The interaction of a subducting slab with a chemical or phase boundary

Christensen & Yuen (JGR 1984)

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1. Introduction

- **Fate of the subducting slab:**

?? stoped at about 670 km (barrier?)

?? went deeper below 670 km (seismic anomalies)

- **Dynamics of convection across 670km:**
  - Chemical distinct ? → layered convection
  - Sammis (1976): **<u>0.1%</u>** density jump will enforce layered convection
  - Olsen & Yuen (1982): **<u>10%</u>** density contrast → steady layered convection; less than 3% density contrast → no possible steady state solution

- **Effects of phase transitions on convection:**

  Calculations found that a phase boundary with negative Clapeyron slope would not pose a serious hindrance to mantlewide convection.

- **This paper**: investigate how a slab interacts with an actively convecting lower mantle by means of a time-dependent finite element model.

  In their model 670-km interface may be either a chemical boundary or a phase boundary or both.

2. Nature of the 670-km Discont.

- Seismic velocity & density jump: 6 – 11%
- Phase transition interface: Sp → Mw + Pv with a negative Clapeyron slope (-2 MPa/K).
- Strong seismic reflection → narrow transition interval → challenge an isochemical phase change of 670-km discontinuity

3. The Numerical Model

- In equation of motions (1) Γ(x,z) is the "phase function" between 0 (pure phase A) and 1 (pure phase B), representing the relative fraction of B. Here "phase" indicates either a isochemical phase transition or a compositional boundary. This paper assumes a sharp boundary in both cases, which makes Γ(x,z) a step function along z-axis.

$$\left(\frac{\partial^2}{\partial z^2} - \frac{\partial^2}{\partial x^2}\right)[\eta(\psi_{zz} - \psi_{xx})] + 4\frac{\partial^2}{\partial x\,\partial z}(\eta\psi_{xz}) = \mathrm{Ra}\,\frac{\partial T}{\partial x} - \mathrm{Rb}\,\frac{\partial \Gamma}{\partial x} \qquad (1)$$

- Numerical Techniques
- Numerical Parameters

$\Delta\rho/\rho$ = 1.5% , …, 9%

Clapeyron slope = 0 $\rightarrow$ - 6 MPa/K

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Fig. 2 (*a*) General sketch of the model. (*b*) Selected initial geotherm of models with a chemical boundary. See the text for detailed explanation.

4. Results: Chemical Boundary

- Density contrast: a - 9%, b - 6%, c - 4.5%, d - 3%, e - 1.5% (pure chemical boundary)
- (top)Penetration depth ~ time (Initial elevation: a-d: 10-25 km; e: 130km)
- (bottom) Average surface Velocity (plate velocity) ~ time. (V_0 = 3.5mm/a, after 35 ma, reach the boundary)

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Fig. 4. Convection model with 6% compositional density contrast at different stages of its evolution. Each column displays from top to bottom the viscosity ($\eta > 3 \times 10^{21}$ Pa s in dotted regions, $\eta > 3 \times 10^{22}$ Pa s in hatched regions, and $\eta > 3 \times 10^{23}$ Pa s in dark regions), isotherms in 200° intervals and streamlines which are plotted in steps of 50 nondimensional units, except for broken lines which are halfway in between. In each diagram the marker chain indicating the chemical boundary is also plotted.

- Density contrast $\Delta\rho/\rho$ and boundary depression due to slab subduction:

9%	70 km depression
6%	130 km depression
4.5%	230 km depression
3%	slab sinks down to the lower mantle with decreasing velocity
1.5%	slab sinks quickly to the bottom

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Fig. 5. Time evolution of a model with 3% chemical density contrast. See Figure 2 for explanations. One should not be confused by the fact that streamlines cross the boundary. The single snapshots are no steady state features and a streamline crossing the boundary only indicates that the boundary itself moves along the flow line.

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Fig. 6. Model with 1.5% compositional density contrast. The streamlines and, as a bold line, the 1000°C isotherm are displayed. See Figure 2 for spacing of streamlines.

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Fig. 7. Model with constant viscosity (10^{21} Pa s) and 1.5% chemical density contrast. The temperature difference between top and bottom is 800 K. Isotherms are shown in 100° steps in the upper diagrams and stream lines in steps of 25 nondimensional units in the lower ones.

5. Results: phase boundary

- Clapeyron slope is (a) – 3
  (b) – 4.5 (c) – 6 MPa/K
- Pure phase boundary of density contrast = 9%
- Top: Penetration depth of subducting plate v.s. time
  solid line: max. depth of
  1000 ^{o}C isotherm
  dotted line: phase boundary
- Bottom: Plate velocity v.s. time

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Fig. 9. State of three different convection models at a time after the sinking slab had encountered the interfacial boundary. Viscosity in the upper diagrams and streamlines in the lower ones; see Figure 2 for contour spacings. (left column) Pure phase boundary with $\Delta\rho/\rho = 9\%$ and $\gamma = -6$ MPa/K. (middle column) Combined phase and compositional boundary with $\Delta\rho_{Ch}/\rho = 1.5\%$, $\Delta\rho_{Ph}/\rho = 7.5\%$, and $\gamma = -3$ MPa/K. (right column) Same densities as before but with $\gamma = -4.5$ MPa/K. Because chemical differences are advected with the flow while the phase boundary adjusts to local p, T conditions, both boundaries may separate in a dynamical mantle.

- Average boundary depression to be 44, 65 and 86 km for Clapeyron slope = - 3, - 4.5, - 6 MPa/K.
- Clapeyron slope = - 6 MPa/K is sufficient to preclude slab penetration into the lower mantle.
- Convecting Model experiment:

  half internal heating and half bottom heat flux with total heat flow of 20 mW m^{-2}.

  Phase boundary layer with density contrast = 9% and clapeyron slope = - 6 MPa/K

  (The latent heat release during a phase transition is of minor influence on the stability of the layering)

Fig. 10. Convection model with constant viscosity of 3×10^{21} Pa s, half internal and half bottom heating of four nondimensional units each, and a phase boundary of $\Delta\rho/\rho = 9\%$ and $\gamma = -6$ MPa/K. Isotherms in 50° intervals and streamlines in steps of 10 units are displayed after a dimensional time of 1.8 Ga. Initially, 300 markers were distributed randomly in the lower layer. After 1.8 Ga, 22 of them are found above the phase boundary, while three had returned into the lower layer after having been in the upper part for one overturn of the circulation.

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Combined boundary:

	$\Delta\rho_{Ch}/\rho$	$\Delta\rho_{Ph}/\rho$	slope
a:	1.5%	7.5%	0
b:	3%	6%	0
c:	3%	6%	-3
d:	3%	6%	-1.5
e:	1.5%	7.5%	-3
f:	1.5%	7.5%	-4.5

Summary & Conclusion

Domain diagram for plate – tectonic style of convection with a combined endothermic phase boundary and chemical boundary at 650 km depth

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- Whole mantle convection: $\Delta\rho_{Ch}/\rho < 2$-3% and Clapeyron slope not too negative
- Strictly Layered convection: (1) large density (4.5 - 9%) jump due to compositional change (2) phase transition+chemical density change
- Pure phase transition with strongly negative value of clayperon slope will cause a leaky layered convection → in accordance with geochemical layered mantle
- Layered convection with slabs plunging deeply into the lower mantle: $\Delta\rho_{Ch}/\rho = 2 – 5\%$ + moderate clayperon slope.

- Seismic implications:

#670 km interface density jump due to phase change: $V_{slab} > V_{warm\ ambient\ mantle}$ → ray travel time in slab will be shorter than in ambient mantle(positive travel time: Jordan and Creager, 1984)

#670 km interface density jump due to chemical distinct: $V_{slab} < V_{ambient\ mantle}$ → negative travel time.

negative travel time anomaly is hard to determine phase boundary if lower mantle is more Fe-rich (Fe:Mg increases → density increases but velocity decreases! → negative travel time)