Subduction zone dynamics and mantle flow

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Revised syllabus

• Fundamentals of Earth Structure and Geophysical constraints for Subduction
• Fundamental of Fluid and Mantle Dynamics
• Regional Subduction Zone Modeling
  – From static to dynamic
• Global Mantle Flow Modeling
• Geological Constraints for Subduction
• Trench Migration and Upper Mantle Convection
Subduction I
Earth Structure and geophysical subduction zone constraints

Figure courtesy Ed Garnero
Rocky planets
Lithosphere (plate tectonics) = Top, cold boundary layer

Core-mantle boundary = Bottom, hot boundary layer
The mantle system

- **Dynamics of mantle largely thermally driven**
  - **Lithosphere:**
    - top thermal boundary layer of the mantle rheology($\rho, T, C$) →
      - strong, elastic with yielding (brittle/plastic)
    - plate tectonics
  - **Heat sources**
    - loss of accretional heat of mantle and core
    - radioactive heat production in mantle and core

- **Role of composition?**
  - melting → compositional variations (crust)
    - affects geochemistry? mantle dynamics?
  - solidifying inner core → chemical source of energy
Some issues: 1) Plate generation

Foley & Becker (2009)
2) Thermo-chemical mantle structure

(a) Compositionally distinct, dense piles

(b) Highest temperatures

(c) Dense piles and temperatures

(d) Shear velocity heterogeneity

Figure courtesy Ed Garnero
3) Post-perovskite and ULVZs

Figure courtesy Ed Gamero
Plate tectonics
Global shallow seismic moment release summed Engdahl catalog < 50 km

$log_{10}(\Sigma M_0/V [N/m^2])$
Seafloor age
Wadati-Benioff zone seismicity

Cross-sections of the Tonga trench

Distance along profile (km)

Depth in km
The hardest part of the puzzle
Subduction zones

- Crust formation exposure to water
- Sediment deposition
- Extent of water circulation and hydration of deep crust and mantle
- Seismic decoupling earthquake hazards
- Arc volcanism, volcanic hazards
- Time evolution of arc volcanism continent formation
- Earthquake source mechanisms
- Deep transport of differentiated material and long-term evolution of the mantle
Subduction zone terms

- continental margin
- back-arc basin
- volcanic arc
- arc-trench gap
- trench (plate boundary)
- flexural bulge
- spreading centre
- volcanic front
- fore-arc basin
- fore-arc high
- oceanic crust
- oceanic lithosphere
- accretionary prism
- mantle wedge
- earthquakes
What drives the plates?
Plate driving forces

Forsyth & Uyeda (1975)
Plate driving forces

Forsyth & Uyeda (1975), plotted by King (2008)
Relevance of subduction

- Plate tectonics and Earth evolution (life) might be intrinsically linked
- Subducted slabs are responsible for ~70% of the plate driving forces
- Subduction zones host the largest earthquakes
- Subduction zone volcanism and sediment transport major players in volatile and carbon cycle
Half space cooling
Thermal structure of oceanic lithosphere

Cooling halfspace

\[ \frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2} \]

\( T = T_m \) at \( x = 0 \)
\( T = 0 \) at \( z = 0 \)
\( T = T_m \) at \( z \to \infty \)

\[ T(x, z) = T_m \text{erf} \left( \frac{z}{2\sqrt{\kappa t(x)}} \right) = T_m \text{erf} \left( \frac{z}{2\sqrt{\kappa x/v}} \right) \]
\[ T(x, z) = T_m \text{erf} \left( \frac{z}{2\sqrt{\kappa x / \nu}} \right) \]

Depth of an isotherm \[ z_{t\infty} = C \sqrt{\kappa} \]

Surface heat flow \[ q_s = -k \left( \frac{\partial T}{\partial z} \right)_{z=0} = \frac{k T_m}{\sqrt{\pi \kappa t}} = \frac{k T_m}{\sqrt{\pi \kappa x / \nu}} \]

Bathymetry \[ h(x) = \frac{2\rho_m \alpha V T_m}{(\rho_m - \rho_w)} \sqrt{\frac{\kappa x}{\pi \nu}} \]
Richardson et al. (1995)

Fig. 1. Evolution of the lithosphere in a halfspace model and a plate model. 
Left: Evolution of the lithosphere in a halfspace model and a plate model. 
Right: Evolution of the heat flow and geoid slope. 

Richardson et al. (1995)
Heat flow data
Seafloor age
Global heat flow
Force balance based on half-space cooling slab pull

\[ F_b = -2 \rho_0 g \alpha b (T_m - T_s) \sqrt{\frac{K \ell_s}{\pi}} \]
Lithospheric thickening

\[ l = a(z_w - d_l) = a\Delta z_w \]

\[ a = \frac{\rho_w - \rho_a}{\rho_a - \rho_l} \]

\[ z_w(x) = c\sqrt{\frac{x}{u_0}} \]

\[ F = \frac{ac^2}{2u_0}g\Delta \rho \Delta x \]
Force estimates from half-space cooling

- Ridge push (lithospheric thickening) $\sim 10^{12}$ N/m
- Slab pull $\sim 10^{13}$ N/m
Geophysical constraints on slab dynamics
Crustal velocities in plate model

Crustal velocities in HS-3 Hot spot reference frame
Kinematic characteristics of present-day plate tectonics:

- **Poloidal component**
- **Toroidal component**
- **Sources and sinks**
- **Strike slip motion, Transform faults**
- **Spin for \( l = 1 \) (net rotation, NR)**
Time variability in plate motions (and heat transport)

**Plate reconstruction A:** Mueller et al. (2008)

**Plate reconstruction B:** Lithgow-Bertelloni et al. (1993)
Modified from Isacks and Molnar (1971)
Structural seismology
Seismic waves
PREM - Preliminary Earth Reference model (1981) based on travel times, surface wave dispersion curves, normal mode frequencies, constraints on mass and moment of inertia + some constraints on $V_P-\rho$ relation.
Figure 5.8. Sequence of pressure-induced transformations and reactions as a function of depth in a mantle of pyrolite composition. Px: pyroxene, Mw: magnesiowüstite, pv: perovskite. After Irifune [44].

from Davies (1999)
Deuss (2002)
<table>
<thead>
<tr>
<th>Mineralogical zones</th>
<th>Seismological layers and Boundaries</th>
<th>Bullen's names</th>
<th>Dynamical layers</th>
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<td>7 km</td>
<td>Crust Mohorovicic ~35 km</td>
<td>A</td>
<td>Lithosphere 10-100 km</td>
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<tr>
<td></td>
<td>(Upper mantle)</td>
<td></td>
<td>Upper Mantle</td>
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<tr>
<td>~350 km</td>
<td>410 km discontinuity</td>
<td>B</td>
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<tr>
<td></td>
<td>(Transition zone)</td>
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<tr>
<td>~750 km</td>
<td>660 km discontinuity</td>
<td>C</td>
<td></td>
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<tr>
<td></td>
<td>(Lower mantle)</td>
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<td>Lower Mantle</td>
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<tr>
<td></td>
<td>~2750 km</td>
<td></td>
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<td></td>
<td>(D&quot;) 2889 km</td>
<td>D</td>
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<td></td>
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<td>D'</td>
<td>TBL</td>
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<tr>
<td></td>
<td></td>
<td>D''</td>
<td>CBL</td>
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<tr>
<td>~2890 km</td>
<td>Core-mantle boundary</td>
<td>E</td>
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<td>Inner core boundary 5154 km</td>
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<td>Inner Core</td>
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Figure 5.2. A partial terminology of mantle layers that distinguishes the different concerns and usages of mineral physics, seismology and dynamical models. TBL: thermal boundary layer; CBL: chemical boundary layer.
SS precursors

Houser et al. (2008)
A modified set of forces

Seismic tomography

- CAT-scan like technique
- Earthquakes: sources
- Seismometers: receivers
- Measure travel times to invert for 3-D velocity structure
Theory of linear, ray tomography

Travel time $t$ of a ray given by integral over slowness $p = 1/\nu$ along path $s$

$$ t = \int_{\text{path}} p [r(s), \theta(s), \phi(s)] ds $$

Travel time anomaly $\delta t$ from reference model given by slowness perturbations $\delta p$, same path

$$ \delta t = \int_{\text{path}} \delta p [r(s), \theta(s), \phi(s)] ds $$

Choose $n$ basis functions for parameterization

$$ \delta p(r, \theta, \phi) = \sum_{i=1}^{n} \delta p_i f_i(r, \theta, \phi) $$

Evaluate path integral for every $\delta t$ observation for $m$ number of observations

$$ \delta t_j = \sum_{i=1}^{n} \delta p_i \int_{\text{path}_j} f_i [r(s), \theta(s), \phi(s)] ds \quad (j = 1, \ldots, m) $$

Write in matrix form, $A$ is $m \times n$, solve

$$ A_{ji} = \int_{\text{path}_j} f_i [r(s), \theta(s), \phi(s)] ds \quad A \cdot x = d $$

For $m > n$, system is overdetermined (and $\delta t$ has errors), solve in least squares sense, $(A^T A)^{-1}$ is the “general inverse”

$$ \|A \cdot x - d\| = \min \iff x = x_{LS} \quad A^T \cdot A \cdot x = A^T \cdot d \quad x_{LS} = (A^T \cdot A)^{-1} \cdot A^T \cdot d $$

Tomographic problems typically ill-conditioned, introduce regularization (“damping”):

$$ B \cdot x = c \quad \begin{bmatrix} A \\ \lambda B \end{bmatrix} \cdot x = \begin{bmatrix} d \\ \lambda c \end{bmatrix} \quad x_{LS} = \left[ A^T \cdot A + \lambda^2 B^T \cdot B \right]^{-1} \cdot \left[ A^T \cdot d + \lambda^2 B^T \cdot c \right] $$
Tomography example

Milner et al. (2009)
P wave tomography

Li et al. (2008)
Ritsema et al. (2000)

S wave tomography

- body waves
- surface waves
- normal modes

Figure 8: Depth slices through S20R TS. High (relatively to PREM) shear velocity regions are indicated by blue and red colours, respectively, with an intensity that is proportional to the amplitude of the shear velocity perturbations. The range of shear velocity variation (in %) is given above each map. Green lines represent plate boundaries.
Slabs in the lower mantle

Li et al. (2008)
Damping and L curves

![Graph showing variance reduction and roughness/number of parameters.](image)
Damping and L curves

![Graph and images showing variance reduction and L curves at different depths.](image)
Damping and L curves
P wave tomography checkerboards

Figure 5. Recovery fields of global resolution tests, using harmonic input patterns with constant amplitude ±1.5% in wave speed throughout the mantle. (a–e) Half-wavelength of \( \sim 5^\circ \) (spatial wavelength of \( \sim 550 \) km at the surface). (f–j) Half-wavelength of \( \sim 10^\circ \) (\( \sim 600 \) km at the CMB).
Cross-section tests

Faccenna et al. (2003)
Quantitative analysis: RMS power
Spherical harmonics

Definition

\[ \delta v(\theta, \phi) \approx \sum_{\ell=0}^{\ell_{\text{max}}} \left[ a_{\ell0} X_{\ell0}(\theta) + \sqrt{2} \sum_{m=1}^{\ell} X_{\ell m}(\theta) \right. \\
\left. \times (a_{\ell m} \cos m\phi + b_{\ell m} \sin m\phi) \right] \]

Power per degree and unit area

\[ \sigma_\ell^2 = \frac{1}{2\ell + 1} \sum_{m=0}^{\ell} (a_{\ell m}^2 + b_{\ell m}^2) \]

Correlation \( r_\ell \)

\[ r_\ell = \frac{\sum_{m=0}^{\ell} (a_{\ell m} c_{\ell m} + b_{\ell m} d_{\ell m})}{\left( \sum_{m=0}^{\ell} (a_{\ell m}^2 + b_{\ell m}^2) \right)^{1/2} \left( \sum_{m=0}^{\ell} (c_{\ell m}^2 + d_{\ell m}^2) \right)^{1/2}} \]

\[ 1 = 8, m = 0 \quad 1 = 8, m = 4 \quad 1 = 8, m = 8 \]

zonal \quad tesseral \quad sectoral
Spherical harmonics: tesseral wavelengths
Power spectra
Figure C2. Absolute power per degree and unit area on a logarithmic scale, $\log_{10}(\sigma^2)$, for $P$, $S$, and geodynamic models (compare Figure 1 and additional online material).