Geodynamics II: Subduction Dynamics

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Overview of Subduction System

- Plate forms at spreading ridge (buoyant crust + harzburgite, dry)
- Cools and thickens (dense lithosphere) as it travels across ocean basin.
- Bends at trench → Sinks into the mantle
What are the key observations that characterize subduction on earth?

How can we use these observations to learn about the process active in the upper and lower mantle?
1. What are the key observations that constrain the dynamics of subduction?

2. How do end-member models inform our understanding of subduction?

3. Some key “simple” (temperature) approximations for asking/answering questions about subduction.

4. What are the key processes during different stages of subduction?
1. Key Observations

- One-sided subduction
- Surface topography
- Seismicity within slab
- Seismic imaging of the slab
One-Sided Subduction

- One-sided subduction: only one plate subducts, even in oceanic-oceanic settings.

[from Richard Allen’s Website]

D. Zhao et al., TectP., 2009

D. Zhao 1996, 1997
Global models of plate tectonics typically show 2-sided subduction.

New models show 1-sided subduction. Key findings:

- Need to allow slab to bend naturally at upper boundary (free surface).
- Need a weak crustal layer to decouple flow from upper plate.

[Crameri et al., 2012]

**Key Point:** Always ask “What are the Boundary Conditions?”

Becker Comment: this may not be “the” requirement, but having a free surface is more realistic.
Key Observations: Topography

- Topography → small outer rise (+200 m), deep trench (-3000 m), small fore-arc high, volcanic arc.

![Graph showing topographic profile across Mariana trench and island arc](Image: GeoMapApp)

- Outer rise faults → fracture, faulting of bending plate
  (Image: Tonga from Google Maps!)
Images from KeckCAVES: ShowEarthModel

Next image is looking down into the Earth at seismicity in slabs beneath the surface shown in the figure.
Earthquakes → delineate slab shape; stop abruptly at about 660 km; activity has minimum at ~350 km; activity varies a lot between slabs
Key Observations:
Slab Shape & Moment Tensors

- Moment tensor → internal deformation (shortening, stretching)

Alpert et al, G-cubed, 2010
Example: Moment Tensors

Dots: earthquakes → Green, blue, purple pink, red → M= 5, 6, 7, 8, 9

3D View: Looking East down into the Earth”

- Earthquakes (M>4): dots
- Compression Axis from Moment Tensor: blue bars

from M. Billen & H. Tears
Central Japan Slab: very uniform down-dip compression in shallow dipping slab (max depth ~660 km)

Some outliers from central band in seismicity: significance?

Bars: compression Axis
Dots: earthquakes
Green, blue, purple, pink, red
M= 5, 6, 7, 8, 9

from M. Billen & H. Tears
Example: Moment Tensors

- Face-on view looking east
- Boundary between Japan and Izu-Bonin
- Clear rotation in compression axis in 100 km wide region.
  - Possible region of bending, stretching of slab
- **Key Point:** There is more information here about how slabs deform in the upper mantle → effects how they sink into the lower mantle.
Key Observations: Seismic Tomography

Fukao and Obayashi, JGR 2012

- Seismic Tomography → slab shape (shallow & deeper).
Sinking into the lower mantle is... complicated.
Tomographic Images

- Give complex view of subduction into lower mantle.

- What causes differences in observed shape of slabs?
  - Different stages of interaction with transition zone and lower mantle?
  - Differences in slab properties?
  - Differences in surrounding mantle properties?
  - Differences in surrounding mantle flow?

- To answer these questions, need to use models to make predictions and compare to observations.
2. End-Member Models

- **Rigid Slab \(\rightarrow\) Corner Flow**
  - What is the model?
  - Why is it useful?
  - What are the assumptions/simplifications?

- **Weak slabs \(\rightarrow\) density controlled (Stokes Sinker)**
  - What is the model?
  - Why is it useful?
  - What are assumptions/simplifications?

- **Key Point**: Behavior of slab is determined by balance between driving forces (buoyancy) and resisting force (viscosity/strength)
Forces Acting on the Slab

Behavior of slab is determined by balance between driving forces (buoyancy) and resisting force (viscosity/strength).

**Bonus Question: Can you find the error in the figure?**
Non-Newtonian Viscosity (e.g., $\frac{\text{d}\varepsilon}{\text{d}t} = \sigma^n$, yielding)

Other factors: water, grain size, composition, melt, phase transitions.
Weak Slab Model

- Weak slabs $\rightarrow$ density controlled
- Prelude: consider a sinking sphere

Drag Force
(Stress* Surface Area)

$$F_d = 6\pi \mu RV$$

$$F_g = (\rho_p - \rho_f) g \frac{4}{3} \pi R^3$$

$$V = \frac{2}{9} \frac{(\rho_p - \rho_f)}{\mu} g R^2$$

Set equal, solve for $V$

Weak Slab Models

What is the model?
- Small viscosity contrast 10-100 with surrounding mantle. (geoid/dynamic topography constraints)

What does it predict?
- Slab sink vertically into the mantle
- Switch from all down-dip tension to deep down-dip compression at x 30.
- Need trench motion to get non-vertical dip

What are assumptions/simplifications?
- Strength is less than expected from experiments/rheology

Gurnis and Hager, GRL 1988
Rigid Slab Models

- Rigid Slab Model $\rightarrow$ strength controlled

Prelude: Corner Flow

- From Batchelor, 1967
- Fixed Upper Plate
- $U=U_0$ Lower Plate and Dipping Plane
- Analytic solution for velocity, pressure
- Solution to Conservation and Mass and Momentum with Boundary Conditions.
- Can calculate stress, shear heating...

![Diagram](Fig. 5)

McKenzie, GJRAS, 1969
What is the model?

Slab dip determined by balance between buoyancy and dynamic pressure (due to flow).

\[ P_A (\theta) = \frac{2\mu U [\sin \theta - \sin (\theta - \theta_s)]}{r[(\pi - \theta_s) + \sin \theta_s]} \]

\[ P_B (\theta) = \frac{-2\mu U [\sin \theta \sin \theta_s + \theta_s \sin (\theta - \theta_s)]}{r[\theta_s^2 - \sin^2 \theta_s]} \]

\[ T_G = \int_0^L \Delta \rho (r) ghr \cos \theta_s \, dr \]

\[ = \frac{1}{2} bL^2 \cos \theta_s \]

\[ b = gh \int_0^L \Delta \rho (x) \, dx \]

\[ T_H = \int_0^L [P_A(\theta_s) - P_B(\theta_s)] \, dr \]

\[ = 2\mu UL \left[ \frac{\sin \theta_s}{(\pi - \theta_s) + \sin \theta_s} + \frac{\sin^2 \theta_s}{\theta_s^2 - \sin^2 \theta_s} \right] \] (2)

(Stevenson & Turner, Nature, 1977)
Rigid Slab Model

- What is the model?
  - Slab dip determined by balance between buoyancy and dynamic pressure.

- What does it predict?
  - Stable slab dip $\sim 63^\circ$
  - Shallower dip for faster velocity, higher mantle wedge viscosity or less slab mass (lower density or less volume).
  - Unstable at very shallow dip $\rightarrow$ runaway flattening
  - Unstable at steep dip $\rightarrow$ runaway steepening

- What are assumptions/simplifications?
  - Perfectly rigid slab, can only pivot.
  - Sinks parallel to slab dip (steady-state dip)

Stevenson & Turner, Nature, 1977
Earth’s Subduction is Somewhere in Between

Slab shape is determined by balance between buoyancy induced sinking and slab strength → these depend on several other things.

\[ \frac{\eta_{\text{slab}}}{\eta_{\text{mantle}}} = \]
Forces Acting on the Slab

Buoyancy: temperature, phase change anomalies (composition dependent)

Strength: temperature, stress-dependence (bending, plastic flow), water, grain size.

Correct if mantle flow Is faster than slab

M. Billen, AREPS 2008
Strong, Deformable Slabs Buckle and Fold

- Moderate increase viscosity with/without phase change induces folding.
- Significant apparent thickening in lower mantle.

Ribe et al., EPSL 2007

Behounkova and Cizkova, EPSL 2008
3. Simple Quantitative Approximations

- Temperature of the slab
  - Half-space cooling model
  - McKenzie (heating of a cold slab)
  - Corner Flow (newtonian vs. non-newtonian)

- Sinking Rate of Slab in Upper vs. Lower Mantle
Initial Temperature of Slab (Option 1)

Conduction of Heat: \( \frac{dT}{dt} = \kappa \frac{d^2T}{dy^2} \)

Half Space Cooling model: \( T \rightarrow T_{mantle} \) as \( y \rightarrow \inf \)

\[
T = (T_{mantle} - T_{surf}) \text{erf}(y/2\sqrt{\kappa t}) + T_{surf}
\]

Predicts broad thermal boundary layer

Slow diffusion of heat through most of this profile.
Initial Temperature of Slab (Option 2)

- **Plate Model**
  - Different boundary conditions.
  - Max thickness of plate is fixed.
  - (Mechanism for doing this in nature is unclear).

- Sharper temperature gradient $\rightarrow$ faster diffusion.
Early Model of Slab Temperature

McKenzie, 1969:

\[ \rho C_p \left( \frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T \right) = \kappa \nabla^2 T. \]

\[ \frac{\partial^2 T'}{\partial x'^2} - 2R \frac{\partial T'}{\partial x'} + \frac{\partial^2 T'}{\partial z'^2} = 0. \]

\[ R = \frac{\rho C_p v_x l}{2\kappa} \]

BC: \( T' = 1.0 \) @ \( x' = +/- 40 \) km

\[ T' = 1 + 2 \sum_n \frac{(-1)^n}{n\pi} \exp \left[ \left( R - \left( R^2 + n^2 \pi^2 \right)^{\frac{1}{2}} \right) x' \right] \sin n\pi z' \]

Captures key process but slab warms up too quickly because of BCs. Slab should cool down surrounding mantle \( \rightarrow \) needed to conserve mass. Slab is too warm and does not have enough total mass.
Early Model of Slab Temperature

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- Captures key process but slab warms up too quickly because of BCs.
- Slab should cool down surrounding mantle \( \rightarrow \) needed to conserve mass.
- Slab is too warm and does not have enough total mass
Use corner-flow to advect initial plate temperature profile.

Predict cooling of mantle of above slab

Less cooling for non-Newtonian mantle viscosity
Improved Treatment of Slab Temperature

- Allow for dynamic flow in the mantle wedge & non-Newtonian rheology (and mechanical decoupling zone at shallow depth).
- Growth of thermal boundary layer above slab.
- Cross section of temperature becomes more symmetric with depth.

van Keken et al., G-cubed, 2002
What is the sinking rate of slab?

- $\rho_p = 3350 \text{ kg/m}^3$
- $\rho_f = 3300 \text{ kg/m}^3$
- $\mu = 1\times10^{18} - 1\times10^{26} \text{ Pa-s}$

$$V = \frac{2}{9} \frac{(\rho_p - \rho_f)}{\mu} g R^2$$

[Graph showing sinking rate vs. mantle viscosity with shaded regions for Upper and Lower Mantle velocities.]

- Upper Mantle $V > 100 \text{ km/My}$
- Lower Mantle $V < 1 \text{ km/My}$
What are the key processes during different Stages?

- **Subduction Initiation** → forced compression; slab is not driving this process.
- **Juvenile** → slab suction followed by increasing density driven sinking (shallow → steep)
- **Young Adult** → Rapid descent through transition zone
  - Increase in density
  - Weakening of slab due shear & latent heat (stretching)
  - Weakening of surrounding mantle
- **Mid-Life Crisis** → interaction with higher viscosity lower mantle
  - Folding, buckling, forced slab rollback, trapped slabs.
- **Senior** → very slow sinking into lower mantle
- **Retirement** → slab break-off (can happen earlier)
Subduction Initiation

- Forced compression; slab is not driving this process.
- Need > 100 km of “proto-slab” to attain self-sustaining subduction.

Hall and Gurnis, EPSL 2002
Subduction Initiation

- Forced compression; slab is not driving this processes.
- Need > 100 km of “proto-slab” to attain self-sustaining subduction.

Onset of self-sustaining subduction is after 125 km of convergence

Hall and Gurnis, EPSL 2002
Juvenile Slab

Slab supported by wedge suction followed by increasing density driven sinking (shallow → steep)

Arredondo & Billen, J. Geodynamics 2016
Young “Adult” Slab: Interaction with Transition Zone

- Rapid descent **INTO** the transition zone
  - Increase in density due to phase transitions
  - Weakening of slab due to shear & latent heat (stretching)
  - Weakening of surrounding mantle

**Observations**

Blue: Subducting Plate Velocity

Arredondo & Billen, in review

Billen, PEPI, 2010
Midlife Crisis
Interaction with Transition zone

Arredondo & Billen, in review
Senior Slab:
Going into the Deep Mantle

- Very slow (<1 – 10 km/Myr sinking into lower mantle)
- 2000 km takes ~100 - 200 Myr (or more)

Arredondo & Billen, in review
Ending Subduction

Retirement → slab break-off (can happen earlier)
Example: ridge approaching the trench

Burkett & Billen, JGR 2009
Phases of Subduction

- What are the key processes during different Stages?
  - **Subduction Initiation** → forced compression; slab is not driving this processes.
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  - **Senior** → very slow sinking into lower mantle
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Observations provide a lot of information on what is happening to the slab; while others remain enigmatic.

End-member models are useful for thinking about trade-offs.

Use order-of-magnitude calculations to get at key processes.

Subduction evolution goes through several stages that depend on the lower mantle structure, phase transitions, etc...
Questions?