CIDER 2012 (Geodynamics V):
Subduction
(sounds better with a french accent)
Mantle Convection vs Subduction

symmetric and two-sided flow

Quelle and Schmelling, 2002
Mantle Convection vs Subduction

Quelle and Schmelling, 2002

Nikolaeva et al., 2010

symmetric and two-sided flow

asymmetric and one-sided flow
Mantle Convection vs Subduction

- symmetric and two-sided flow
- asymmetric and one-sided flow

Quelle and Schmelling, 2002

Nikolaeva et al., 2010

- heat transfer in the mantle
- thermal evolution
- cold thermal boundary layer
- fluid dynamics
- deformation / recycling of lithosphere
- tectonic evolution
- tectonic plates (including continents)
- multi-scale and multi-physics

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Forces that drive plate motion

- driving forces: slab pull, ridge push, slab suction (from the lower mantle)
- resisting forces: mantle drag, slab drag, trench suction

after Forsyth and Uyeda., GJI, 1975
Anatomy of a subduction zone
How subduction works
Questions still unanswered

• Why do plates subduct the way they do?
Questions still unanswered

• Why do plates subduct the way they do?

• What controls the stability of a subduction zone?
Questions still unanswered

- Why do plates subduct the way they do?
- What controls the stability of a subduction zone?
- How do subduction zones evolve?
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• How do subducting plates interact with the overriding plate?
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• How did plate tectonics operate in the past?
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• How do subducting plates interact with the overriding plate?
• What controls the variation of the dip angle?
• When did plates start subducting like they do today?
• How did plate tectonics operate in the past?
• Is Earth-like subduction unique to Earth?

If we want to think about plate tectonics on early Earth, we better start by figuring out how plate tectonics works in the present day.
CHAPTER 1
KINEMATICS: plate motions and trench migration

CHAPTER 2
TWO MODES OF SUBDUCTION: partitioning

CHAPTER 3
TRENCH CURVATURE: induced by mantle flow

CHAPTER 4
SLAB MORPHOLOGY: trench motion + layered visc

CHAPTER 5
OUTLOOK: mantle convection + subduction
Chilean vs Mariana Types

- upper plate in compression
- shallow dipping slab
- usually has continental upper plate
- forward-moving subducting plate

Uyeda and Kanamori, 1979

- upper plate in tension/extension
- steeply dipping slab
- usually has oceanic upper plate
- subducting plate has more rollback

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Erosional vs Accretionary Types

- no prism, evidence for erosion
- clear topographic expression of trench, easily identified
- large accretionary prism
- deep trench filled up and covered over by sediments
## Classification of subduction zones

<table>
<thead>
<tr>
<th>Subduction zone</th>
<th>Seismic moment magnitude</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>SChile (S.Chil)</td>
<td>9.5</td>
<td>1-CA</td>
</tr>
<tr>
<td>Alaska (Ala)</td>
<td>9.2</td>
<td></td>
</tr>
<tr>
<td>Aleutians (W.Ale)</td>
<td>9.1</td>
<td></td>
</tr>
<tr>
<td>Sumatra (Java-Sum)</td>
<td>9.1</td>
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</tr>
<tr>
<td>Cascadia (Casc)</td>
<td>9.0</td>
<td></td>
</tr>
<tr>
<td>Japan (Nan)</td>
<td>8.4</td>
<td></td>
</tr>
<tr>
<td>Central America (Mex-Cost)</td>
<td>8.1</td>
<td>2-TE</td>
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<tr>
<td>New Hebrides (NHeb)</td>
<td>7.9</td>
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<td>Marianas (Mar)</td>
<td>7.8</td>
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<td>Izu-Bonin (Izu)</td>
<td>7.2</td>
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</tr>
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<td>Philippines (Phil)</td>
<td>7.9</td>
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<tr>
<td>Tonga (Tong)</td>
<td>8.0</td>
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</tr>
<tr>
<td>Kermadec (Ker)</td>
<td>7.4</td>
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</tr>
<tr>
<td>Ryukyus (Ryu)</td>
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<tr>
<td>Lesser Antilles (Barb)</td>
<td>7.5</td>
<td>3-TA</td>
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<td>Aegean arc (Aeg)</td>
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<td>Makran (Mak)</td>
<td>8.0</td>
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<td>Peru (Peru)</td>
<td>8.4</td>
<td>4-CE</td>
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<tr>
<td>Japan (Honshu)</td>
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<tr>
<td>Kurile (Kur)</td>
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</tr>
<tr>
<td>N.Chile (N.Chil)</td>
<td>8.5</td>
<td></td>
</tr>
</tbody>
</table>

De Franco, Govers, and Wortel, EPSL, 2008
Two modes of subduction

• forward plate advance

• stationary trench

• slab rollback

• retreating trench

after Schellart (2006; 2008)
Kinematics of subduction zones

B Subducting plate velocity $v_{SP\perp}$

- Slow trenchward subducting plate motion $\rightarrow$ extension
- Fast trenchward subducting plate motion $\rightarrow$ shortening

C Trench migration velocity $v_{T\perp}$

- Trench retreat extension
- Slab rollback
- Trench advance $\rightarrow$ shortening

E Subduction velocity $v_{S\perp}$

- Slow subduction velocity $\rightarrow$ extension
- Fast subduction velocity $\rightarrow$ shortening

Schellart, GSA Bulletin, 2008

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Kinematics of subduction zones

• plate/trench motions depend on reference frame

\[ v_{OP1} = 0 \Rightarrow v_{SP1} > v_{C1} = v_{OP1} + v_{SP1} \]
\[ v_{OPD1} = v_{T1} - v_{OP1} > 0 = \text{extension} \]

• total rates independent of reference frame

\[ v_{C1} \]

\[ v_{A1} \]

Schellart, GSA Bulletin, 2008
Diversity of subduction zones

- 24 distinct subduction zones
- Some are *retreating*, some are *stationary*, few are *advancing*

Diversity of subduction zones

• 24 distinct subduction zones
• vary in lateral extent between 200-6000 km


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Global Diversity of Subduction Zones

- Individual subduction zones have variable trench curvature, variable dip along the trench, variable dip with increasing depth, and evolve with time.

- Subduction zones are dynamic features arising from slab-mantle interaction.

Controls on subducting plate motions

• plate-scale segmentation

• 16 subduction zones - 16 segments

Plate velocity vs slab width

Schellart, Stegman, et al., Science, 2010
Controls on subducting plate motions

- plate-scale segmentation
- 16 subduction zones - 16 segments

Trench retreat vs slab width

\[ v_{TL} = k_2 / (W/2 + k_3) \]

\[ R = 0.72 \]

Schellart, Stegman, et al., Science, 2010

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Controls on subducting plate motions

- plate-scale segmentation
- 16 subduction zones - 16 segments

Partitioning vs slab width

Schellart, Stegman, et al., Science, 2010

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OUTLOOK: mantle convection + subduction
Top-down model of free subduction

Stegman et al., Tectonophysics, 2010a
Top-down model of free subduction

\[ 0 = -\nabla P + \eta \nabla^2 \vec{u} - \rho g \hat{z} \]

\[ 0 = \nabla \cdot \vec{u} \]

Stegan et al., Tectonophysics, 2010a
Top-down model of free subduction

\[ 0 = -\nabla P + \eta \nabla^2 \vec{u} - \rho g \hat{z} \]
\[ 0 = \nabla \cdot \vec{u} \quad \eta_{eff} = \min \left[ \eta_0, \frac{\sigma_y}{2\sqrt{\dot{\varepsilon}_{II}}} \right] \]

Stegman et al., Tectonophysics, 2010a
Top-down model of free subduction

- 3-D mechanical model of a lithosphere with a layered structure

BUFFETT AND BECKER, JGR, 2012
Top-down model of free subduction

- 3-D mechanical model of a lithosphere with a layered structure
- nothing prescribed *a priori* except slab buoyancy and plate strength
Top-down model of free subduction

- 3-D mechanical model of a lithosphere with a layered structure
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- subduction motions (trench retreat velocity, convergence rate, and plate speed), radius of curvature, and trench curvature are all emergent from the dynamics
Top-down model of free subduction

- 3-D mechanical model of a lithosphere with a layered structure
- nothing prescribed *a priori* except slab buoyancy and plate strength
- subduction motions (trench retreat velocity, convergence rate, and plate speed), radius of curvature, and trench curvature are all *emergent* from the dynamics
- assumptions: Earth is flat, the mantle is a cube, thermodynamics do not exist in the cube, plate subducts in isolation of any other plates, mantle viscosity is Newtonian
Coupled lithosphere-mantle system

- 3-D geometry and variable viscosity of slab induces toroidal flow (T1, T2)

*after Schellart et al., 2004, Stegman et al., 2006*
Coupled lithosphere-mantle system

- 3-D geometry and variable viscosity of slab induces toroidal flow (T1, T2)
- Toroidal flow diminishes cornerflow
Coupled lithosphere-mantle system

- 3-D geometry and variable viscosity of slab induces toroidal flow (T1, T2)
- Toroidal flow diminishes cornerflow
- Trench curvature arises from slab interaction with induced flow

after Schellart et al., 2004, Stegman et al., 2006
Two modes of subduction

- Plates that are 1500 km or less in lateral extent predominantly subduct through slab rollback and trench retreat (Scotia, Calabria, Hellenic)

Schellart, Stegman, et al., Science, 2010
Narrow plates have retreating trenches

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Schellart, Stegman, et al., Science, 2010
Intermediate and wide plates

- Subduction of plates that are intermediate in width (2000-3000 km) is accommodated with both forward plate advance and trench retreat, with increasing more plate advance for wider plates (>4000 km)

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Schellart, Stegman, et al., Science, 2010
Slab pull alone explains plate motions

Schellart, Stegman, et al., Science, 2010
Slab pull alone explains plate motions

- partitioning of subduction motions
- strong dependence on slab width

Schellart, Stegman, et al., Science, 2010
Slab pull alone explains plate motions

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Schellart, Stegman, et al., Science, 2010

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Schellart, Stegman, et al., Science, 2010
Slab pull alone explains plate motions

- partitioning of subduction motions strong dependence on slab width
- simple dynamical scaling relations for a sinking oblate ellipsoid
- increasing importance of drag from toroidal component of flow around slab edges for narrow plates
- origin for narrow plates favoring trench retreat over plate advance

Schellart, Stegman, et al., Science, 2010
The Myth of how subduction works..
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The Myth of how subduction works..
Why are subduction zones curved?

- The physics that govern buckling in spherical geometry are more complicated than what Frank (1968) had originally proposed.
Why are subduction zones curved?

- The physics that govern buckling in spherical geometry are more complicated than what Frank (1968) had originally proposed.

  - Stresses generated by buckling of viscous doubly curved shells take the form of a dimpling instabilities - wavelength of cusps related to material properties.

  - No interaction with the underlying mantle --> still missing essential physics

  

  Mahadevan et al, Tectonics, 2010
Some arcs are curved the wrong way, others aren’t curved at all...

- South America the curvature changes from concave near Peru, to convex near Bolivia, back to concave in S. Chile

- Tonga-Kermedec is only curved in the very north, and is relatively straight towards New Zealand

Gudmundsson and Sambridge, JGR, 1998
Narrow plates have retreating trenches

- Numerical Model (600 km)
- Caribbean (1900 km)
- Scotia (800 km)
- Calabria (1200 km)

Govers and Wortel, EPSL, 2005
Narrow plates have retreating trenches

- Plates that have retreating trenches become more curved over time and produce flat-lying slab geometries on top of the lower mantle.
Wider plates have stationary trenches

- Numerical Model (2000 km)

- Mariana (3000 km)

Sdrolias and Mueller, G-Cubed, 2006
Intermediate and wide plates

- Plates that have stationary trenches develop along-trench variations of curvature over time and produce piles of folded slab atop the lower mantle.
Very wide plates have retreating edges

- Numerical Model (6000 km)

- South America (6000 km)

Development of trench curvature

- Free subduction model done in 3D spherical geometry

Morra et al., G-Cubed, 2012
Development of trench curvature

- Free subduction model done in 3D spherical geometry
- Lengthscale of induced mantle flow depends on length of plate
- Toroidal component of induced mantle flow dominant in determining shape of the slab (expressed as trench curvature at the surface)

*Morra et al., G-Cubed, 2012*
Top-down model of free subduction

Morra et al., G-Cubed, 2012
Styles of subduction

- Subduction behavior characterized by 100’s of previous experiments (both numerical and laboratory)
  - C.f. work by Becker, Faccenna, Funicello, Kaus, Ribe, Enns, Schellart, Capitanio, Morra, Goes, Kincaid, Bellahsen, Royden, Husson, DiGiuseppe, and many others

- 5 distinct subduction styles observed

Stegman et al., Tectonophysics, 2010

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Kinematics: plate motions and trench migration

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Two modes of subduction: partitioning

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Trench curvature: induced by mantle flow

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Slab morphology: trench motion + layered visc

CHAPTER 5
Outlook: mantle convection + subduction
Slab Morphology: highly variable

van der Hilst and de Hoop, GJI, 2005
Replumaz et al, EPSL, 2004

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Flat-lying slabs under retreating trenches

- Calabria

Wortel and Spakman, Science, 2000

- Japan Sea

Flat-lying slabs under retreating trenches

- Plates that have retreating trenches produce flat-lying slab geometries on top of the lower mantle
Slab morphology indicates folded piles

- Slabs in the upper mantle are about 100 km thick as imaged by tomography (best with dense station coverage and high seismicity)

- Slabs appear to become 3-5x thicker upon entering the lower mantle (is this due to the resolution of tomography or a physical effect?)

Zhao, PEPI, 2004

Ribe et al., EPSL, 2007
Folded slabs under stationary trenches

- Stationary trenches lead to slab piles

van der Hilst and Seno, EPSL, 1995
Widiyantoro et al., GJI, 2000

Widiyantoro et al. 2000

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Slab folding and piling at 660 km

Stegman et al., Tectonophysics, 2010a
Folded slabs under stationary trenches

- Plates with stationary trenches produce slab piles on top the lower mantle
Folded slabs under stationary trenches

- Folding of weak slabs atop lower mantle due to increase in viscosity
- Increases diffusion time of thermal heterogeneities, concentrates buoyancy
- 660 km interface is low-pass filter

sinking velocity in upper mantle ~7cm/yr
slabs reach 660 km depth in 8 Myr
not diffusing too much in transit to 660

Ribe et al., EPSL, 2007
Summary of trench and slab behavior

slab morphology = f(radial layering of viscosity mantle, slab strength, plate width)

• Narrow plates: trench retreat and flat-lying slabs

• Wider plates: quasi-stationary trenches and folded slab piles

• Weak slabs/bending regions indicated by development of lateral trench curvature and recumbent folding of slabs into piles
Ingredients for single-sided subduction

- weak subduction hinges (able to bend easily)
  - arising from brittle crust
- free surface (also promotes bending)
- strong core in slab (able to maintain stress guide to the trailing plate)
- low viscosity wedge (keep upper plate decoupled from subducting plate)
  - arises from dehydration of the slab and wet sediments

see Review paper by Gerya (2011), Journal of Geodynamics

Gerya et al., (2008)
Wedge hydration -> one-sided subduction

Gerya et al., (2008)
Development of back-arc basin

Model includes spontaneously bending slab, free erosion/sedimentation upper surface, variable non-prescribed subduction rate, visco-plastic pressure-temperature-stress-dependent rheology, non-steady temperature field, spontaneous extension of the overriding plate associated with back arc basin development, slab dehydration and water transport above the slab associated with progressive mantle wedge hydration, fluid fluxed and decompression melting of the mantle wedge, melt extraction and volcanic crust growth

Gerya and Meilick, (2010)
Petrologic feedback and crustal growth

Vogt et al., (2012)

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Predicting Plate Motions with Convection

- Turns out it is not an easy problem to solve at all, but there is progress
One-sided Subduction within Convection

- “Earth”-like subduction with strongly asymmetric, migrating downwellings
One-sided Subduction within Convection

Two-sided, symmetric
initial wedge size: 50 km

Two-sided, asymmetric
initial wedge size: 100 km

One-sided, asymmetric
initial wedge size: 150 km

``Earth”-like subduction seems to require maintaining a low-viscosity wedge

most likely mechanism: slab dehydration
A different sort of laboratory

- simulation software
- visualization software
- high-performance computing
- develop computer models that help us understand planets
Regime I: Viscous beam mode

- Very Strong Slabs
- fast subduction velocities
- approx. 2-D, linear trench
- trench retreat dominates
- flat-lying slab
- large radius of curvature
Regime I: Viscous beam mode

Stegman et al., Tectonophysics, 2010a
Regime II: Advance-Fold-Retreat mode

- Heavy, Strong Slabs
- moderate subduction velocities
- slightly concave trench
- trench advance transitions into retreat
- slab has a single recumbent fold
- medium radius of curvature

Stegman et al., Tectonophysics, 2010a
Regime II: Advance-Fold-Retreat mode

Stegman et al., Tectonophysics, 2010a
Regime III: Advancing mode

- Strong Slabs
  - moderate subduction velocities
  - slightly concave, advancing trench
  - strength of plate supports entire weight of the slab
  - slab rollover geometry produces after interaction with 660 km
  - medium radius of curvature

Stegman et al., Tectonophysics, 2010a
Regime III: Advancing mode

Stegman et al., Tectonophysics, 2010a
Regime IV: Retreating mode

- Heavy, Weak Slabs
  - faster subduction velocities
  - highly curved trench
  - dominated by trench retreat
  - flat-lying, backwards-draping slabs atop 660 km
  - medium radius of curvature

Stegman et al., Tectonophysics, 2010a
Regime IV: Retreating mode

Stegman et al., Tectonophysics, 2010a
Regime V: Folding mode

- Weak Slabs
  - faster subduction velocities
  - highly curved trench
  - subducts through trench retreat and plate advance (partitioning depends on plate width)
  - accumulation of recumbent folds into slab pile
  - small radius of curvature

Stegman et al., Tectonophysics, 2010a
New suite of numerical models

Styles of subduction

a. Style I
b. Style II
c. Style III
d. Style IV
e. Style V

Viscous Beam Mode
Advance-Fold-Retreat
Advancing Mode
Retreating Mode
Folding Mode

Stegman et al., Tectonophysics, 2010
Observed radius of curvature in nature

Wu, Conrad, et al., EPSL, 2008

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