Subduction III
Regional subduction zone modeling

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Short course at Universita di Roma TRE
April 18 – 20, 2011
Reading

• King, S. (Elsevier Treatise, 2007)
• Billen, M. (Ann Rev, 2009)
• Becker & Faccenna (2009)
Figure 3  Covariance matrix for nine observations compiled from 39 modern subduction zones (Jarrard, 1986). The color scale represents the value of the correlation coefficient, with +1.0 being strongly correlated and −1.0 being strongly anticorrelated. Rollback is the rate of trench migration estimated from the global plate models (Minster and Jordan, 1978). Velocity is the velocity of the plate at the trench from the same global plate models. Slab age is the age of the plate entering the trench, and slab-tip age is calculated using the length of the slab and rate of change of plate age for the plate entering the trench. The intermediate dip is calculated from the trench to the 100 km depth of the slab. The deep dip is calculated from the 100–400 km depth of the slab. The thermal parameter is the product of the slab age and the length of the slab.
Pre-Plate Tectonics

- Subduction into the mantle was one of the last pieces of the plate tectonics puzzle.

1940s
- Mantle Convection
  - Holmes, 1944

1950s
- Mega-shear to 700 km
  - Benioff, 1954

1960s
- Internal deformation of subducted lithosphere.
  - Isacks & Molnar, 1969
- Deep planar fault zone
  - Elsasser, 1968
- Lithospheric thrusting
  - Plafker, 1965
- Crustal-scale thrusting
  - Hess, 1962

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Plate Tectonics: in the SZ

**Corner-flow model.**
- McKenzie, 1969

**1960s**

- Decreases Slab Dip
- Hydrodynamic Stresses (viscous flow)

**1970s 1980s**

- Travel time
- Slab thermal structure
- Linking slab temp. to mineralogy & petrology
  - Peacock, 1990

**1970s 1990s**

- Dynamic topography from corner-flow
  - Sleep, 1975
- Layered mantle visc.
  - Yokokura, 1981

- Newtonian
- Non-Newtonian

**Early analytic models capture major processes.**
- Force balance on slab.
- Slab thermal structure.
Kinematic Slab - Dynamic Wedge

- Slab & mantle wedge thermal/min./pet. structure.
- Fluid transport
- Seismic anisotropy.
Observations

- Arc curvature, slab dip, subduction velocity. - Tovish & Schubert, 1978
- Plate kinematics & characteristics - Jarrard, 1986
- Geoid & dynamic topo. - Hager 1984
- Plate tectonic recons. - e.g., DeMets, 1990
- Plate kinematics & characteristics - Mueller et al., 1997
- Lallemand et al., 2005
- Seismic anisotropy - Russo & Silver, 1994
- Fischer et al., 1998
- Long & Silver, 2008
- Seismic tomography - e.g., van der Hilst, 1997

- Connecting *kinematics* to *dynamics*.
Instantaneous (quasi) Dynamic

1980s

- **Rheologic Structure:**
  - mantle, slab, plate boundaries, wedge, crust...

- **Surface deformation:**
  - topography, geoid, stress-state.

1990s

- Rheologic Structure:
  - mantle, slab, plate boundaries, wedge, crust...

- Surface deformation:
  - topography, geoid, stress-state.

2000s

- 2D, Overriding plate root geometry & slab suction
  - Driscoll et al., 2009

- 3D, Slab strength effect toroidal & poloidal flow
  - Piromallo et al., 2006

- 3D, Lateral (moderate) viscosity variations
  - Moresi et al., 1996

- Stress-state in slab
  - Vassiliou, 1984

- 2D, Weak plate bndy, non-linear rheology
  - Zhong & Gurnis, 1996

- 3D, Lateral (moderate) viscosity variations
  - Moresi et al., 1996

- 2D, Faults & non-linear viscosity
  - Zhong & Gurnis, 1994

- 3D, Slab strength effect toroidal & poloidal flow
  - Piromallo et al., 2006

- 3D, Temp-dep, low viscosity wedge
  - Billen & Gurnis, 2001

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## Fully Dynamic (t-dependent)

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<tr>
<th>1980s</th>
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<td><strong>Buoyancy forces:</strong> phase transition, slab, crust...</td>
<td><strong>Rheologic structure:</strong> mantle, slab, wedge...</td>
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<td><strong>Geometry:</strong> 2-D, 3-D, slab edges, interactions...</td>
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<td><strong>2D, Phase trans. (T-dep. viscosity)</strong></td>
<td><strong>Arcay et al., 2008</strong></td>
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  - Griffiths et al., 1995
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  - King, 1991

2000s

• 3D, Slab-edge flow & slab depth
  - Honda, 2009
• 2D, Slab Buckling LM.
  - Behounkova & Cizkova, 2008
• 2D, Double-slab sub.
  - Mishin et al., 2008
• 2D, 1-sided subduction
  - Gerya et al., 2008
• 2D, Flat slabs & LVC
  - Manea & Gurnis, 2007

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- Schmeling, 1999
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2000s

- 2D, Compressibility - Lee & King, 2009


- 2D, Coupled/uncoupled continental collision - Faccenda et al., 2009

- 2D, Meta-stable olivine, - Schmeling, 1999

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- 2D, Coupled/uncoupled continental collision - Faccenda et al., 2009

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Mineralogical-Petrological

- Need coupled solid & fluid flow, density & rheology, detailed tracking of composition & phase.

Fully-coupled mantle-wedge dynamics & petrology
- Baker-Hebert et al., 2009

Fluid transport, melting
- Cagniocle et al., 2007

Composite crust-mantle density & rheology in wedge
- Gerya & Yuen, 2003

Min./pet. implications
- Davies & Stevenson, 1992

1990s  2000s

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A Multi-variate System

- **Geometrical Variables**
  - 2D vs. 3D
  - Over-riding plate
  - Interaction w/ other plate boundaries.

- **Physical Properties**
  - Rheology
  - Thermal parameters \((\alpha, \kappa)\)
  - Compressibility

- **Mineral-/Petro-logical**
  - Compositional variation
    - Density
    - Rheology

- **Coupled Systems**
  - Solid phase changes
  - Hydration/dehydration
  - Melting

**Link to Observations & Time Evolution**

*Transform a kinematic theory to a dynamic theory.*
Kinematic models
Peacock, 1996
Figure 7  A comparison of slab thermal structures from a 50-Myr-old, 45° dipping slab descending at 5 cm yr\(^{-1}\) with kinematic slab approximations (left) (Minear and Toksöz, 1970) and (right) the analytic corner flow solution for flow and ConMan's temperature solver. Below 50 km depth, the Minear and Toksöz slab is colder than the corner flow plus ConMan solution.
**Figure 9** Thermal structure from two slab calculations using ConMan (King et al., 1990). Both calculations have a slab descending at 45° at a fixed velocity of 5 cm yr⁻¹. The incoming plate material is 50 My old. The left image is a constant-viscosity mantle wedge and the right image is a temperature-dependent viscosity wedge, with an activation energy of 335 kJ mol⁻¹.
Heatflow
Constraints on decoupling zone

Wada and Wang, G3, 2009
Water distribution in incoming slab
  Compacted sediments: 0.4-5 wt%
  Upper crust: few wt%
  Serpentinite in upper mantle: up to 2 wt%

Slab structure outboard of trench at Nicaragua (Ivandic et al., 2008)
Faccenda et al. (2009)
Temperature in subducted oceanic crust

Van Keken et al., G$^3$, 2002: model for Honshu
See also: Kelemen et al., 2003; Conder et al., 2003; Wada and Wang, 2008
Update to Hacker, Gcubed, 2008
with full thermal models from Syracuse et al. (2010)
Cascadia

temperature

rock facies

water carrying capacity

Syracuse et al. (2010)
Tohoku

Syracuse et al. (2010)
Coupled Solid-Fluid-Min.

Hebert et al. (2009)

- Composition evolves including fluid & melt content.
  - Affects density (T, X) & rheology.
- Fluids move according to Darcy flow.
Figure 9. Schematic diagram of fluid migration at subduction zones. Hydrous fluids (grey streamlines) are released from the slab by dehydration reactions and rise buoyantly into the wedge. Fluids do not rise vertically into the wedge but are influenced by solid flow. A melting front (pale red triangle) develops where the water which was not advected to greater depth reaches a region hot enough to melt. The fluid is then a mixture of dissolved oxides and a hydrous component (black streamlines). The large fluid fraction after melting front prevents solid flow from affecting fluid migration, and fluids migrate vertically to the surface until they reach colder temperatures (pale blue ellipse). The present study does not explicitly treat the final fate of melt, but a potential melt transport mechanism, shown by the red arrow, is discussed in the text.
Fluids Affect Solid Flow.

- Form low viscosity channel above slab.
- Spatially & temporally variable melt fraction.
  - Limits region of water effect on rheology.

Hebert et al. (2009)
Semi-dynamic models
Fig. 1. Thermal fields from two convection calculations with plates. In both calculations the Rayleigh number is $10^6$, the top and bottom are isothermal free-slip boundaries, the fluid is internally heated, and the viscosity is temperature dependent. The initial temperature field has a square root of age plate thermal field on the left side of the box and a uniform boundary layer on the right side of the box. Weak material zones allow the plate to deform at the trench and the ridge. The ‘ridge’ is in the left corner of the box and the ‘trench’ is in the center of the box. Further details on this type of calculation can be found in Chen and King (1998). (a) The side velocity boundary conditions are free-slip (material is free to move vertically along the edge). (b) Identical to (a) except that the velocity of a single node on the right-hand side is set to zero, breaking the symmetry of the top boundary layer velocities. (c) Identical to (b) except that the side velocity boundary conditions are an imposed horizontal velocity of 20 mm per year. This is identical to moving the trench and plate relative to the center of mass of the mantle.
Grain size weakening at 410

\[ \nu_{trench} \text{ and } GW \text{ varied à la van Hunen et al. (2002)} \]

\[ \Rightarrow \text{strong slabs penetrate (Davies, 1995)} \]

\[ \Rightarrow \text{GW could explain weak, bent slabs (c.f. Karato et al., 2001)} \]

\[ \Rightarrow \text{alternatives: faults, } \eta_y \]

\[ \text{Čížková et al. (2002)} \]
Fig. 1. Snapshots from a laboratory experiment by Guillou-Frottier et al. (1995). A sheet of chilled and dyed corn syrup is extruded into a tank with two layers of syrup. Initial rapid trench migration leads to a flat slab. After (B), trench-rollback is stopped and slab material accumulates in a pile that sinks into the lower layer. The whole sequence corresponds to approximately 400 million years of subduction.
Figure 14  Experimentally observed styles of slab penetration through a density discontinuity (left) compared with 2-D calculation by Christensen and Yuen (1984) (right). (a) Slab deflection with $R \approx -0.2$. (b) Partial slab penetration with $R \approx 0.0$. (c) Complete slab penetration with $R \approx 0.5$. Reproduced from Kincaid C and Olson PL (1987). An experimental study of subduction and slab migration. *Journal of Geophysical Research* 92: 13832–13840, with permission from American Geophysical Union.
reference
$v_{plate} = 5 \text{ cm/yr}$
$v_{trench} = 1 \text{ cm/yr}$

$v_{trench} = 2 \text{ cm/yr}$

$v_{trench} = 3 \text{ cm/yr}$

negative Clap. sl. & viscosity contrast at the 6

$v_{trench}$ increased with time

$v_{trench} = 3 \text{ cm/yr}$ & phase transition at the 4

weak slab

large negative Clapeyron slope & slow $v_{trench}$

Christensen (1996)
Effect of negative Clapeyron slope on slabs and plumes

Tan et al. (2001)
Ponding as $f(\text{strength, rollback})$

Do slabs make it all the way to the CMB?

Yep.

\[ \frac{dp}{dT} = -3 \text{ MPa/K} \checkmark \]

\[ \Rightarrow \text{increase in } \kappa \text{ with depth } \checkmark \]

\[ \Rightarrow \text{internal heating } \checkmark \]

\[ \Rightarrow \text{substantial (} \sim 500 \text{ K) anomaly at CMB} \]

Tan et al. (2002)
Fig. 10. Compilation of the subduction style of all presented calculations. Green blocks indicate a subduction style like at present. Blue diamond indicate frequent slab detachment events, and red triangles denote no continuing subduction.
Tomographic slabs and Stokeslets for a moving trench scenario

- Weak, fluid slab \( (\eta' = \frac{\eta_{\text{slab}}}{\eta_{\text{mantle}}} = 1) \) hits the 660
- Prescribed trench motion

Karason (2002)
Stokeslets and tomography

- Best fit for Sunda for a viscosity contrast between upper and lower mantle of $> \sim 200$
- Strong anchoring of weak slab
- cf. slablets of Morra et al.

Karason (2002)
3D
Interactions: rollback and episodicity in 3D

laterally unconfined

laterally confined

10 Myrs

15.5 Myrs

before interaction

after interaction

→ episodicity in case of lateral and vertical flow confinement

Funiciello et al. (2003)
Changes in plate motions

Tan and Gurnis (2002)
What should slabs look like in tomography?

90 Ma:
- Complicated.
- \( \Rightarrow \) regional 3-D forward model

30 Ma:
- \( \Rightarrow \) prescribed plate motions
- \( \Rightarrow \) slab segmentation expected

0 Ma:
- \( \Rightarrow \) ambiguous cross-sections in tomography \( \Rightarrow \) convection is layered

Tan et al. (2002)
Kincaid & Griffith (2003)
Kincaid & Griffith (2003)
Piromallo et al. (2006)

$\eta' = 1$

$\eta' = 1,000$

$\eta' = 1,000$
Instantaneous toroidal partitioning

- Toroidal flow increases with slab width and peaks at moderate viscosity contrasts
- TPR increases with viscosity contrast

Piromallo et al. (2006)
Fully dynamic (free slab) models
Trench rollback

Zhong and Gurnis (1995)
(a) case 1
 temperature dependent viscosity, yielding
 + viscosity increase for the lower mantle

(b) case 2
 temperature dependent viscosity, yielding
 + viscosity increase for the lower mantle
 + phase transition at 410 km and 660 km

Yanigasawa et al. (2010)
silicon putty (viscoelastic)

honey (viscous)

Bellahsen et al., JGR, 2005
‘subduction = plate motion + trench motion’

Controls on modes:
- bending resistance
- curvature of subduction
- mantle depth
- strength of slab

Bellahsen et al., JGR, 2005
Strong slab trench dynamics

- For slabs with $\eta' \sim 2,000 - 10,000$, a mixed mode regime with advance and retreat exists for free slab models.
- Analyze a wide set of experiments with different slab widths, viscosities, thickness, etc. (cf. Enns et al., 2005)

Bellahsen et al. (2005)
Subduction velocity scaling

Subduction velocity = modified Stokes velocity accounting for bending

\[ V' \approx \frac{\Delta \rho ghL}{[2\eta_i(h/r)^3 + 3\eta_m A]} \]

\[ V^\circ = \frac{(\Delta \rho^\circ gH^\circ h^\circ)}{\eta_m^\circ} \]

\[ V = \frac{V'}{V^\circ} \]

\[ = \frac{hL}{h^\circ H^\circ} \left[ \frac{1}{2(\eta_i/\eta_m)(h/r)^3 + 3A} \right] \]

- Subduction velocity = modified Stokes velocity accounting for bending
- Conrad & Hager (1999); Becker et al. (1999)
Strong slab force balance

- Stiff slab experiments are dominated by bending vs. mantle drag
- cf. Buffett (2006) for proper force estimate (for $r = \text{const.}$)

- It's a percentage numbers game, $f(\text{strength of slab})$, which is not well known

Bellahsen et al. (2005)
Top boundary conditions I

free surface

crustal package

zoom-in

free-slip

upper mantle

Elasto-visco-plastic rheology & erosion, finite elements (SloMo)

Kaus et al. (2008)
Top boundary conditions II

- Boundary condition important for isolated plate experiments (cf. Enns et al., 2005; Schmeling et al., 2006)
- Boundary condition not important for two-plate models (cf. Zhong, Moresi), and tests of Kaus et al. (20078)
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<th>Weak slabs</th>
<th>Strong slabs</th>
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<tr>
<td>Trench rollback</td>
<td>Shallow box</td>
<td>Deep-wide box</td>
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<tr>
<td></td>
<td>a 660 km</td>
<td>b 660 km</td>
</tr>
<tr>
<td></td>
<td>Periodic side-walls</td>
<td>Reflecting side-walls</td>
</tr>
<tr>
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<td></td>
<td>e 660 km</td>
<td>g 660 km</td>
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<td></td>
<td>Relative mantle flow</td>
<td>t_1 t_2 t_3</td>
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<td>Trench advance</td>
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<td></td>
<td>h 660 km</td>
<td>i 660 km</td>
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Billen (2009)
Effect of slab strength

- Toroidal power increases with viscosity contrast, i.e. flow becomes progressively less Stokes-sinker like (Piromallo et al., 2006)
- Subduction velocities (poloidal RMS) decrease with viscosity contrast, i.e. the slab strength has an important effect on mantle flow and subduction rates (Conrad & Hager, 1999; Becker et al., 1999; Bellahsen et al., 2005)
- Trench curvature is more convex for stiff slabs (cf. Fucicello et al., 2004, Schellart et al., 2007)
- No elasticity needed to explain trench morphology (cf. Morra et al., 2006)
The moderately weak slab

- Consistent with Becker et al. (1999) and Conrad & Hager (1999) bending related estimates which yielded upper bound of $\eta' \sim 500$
- Moresi & Gurnis (1996) geopotential argument
- Billen & Gurnis (2005) trench admittance work
- ...

Becker et al. (1999)
Lab model behavior as $f(\eta')$

- **lithosphere controlled**
- **mantle controlled**

Strength $\eta'$, buoyancy $\sim \sqrt{\eta'}$

Stegman et al. (2010)

\[ D_{\text{vis}}^* = \frac{D_{\text{vis}}}{\frac{1}{3} \eta_{\text{um}} H^3} = \frac{\eta_{\text{plate}}}{\eta_{\text{um}}} \left(\frac{h_{\text{plate}}}{H}\right)^3 \]

\[ B_S = \frac{\Delta \rho g h_{\text{plate}}}{\eta_{\text{um}}} \]
Thin sheet BEM models of free slabs

Figure 12. Shapes of subducting viscous sheets that have reached a depth $D = 9.17h$, starting from the initial conditions $L(0) = 16h$, $d/h = 0.2$, $\ell(0) = 4h$ and $\theta_0(0) = 15^\circ$ shown in panel a). The viscosity contrast $\gamma$ is indicated at the lower left-hand corner of panels (b)–(h). The inverted triangles indicate the initial position of the trench.

Ribe (2010)
Thin sheet BEM models of free slabs

\[ \gamma \left( \frac{h}{\ell_b} \right)^3 \equiv S. \]

Capitanio et al. (2007) models

Ribe (2010)
Thin sheet BEM models of free slabs

$R_{\text{min}} \approx 0.50h \gamma^{0.25}$

Wu et al. (2008) compilation

Figure 13. Minimum radius of curvature $R_{\text{min}}$ of a subducting sheet at the time when its tip reaches a depth $D = 8.25h$, as a function of the viscosity contrast $\gamma$. The initial condition is the same as in Fig. 12(a).

$\gamma \in [140; 410]$ Consistent with Funiciello et al. (2009) $\gamma \in [150; 500]$

Ribe (2010)
Role of the dip at touchdown

Figure 10. Modes of free subduction observed in analogue laboratory experiments. (a) ‘dripping’ (D) mode; (b) ‘weak retreating’ (WR) mode; (c) ‘folding retreating’ (FR) mode; (d) ‘advancing’ (A) mode and (e) ‘strong retreating’ (SR) mode. The photographs in the left-hand column were taken before the sheet’s leading end reached the bottom of the experimental tank, and those in the right-hand column some time after. The viscosity contrast $\gamma$ for each experiment is indicated at far right-hand side. The depths of the fluid layers are 9.4 cm for (a), 11 cm for (b)–(d) and 9.7 cm for (d). Photographs courtesy of F. Funiciello.

Figure 11. (a) Phase diagram showing the modes of free subduction observed in laboratory experiments as a function of the viscosity contrast $\gamma$ and the ratio $D/h$ of the layer depth to the sheet thickness (adapted from Fig. 13 of Schellart 2008). WR: weak retreating mode. FR: folding retreating mode. A: advancing mode. SR: strong retreating mode. (b) Contours of the dip $\theta_D$ (in degrees) of the tip of the slab at the time when it reaches the depth $D$, predicted numerically using the BEM model. The initial condition for the calculations is $\epsilon(0) = 0.455, D, \theta_D(0) = 15^\circ$, $L/h = 16$ and $d/h = 0.2$.

Ribe (2010)
Why not $f(\Delta \rho)$?

Lab: surface tension (Bellahsen et al., 2005)

$$Bo^{-1} = \frac{\sigma}{h^2 g \Delta \rho} \quad Bo^{-1} \in [0.37; 2.2]$$

Numerics: plastic yielding (Stegman et al., 2009)

$$\Pi = \frac{\tau}{h g \Delta \rho} \quad \Pi \in [0.06; 1.85]$$

Ribe (2010)
Real slabs aren't free

Yamato et al. (2009)
Yamato et al. (2009)
From regional to global