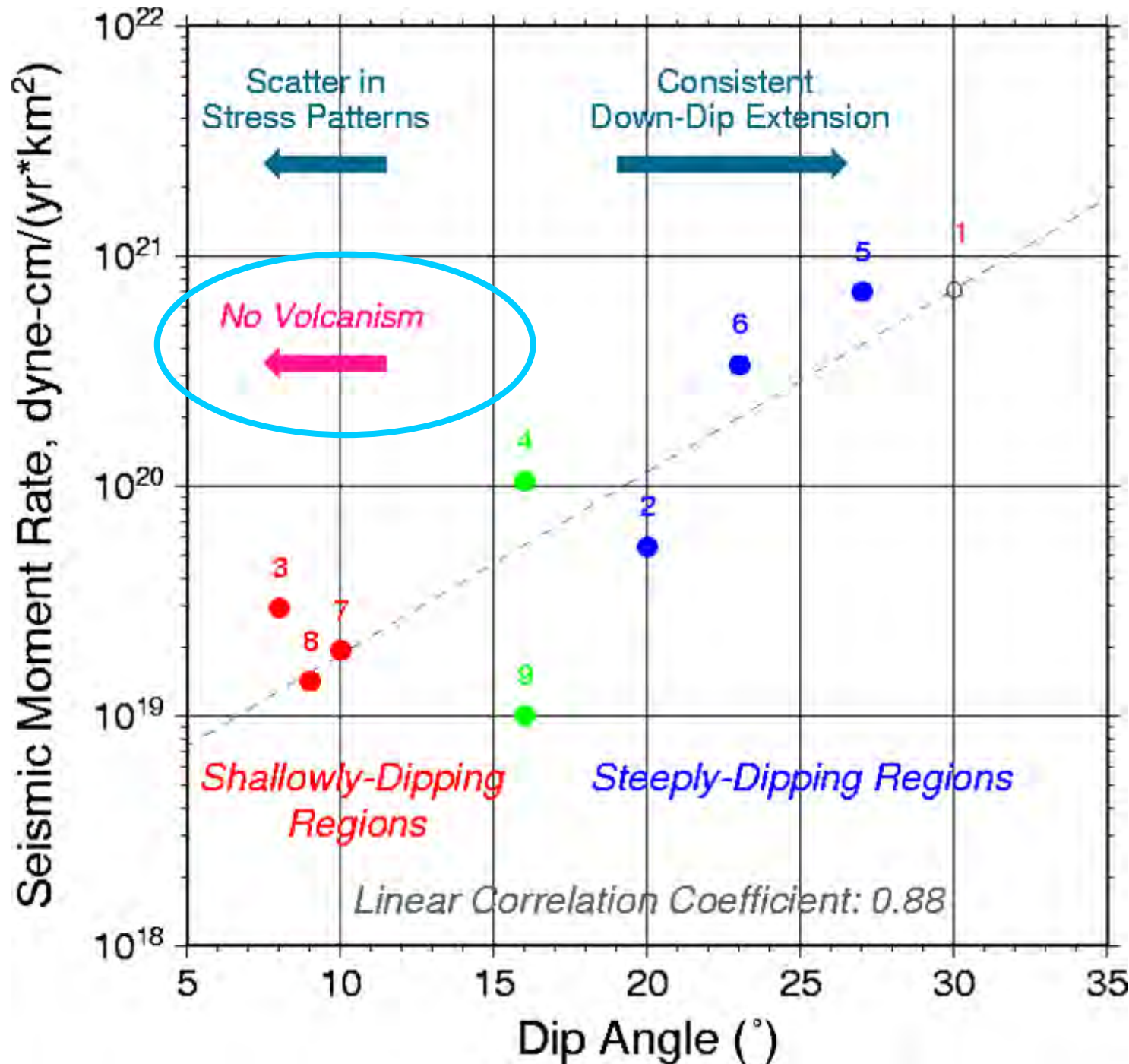
Volcanism: Some Observations

Volcanism without seismicity:

Davies [1999] proposed that faulting during intermediate-depth earthquakes facilitates the transport of water into the mantle wedge, thereby generating subduction-zone volcanism. However, the fact that the northern and southern South American volcanic zones overlay aseismic slab segments suggests that this is not a necessary condition.

South American Subduction: Volcanism

(Figure 2 from Chen, Bina, and Okal [2001])



Seismic moment rate (normalized per unit area of subducting slab) as a function of dip angle, keyed to regional box numbers, estimated over the depth range of intermediate-depth seismicity for each box. An overall positive correlation is seen. We also identify shallowly dipping regions and steeply dipping regions and note their correlation with volcanism and stress patterns.

Volcanism: Some Observations

Volcanism without seismicity:

Davies [1999] proposed that faulting during intermediate-depth earthquakes facilitates the transport of water into the mantle wedge, thereby generating subduction-zone volcanism. However, the fact that the northern and southern South American volcanic zones overlay aseismic slab segments suggests that this is not a necessary condition.

No volcanism at shallow dip angles:

We conclude that there is little or no volcanism at the surface above shallowly dipping regions, confirming the results of Cahill and Isacks [1992].

Why?

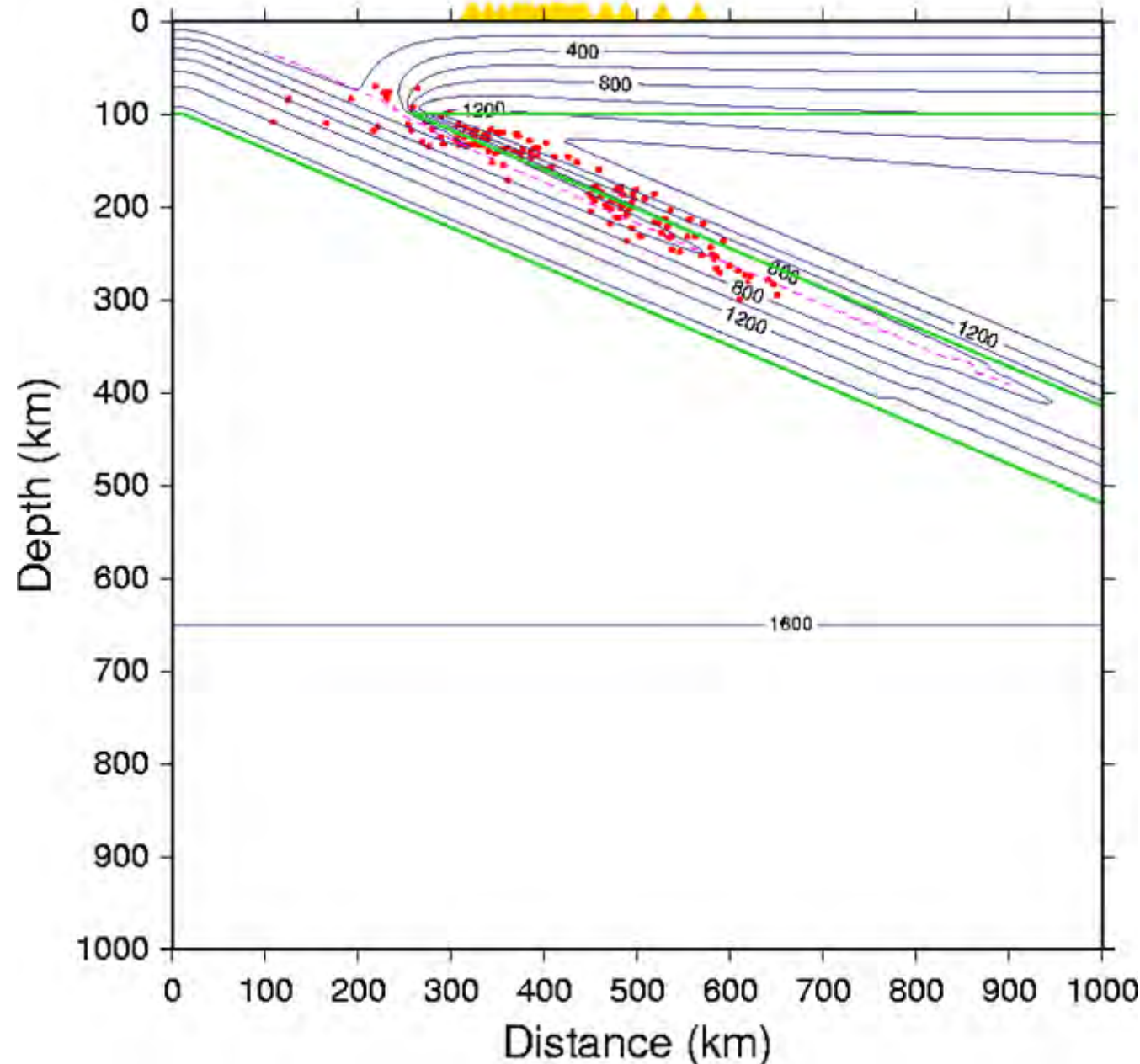
Box 6

(Figure 8 from Chen, Bina, and Okal [2001])

$v = 8.3 \text{ cm/yr}$, $\theta = 23^\circ$, Age = 58 Ma

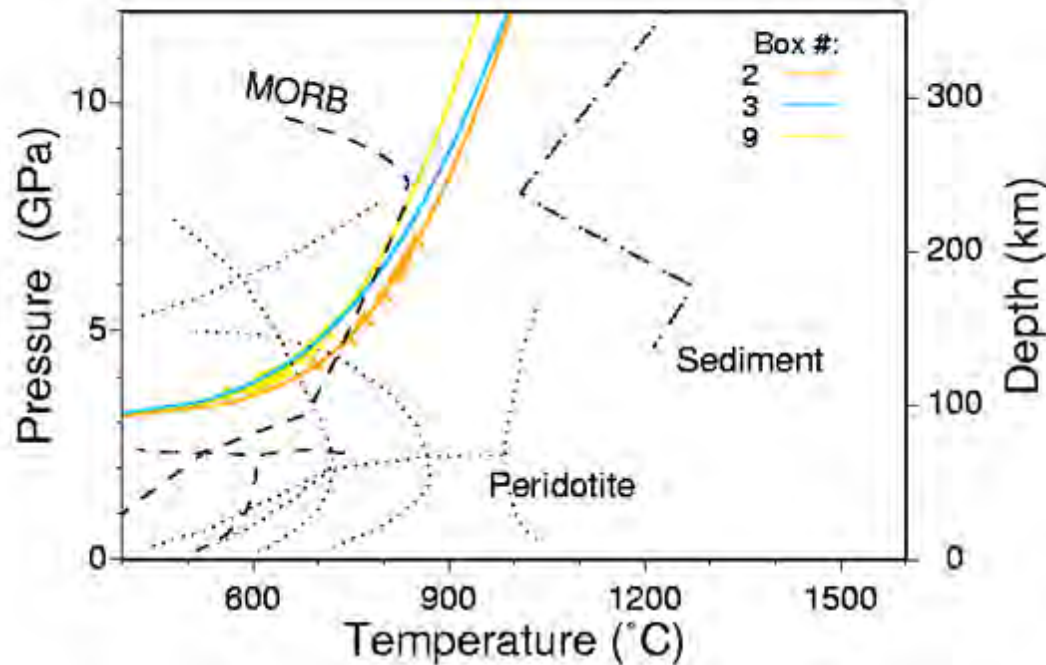
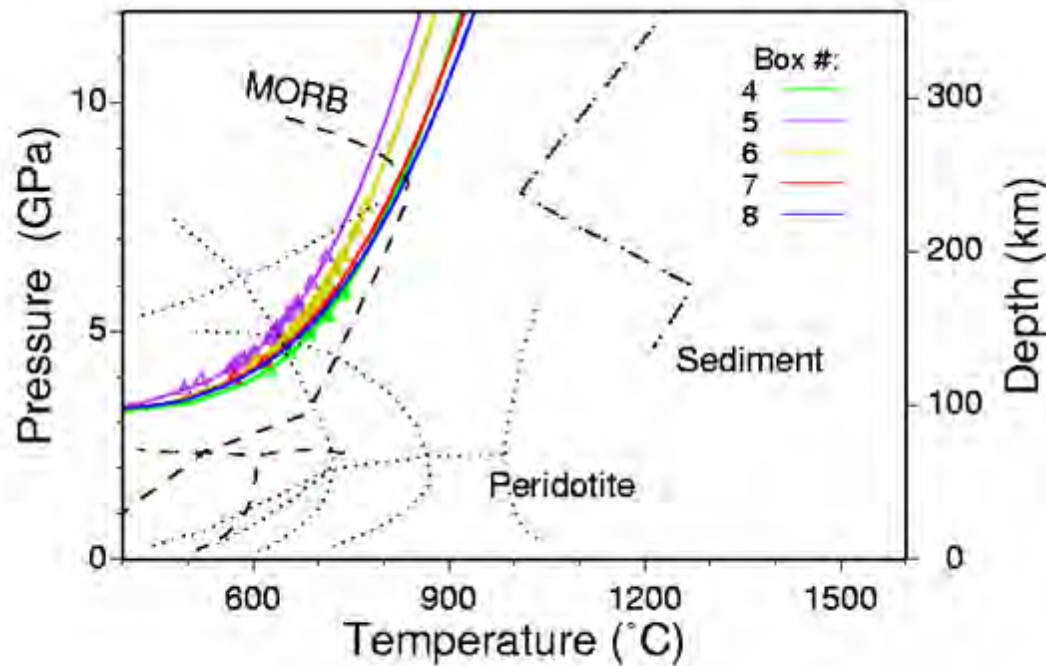
Method of analysis

Portion of the thermal structure of the slab, as computed in the geometry of regional box, showing a segment extending 1000 km in the down-dip direction. Temperature contours are shown in $^\circ\text{C}$. The plane of Figure 8 is the best-fitting cross section. The locus of minimum temperature at each depth is shown as the red dashed line, projected seismicity as red dots, and projected volcanism as yellow triangles. The inferred top surface of the subducting slab is shown as the green line and is the locus of our computation of the P - T path.

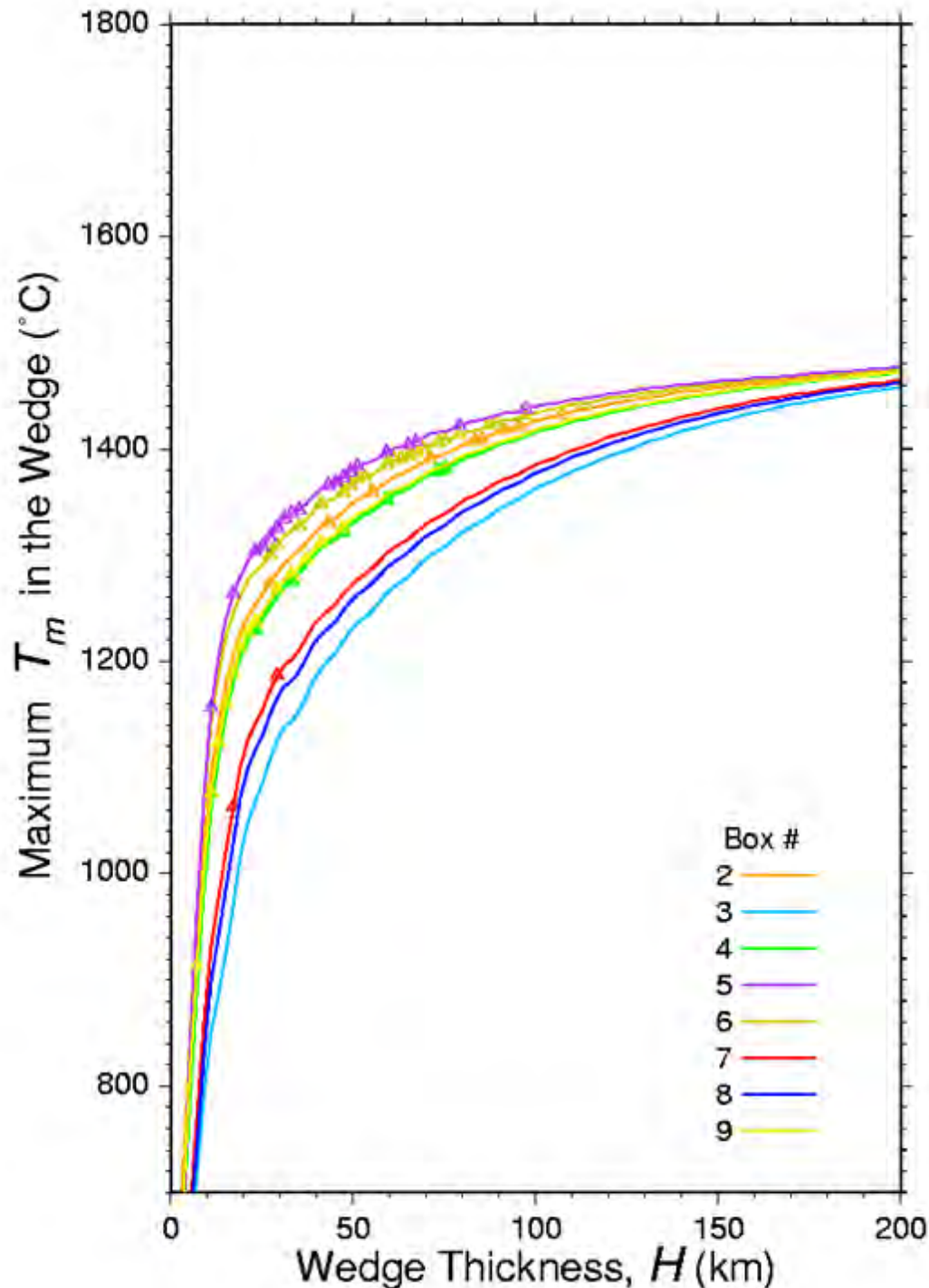


(Figure 9 from Chen, Bina, and Okal [2001])

Intersection of slab P-T-t paths with dehydration reaction boundaries



P-T paths along slab surface for different regions. (Top) Regional boxes featuring older oceanic lithosphere at the trench (>45 Ma). (Bottom) Regional boxes with younger lithosphere. Triangles are the relative positions of volcanic sites, vertically projected onto the surface of the slab. Dotted and dashed lines are phase diagrams of hydrous minerals present in MORB, peridotite [Schmidt and Poli, 1998], and sediment [Ono, 1998], as labeled. Note that, in both age groups, no clear distinction can be resolved in *P-T* paths for regions with and without volcanism.



Role of peak temperatures in overlying mantle wedge

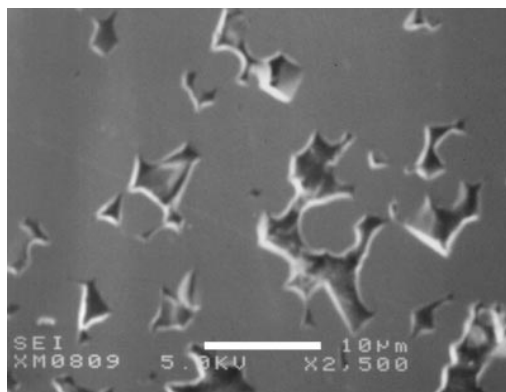
Maximum temperature in the overlying mantle wedge as a function of wedge width for all regional boxes. Note that the three most shallowly dipping regions (Boxes 3, 7, and 8) feature the lowest temperatures and exhibit almost no volcanism.

Volcanism: A Suggestion

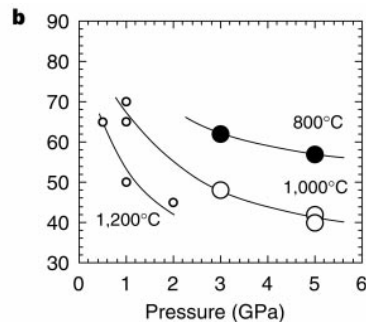
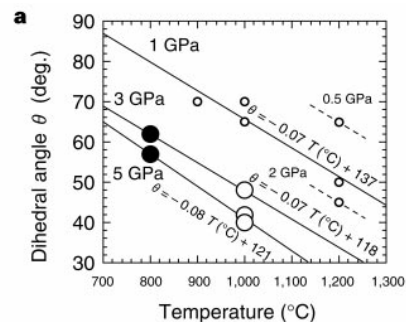
Even though water is liberated at similar depths, *the absence of volcanism above shallowly dipping slabs can be attributed to lower temperatures within the overlying mantle wedge.*

Such low temperatures may be below the solidus for wet peridotite, and/or may hinder fluid transport.

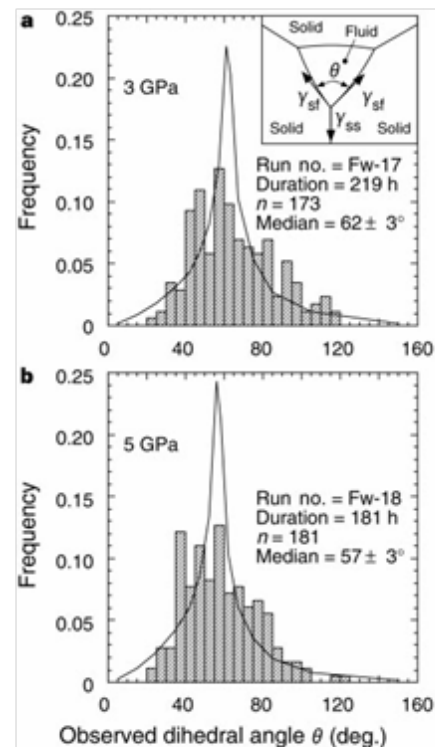
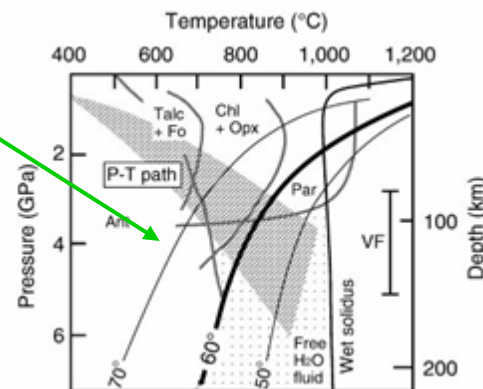
[Chen, Bina, and Okal, 2001]



Low temperatures may possibly inhibit fluid transport by increasing the dihedral angle ($>60^\circ$) between grains, thereby hampering development of interconnected networks for supplying aqueous fluids to the wedge.



low T ,
high θ



(Figures 1, 2, 3, and 4 of Mibe et al., 1999)

Volcanism: A Suggestion

Even though water is liberated at similar depths, *the absence of volcanism above shallowly dipping slabs can be attributed to lower temperatures within the overlying mantle wedge.*

Such low temperatures may be below the solidus for wet peridotite, and/or may hinder fluid transport. [Chen, Bina, and Okal, 2001]

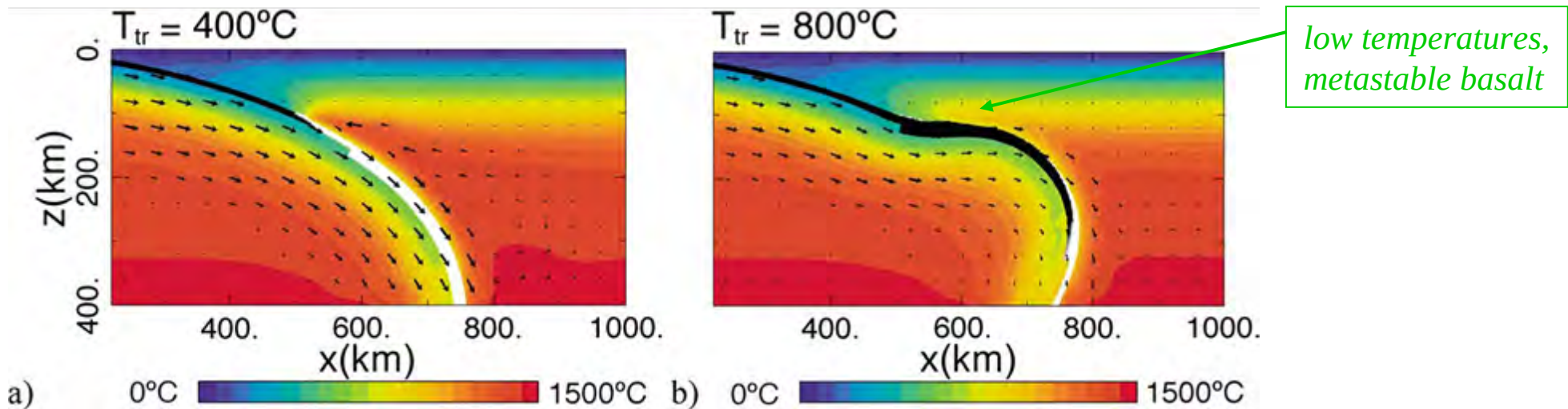


Fig. 4. Temperature contour plot of the plateau subduction process at $t=12.8$ Ma after initiation of plateau subduction. (a) With a transition temperature $T_{tr}=400^\circ\text{C}$, the compositional buoyancy is removed before flattening can start. (b) With $T_{tr}=800^\circ\text{C}$, the compositional buoyancy of the plateau flattens the slab. (Van Hunen et al., 2002)