Geodynamics

Day	Lecturer	Lectures
1	LHK	Introduction
1	CLB	Dynamical Observations of the Earth
3	PVK	Present-day mantle convection: slabs, plumes and hotspots
4	PVK	Tutorial 1: Mantle convection modeling
5	CLB	Instantaneous flow models: Theory and applications
5	CLB	Tutorial 2: Geoid modeling
8	LHK	Heat budget, thermal evolution models
8	LHK/PVK	Tutorial 3: Thermal evolution modeling
10	PVK	Long-term evolution of the mantle, looking back in
12	LHK	Thermochemical Convection
12	LHK/PVK	Tutorial 4: Chemical Geodynamics

Geological and Geophysical Observations

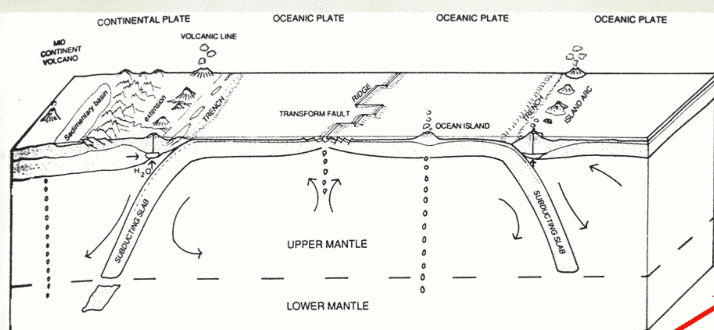
Lecture 1: Geodynamics

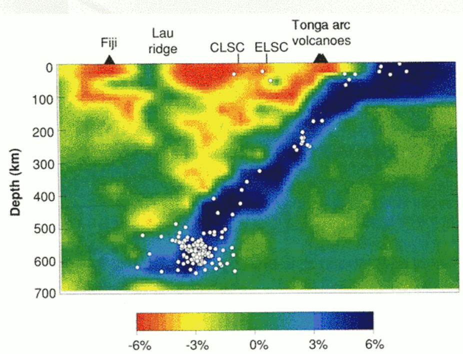
Carolina Lithgow-Bertelloni

Types of Observations

- Elements of Plate Tectonics
  - Plate kinematics/dynamics
    - Poloidal/Toroidal partitioning
      - Nature of plates
      - Nature of plate driving forces
  - Implications
    - Mantle convection
    - Speed (absolute viscosity)
    - Coupling to mantle (viscosity structure-radial, geographical)
- Plate motions past and present
  - Magnetic anomalies
  - Plate reconstructions
    - Changes in Plate Dynamics?
    - Subduction History
- Topography and Heat flow
  - Bathymetry and Heat Flow
  - Half-space cooling, plate model
    - Secondary convection
  - Dynamic topography
    - Flooding record
    - Sea level
- Mass distribution and change
  - Post-Glacial Rebound
  - Geoid and free air gravity
    - Viscosity structure
  - Geoid and topography over subduction zones

Plates ⟷ Mantle Convection





Continuous generation of dynamical (thermal) + geochemical (compositional) = seismic heterogeneity

[including phase transitions (TZ!!)]

[*Zhao et al.*, 1997]

Mantle Convection and Plate Tectonics

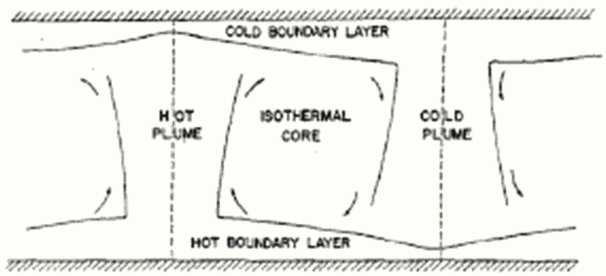


FIGURE 7. Illustration of the boundary-layer model for two-dimensional thermal convection.

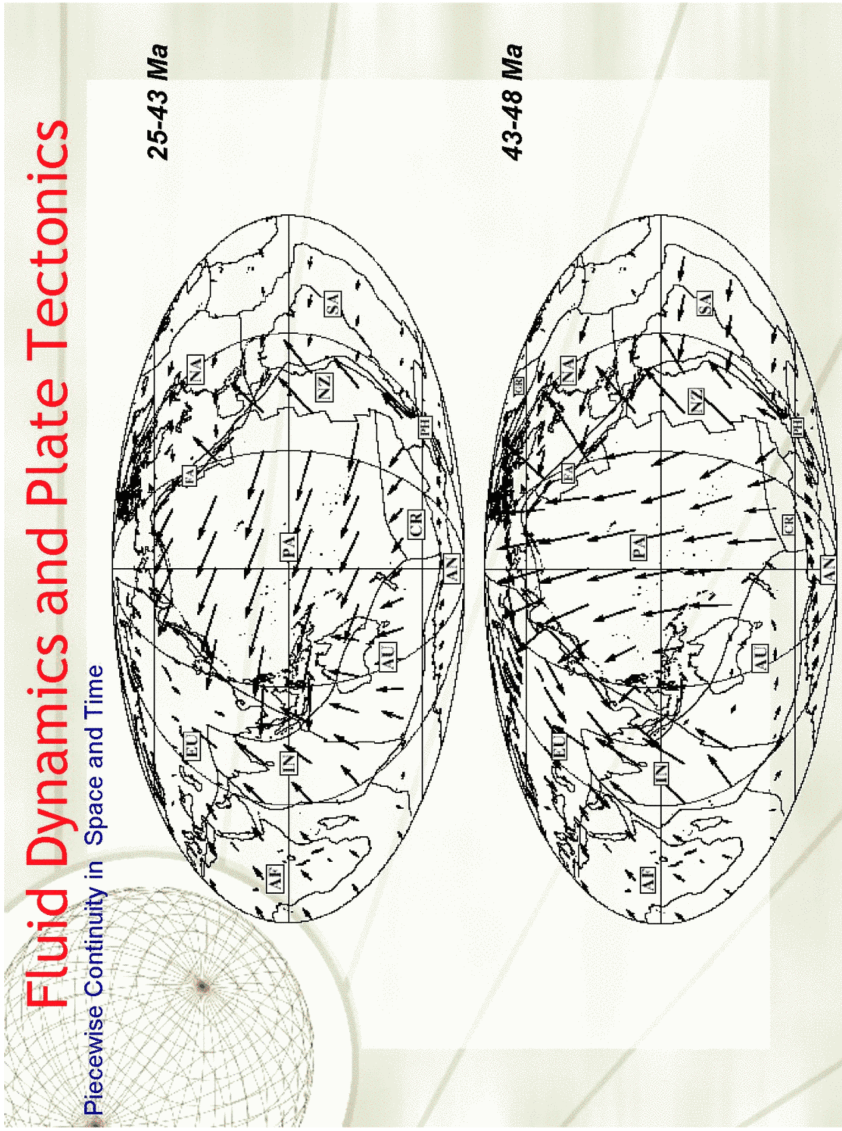
[*Turcotte and Oxburgh*, 1972, Annual Reviews of Fluid Mechanics]

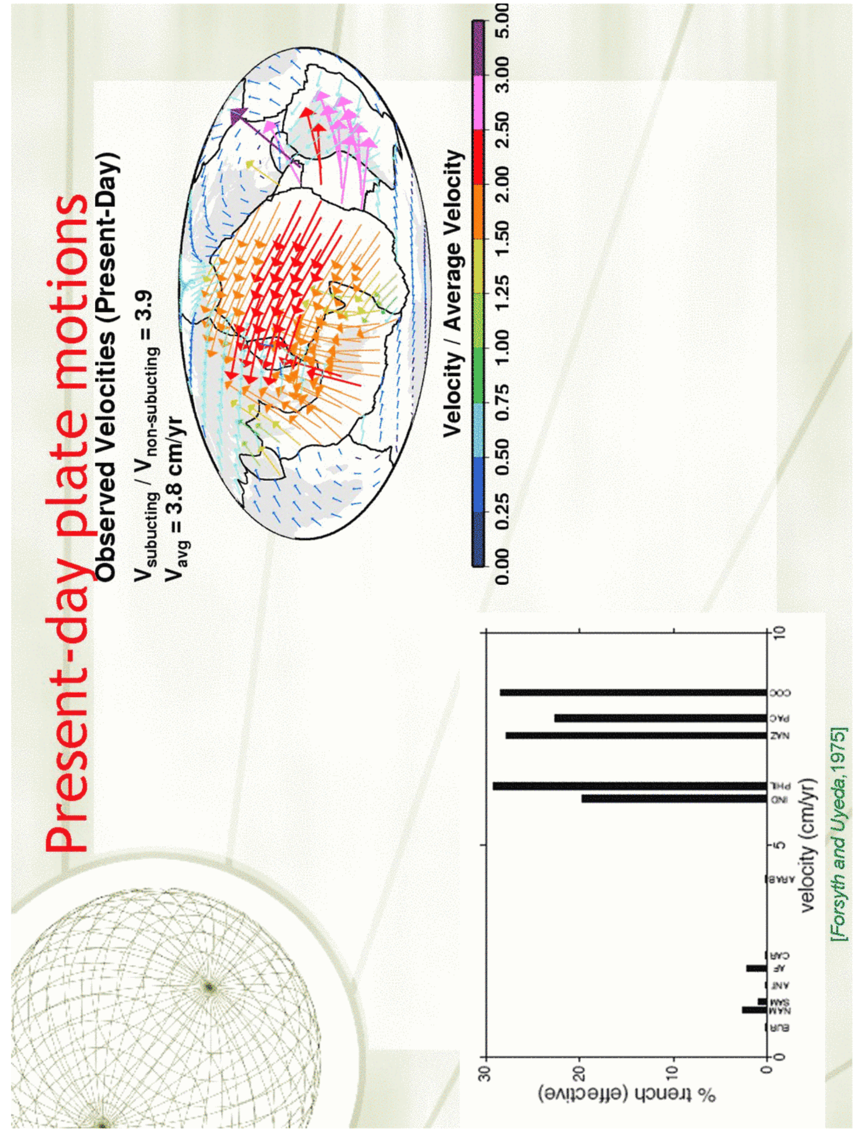
What is a plate?

- Lithospheric Fragment
  - Strong non-deforming interior
    - Diffuse plate boundaries?
  - Narrow, weak, rapidly deforming boundaries
    - Ridges-passive
    - Subduction zones-asymmetric
    - Transforms?
  - Motion described by rotation

- Plate motions
  - Non-accelerating
  - Piecewise continuous velocity field in space and time
    - Hard for fluid dynamics
  - Significant toroidal motion (I.e transform-like)

- Part of convecting system (top thermal boundary layer…)
  - Continental plates


Fluid Dynamics and Plate Tectonics
Piecewise Continuity in Space and Time
25-43 Ma
43-48 Ma
NA
SA
NZ
PH
EA
PA
CR
AN
AU
EU
IN
AF


Present-day plate motions
Observed Velocities (Present-Day)
$V_{subucting} / V_{non-subucting} = 3.9$
$V_{avg} = 3.8$ cm/yr
Velocity / Average Velocity
0.00 0.25 0.50 0.75 1.00 1.25 1.50 2.00 2.50 3.00 5.00
% trench (effective)
velocity (cm/yr)
[Forsyth and Uyeda, 1975]

Toroidal Motions

-Homogeneous convecting fluid-No toroidal power

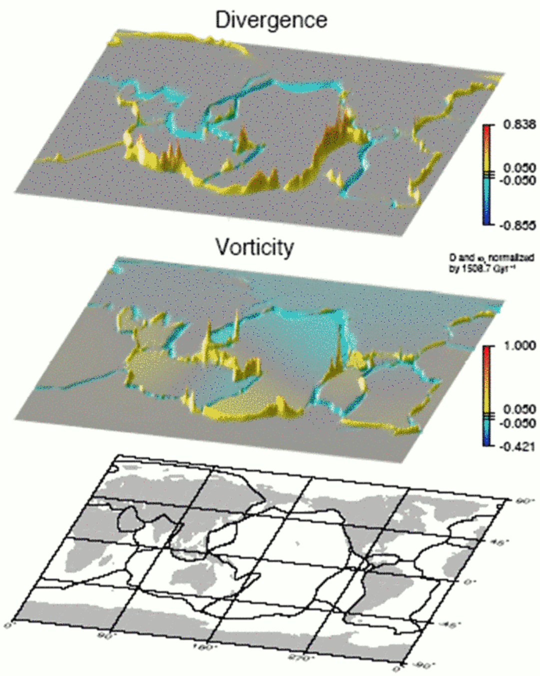
-Lateral viscosity variations i.e. PLATES!

-But why? Dissipates no heat

-Ratio: Plate characteristic

$$\nabla_H \bullet \vec{V} = \sum_l \sum_m D_e^m y_e^m$$ Horizontal divergence (poloidal)

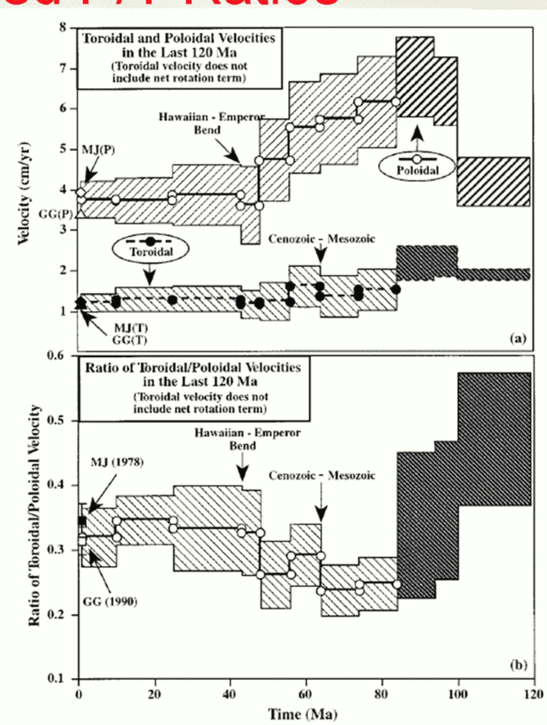
$$(\nabla \times \vec{v}) \bullet \vec{r} = \sum_l \sum_m V_e^m y_e^m$$ Radial vorticity (toroidal)



[*Dumoulin et al.*, 1998]

Observed P/T Ratios

- P/T power not equipartitioned
  - Reference Frames!
- Toroidal power
  - Pacific basin (largely)
  - Oblique subduction

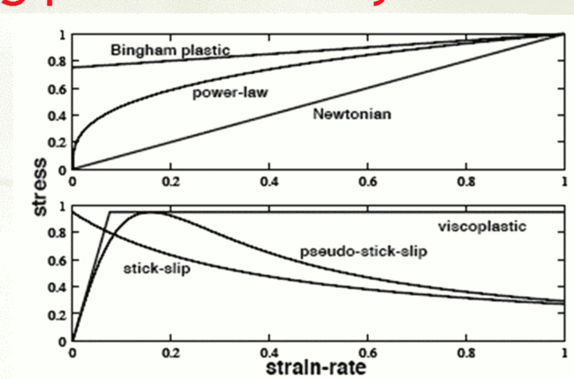


[*Lithgow-Bertelloni et al.*, 1993]

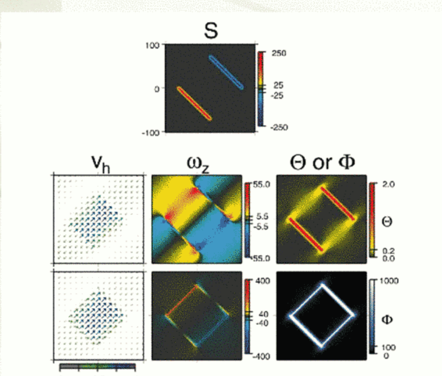
Implications of plate kinematic observations

- Nature of plates, i.e. What is a plate?
  - "Exotic" Rheologies with a physical basis
- Connection to mantle convection
  - Effect of changes in plate motion on heterogeneity
  - Viscosity structure (plate mantle coupling)
    - Radial and geographical variability
    - Strength of slabs, Deep Earthquakes
- Changes in the character of plate tectonics with time?
  - Importance of plumes as plate driving force?

Making plates: theory



- Shear-localizing feedback mechanisms required
  - Broad, strong plate-like regions
  - Weak, narrow plate boundaries
  - Toroidal motion (almost transforms)
  - Ridge localization
- Physical basis?
- Many characteristics not reproduced
  - Subduction initation
  - Asymmetry
  - Temporal evolution and plate rearrangement



[*Bercovici*, 2003]

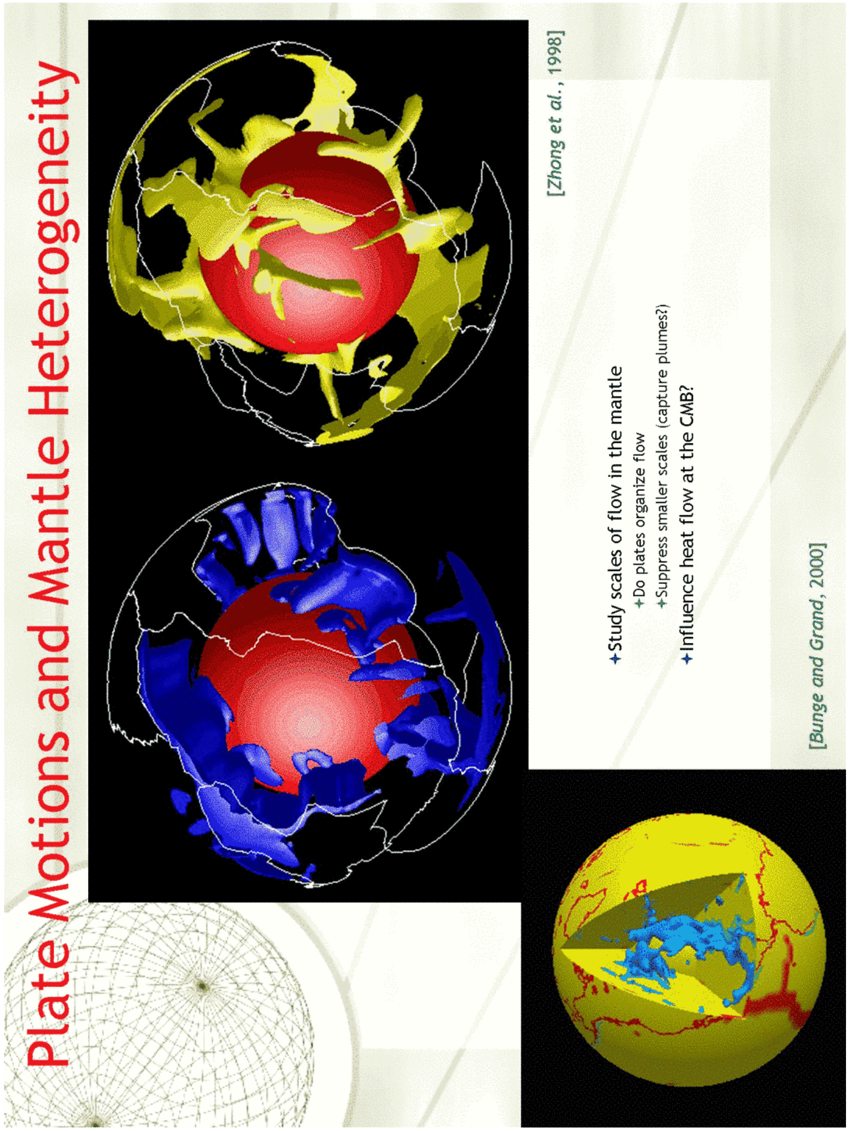


Plate Motions and Mantle Heterogeneity
[Zhong et al., 1998]
Study scales of flow in the mantle
Do plates organize flow
Suppress smaller scales (capture plumes?)
Influence heat flow at the CMB?
[Bunge and Grand, 2000]

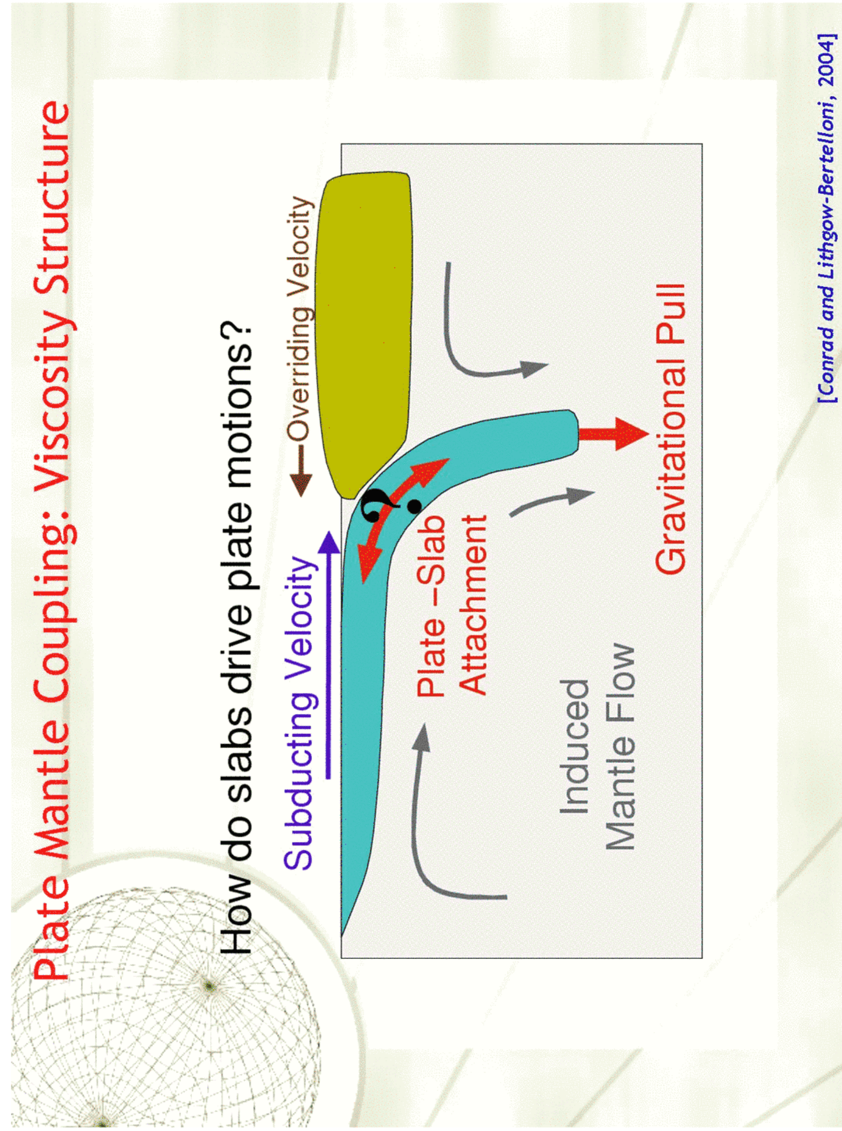


Plate Mantle Coupling: Viscosity Structure
How do slabs drive plate motions?
Subducting Velocity
Overriding Velocity
?
Plate –Slab
Attachment
Induced
Mantle Flow
Gravitational Pull
[Conrad and Lithgow-Bertelloni, 2004]

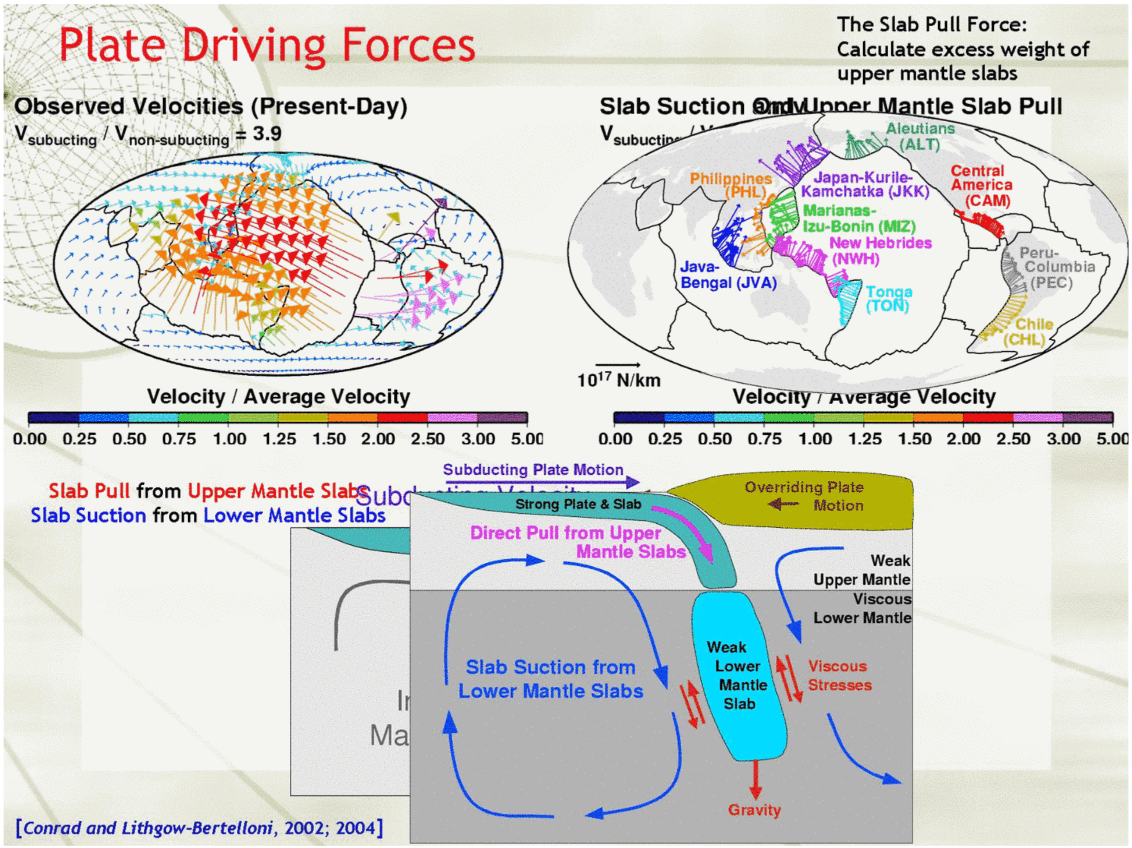


Plate Driving Forces
The Slab Pull Force:
Calculate excess weight of
upper mantle slabs
Observed Velocities (Present-Day)
V subucting / V non-subucting = 3.9
Velocity / Average Velocity
0.00 0.25 0.50 0.75 1.00 1.25 1.50 2.00 2.50 3.00 5.00
Slab Suction and Upper Mantle Slab Pull
Aleutians (ALT)
Philippines (PHL)
Japan-Kurile-Kamchatka (JKK)
Central America (CAM)
Marianas-Izu-Bonin (MIZ)
New Hebrides (NWH)
Java-Bengal (JVA)
Tonga (TON)
Peru-Columbia (PEC)
Chile (CHL)
10^17 N/km
Velocity / Average Velocity
0.00 0.25 0.50 0.75 1.00 1.25 1.50 2.00 2.50 3.00 5.00
Slab Pull from Upper Mantle Slabs
Slab Suction from Lower Mantle Slabs
Subducting Plate Motion
Overriding Plate Motion
Strong Plate & Slab
Direct Pull from Upper Mantle Slabs
Weak Upper Mantle
Viscous Lower Mantle
Weak Lower Mantle Slab
Slab Suction from Lower Mantle Slabs
Viscous Stresses
Gravity
[Conrad and Lithgow-Bertelloni, 2002; 2004]

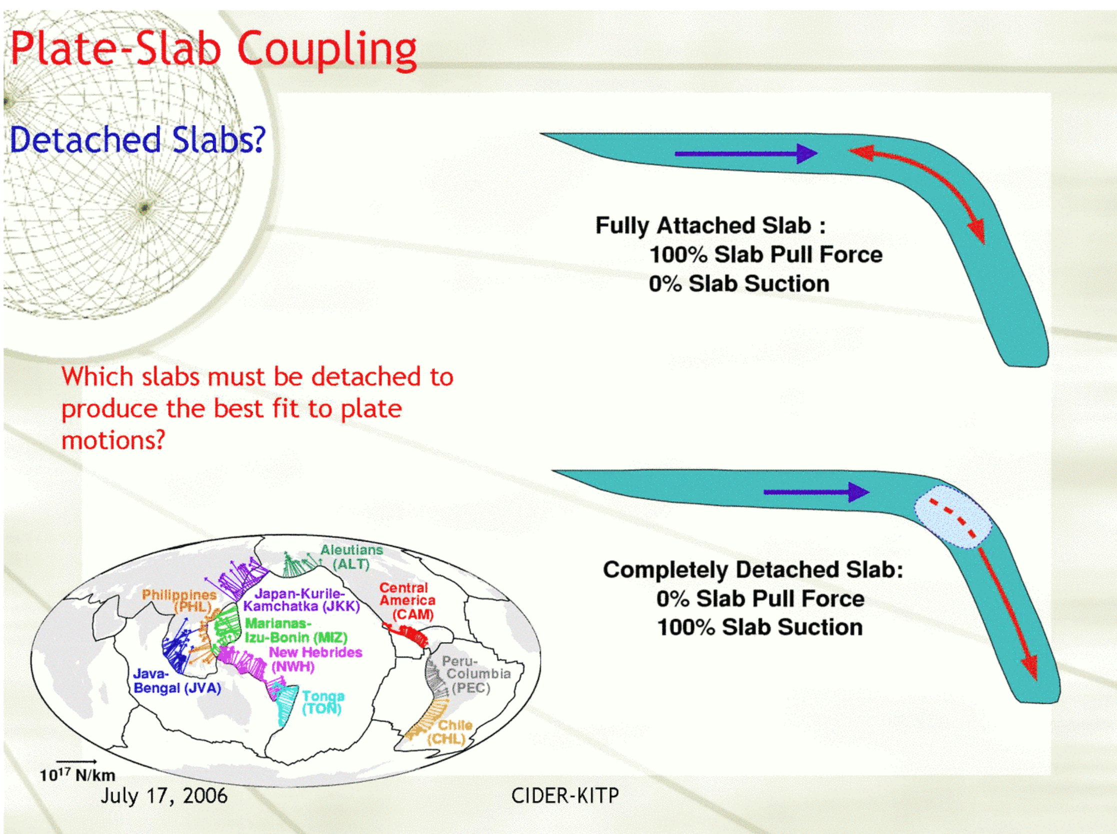


Plate-Slab Coupling
Detached Slabs?
Fully Attached Slab :
100% Slab Pull Force
0% Slab Suction
Which slabs must be detached to produce the best fit to plate motions?
Completely Detached Slab:
0% Slab Pull Force
100% Slab Suction
Aleutians (ALT)
Philippines (PHL)
Japan-Kurile-Kamchatka (JKK)
Central America (CAM)
Marianas-Izu-Bonin (MIZ)
New Hebrides (NWH)
Java-Bengal (JVA)
Tonga (TON)
Peru-Columbia (PEC)
Chile (CHL)
10^17 N/km
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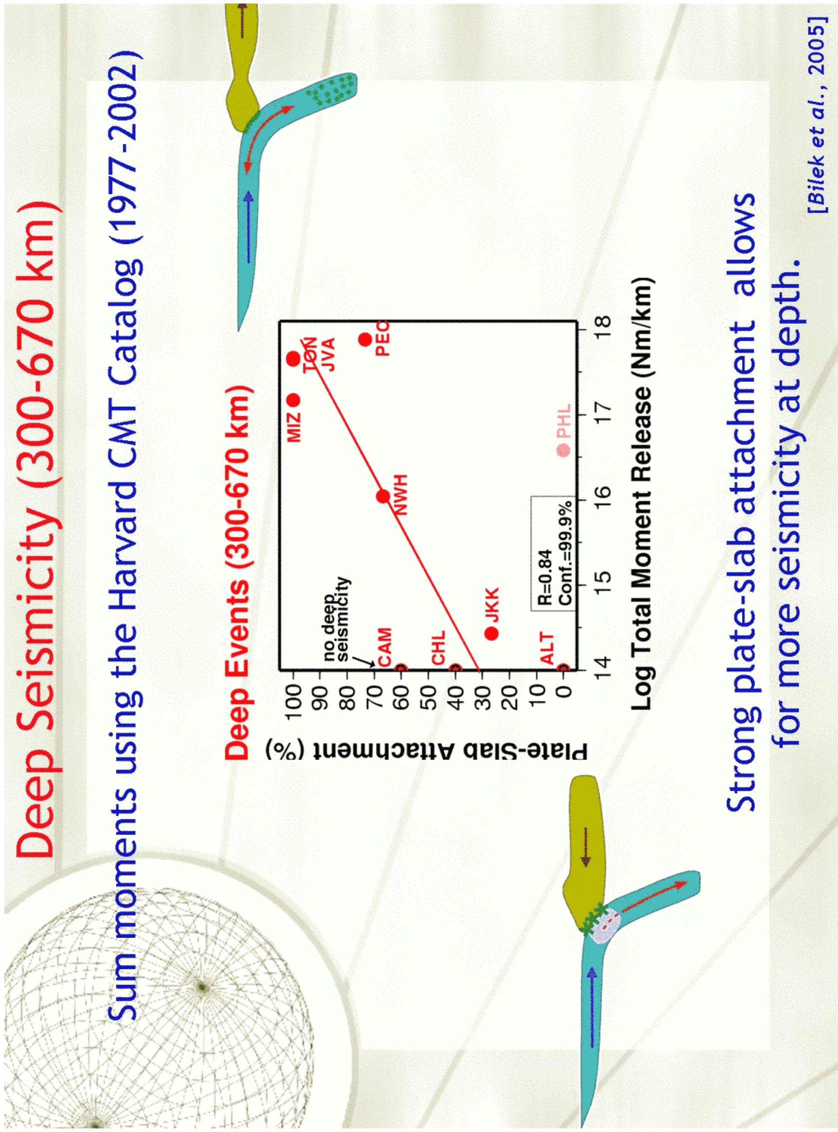
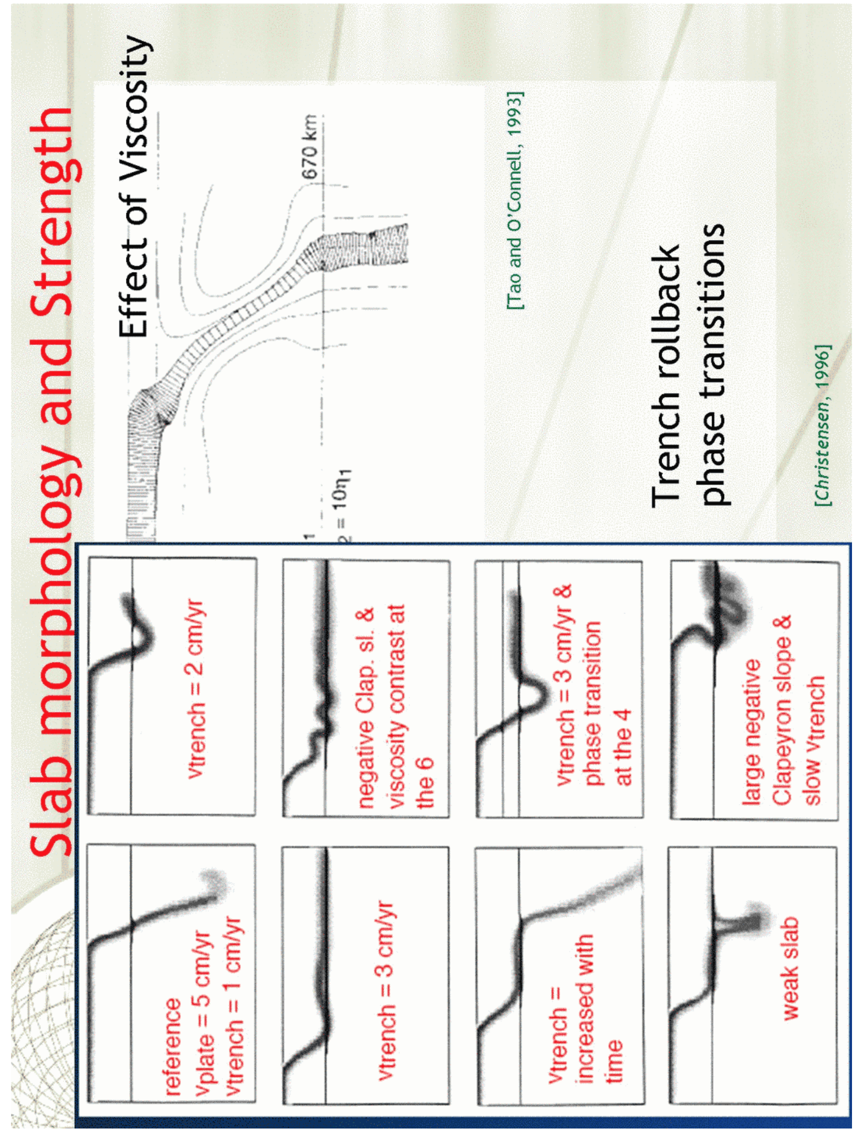
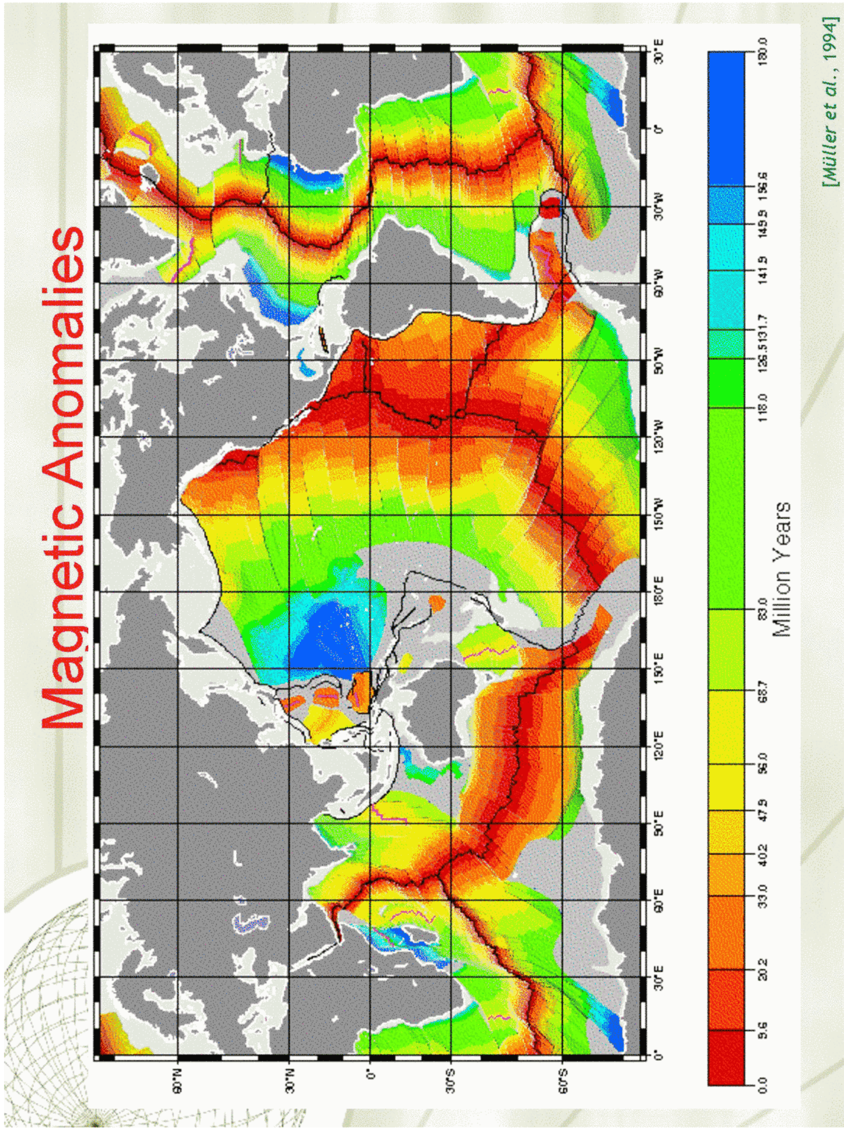

Deep Seismicity (300-670 km)
Sum moments using the Harvard CMT Catalog (1977-2002)
Deep Events (300-670 km)
Plate-Slab Attachment (%)
Log Total Moment Release (Nm/km)
MIZ
TON
JVA
PEC
NWH
PHL
JKK
CAM
CHL
ALT
no deep seismicity
R=0.84
Conf.=99.9%
Strong plate-slab attachment allows for more seismicity at depth.
[Bilek et al., 2005]


Slab morphology and Strength
Effect of Viscosity
670 km
[Tao and O'Connell, 1993]
Trench rollback
phase transitions
[Christensen, 1996]
reference
vplate = 5 cm/yr
vtrench = 1 cm/yr
vtrench = 2 cm/yr
vtrench = 3 cm/yr
negative Clap. sl. & viscosity contrast at the 6
Vtrench = increased with time
vtrench = 3 cm/yr & phase transition at the 4
weak slab
large negative Clapeyron slope & slow vtrench


Magnetic Anomalies
[Müller et al., 1994]
Million Years

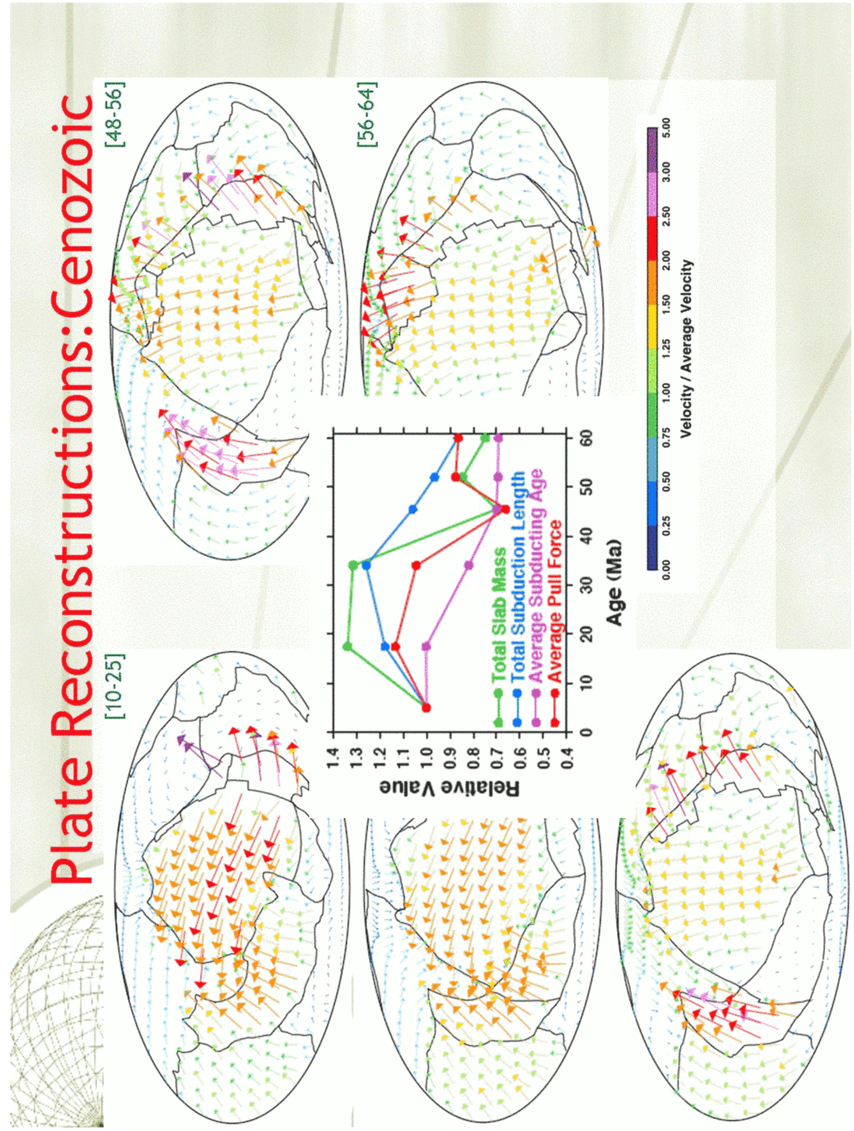
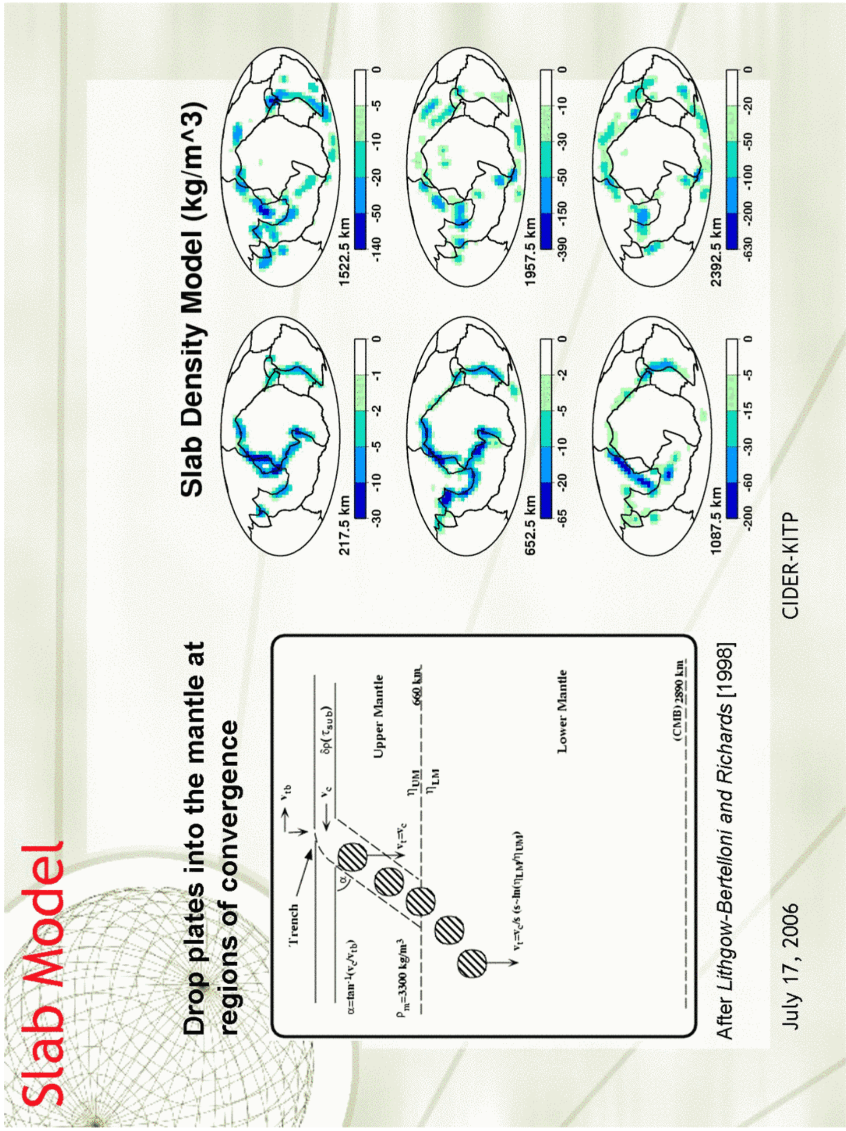


Plate Reconstructions:Cenozoic
[48-56]
[56-64]
[10-25]
Total Slab Mass
Total Subduction Length
Average Subducting Age
Average Pull Force
Age (Ma)
Relative Value
Velocity / Average Velocity


Slab Model
Drop plates into the mantle at regions of convergence
Trench
Upper Mantle
660 km
Lower Mantle
(CMB) 2890 km
Slab Density Model (kg/m^3)
217.5 km
-30 -10 -5 -2 -1 0
652.5 km
-65 -20 -10 -5 -2 0
1087.5 km
-200 -60 -30 -15 -5 0
1522.5 km
-140 -50 -20 -10 -5 0
1957.5 km
-390 -150 -50 -30 -10 0
2392.5 km
-630 -200 -100 -50 -20 0
After Lithgow-Bertelloni and Richards [1998]
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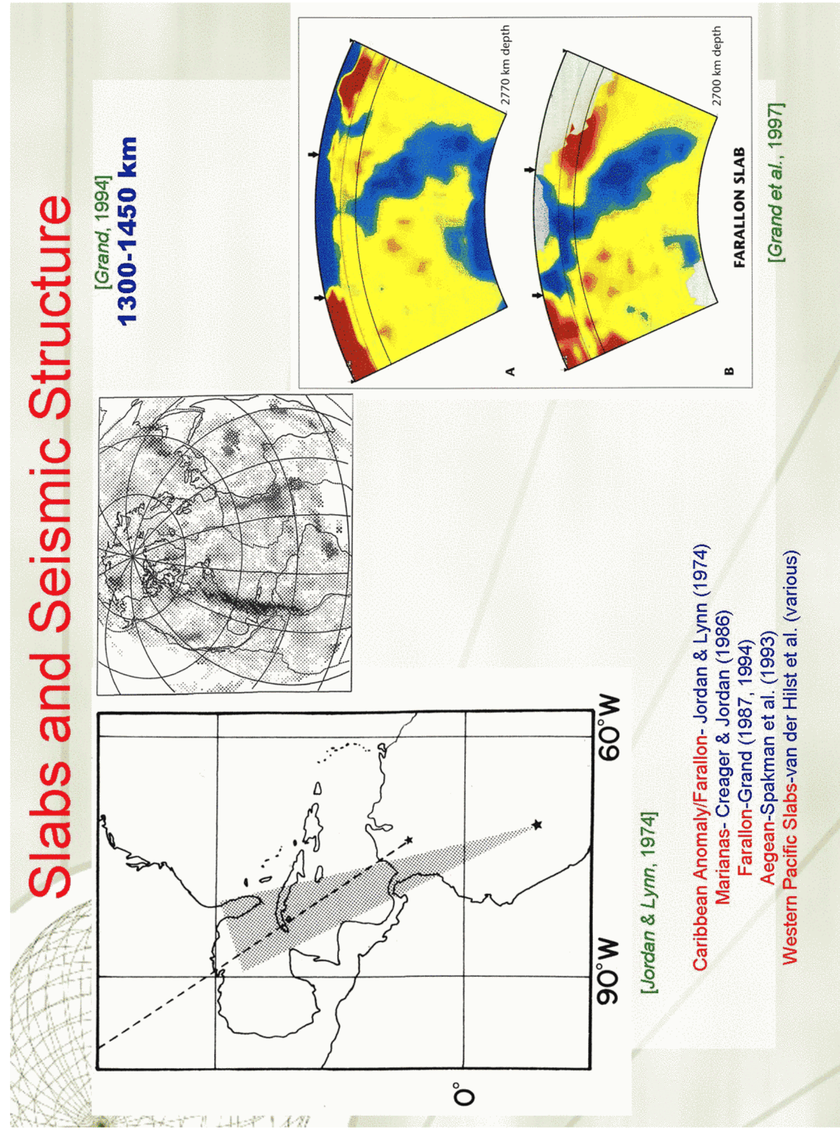
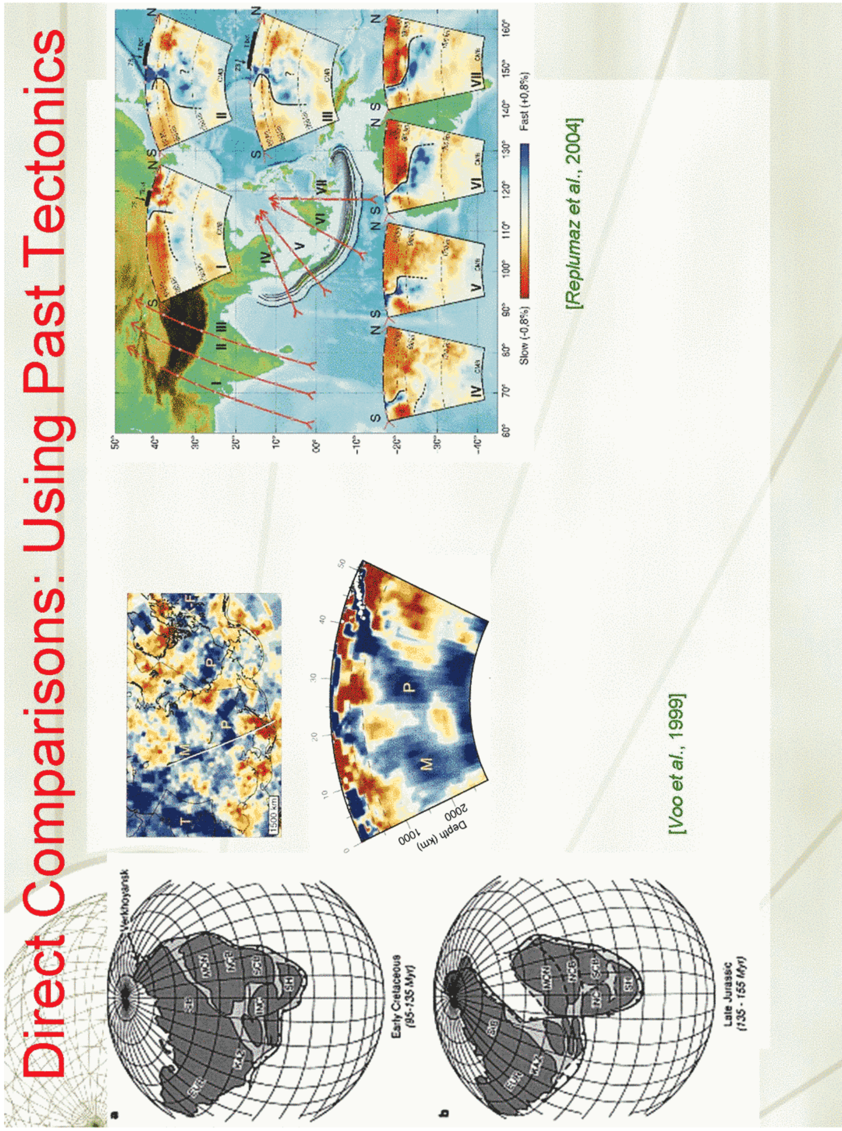
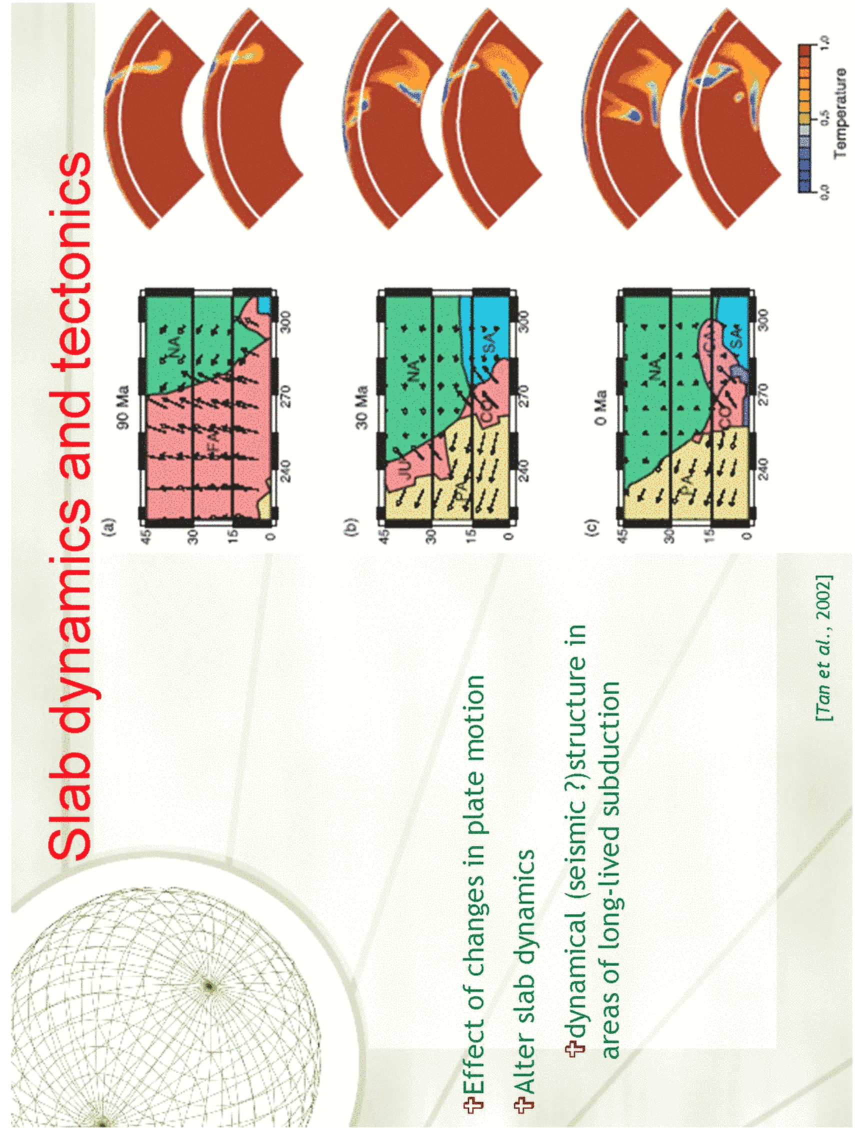
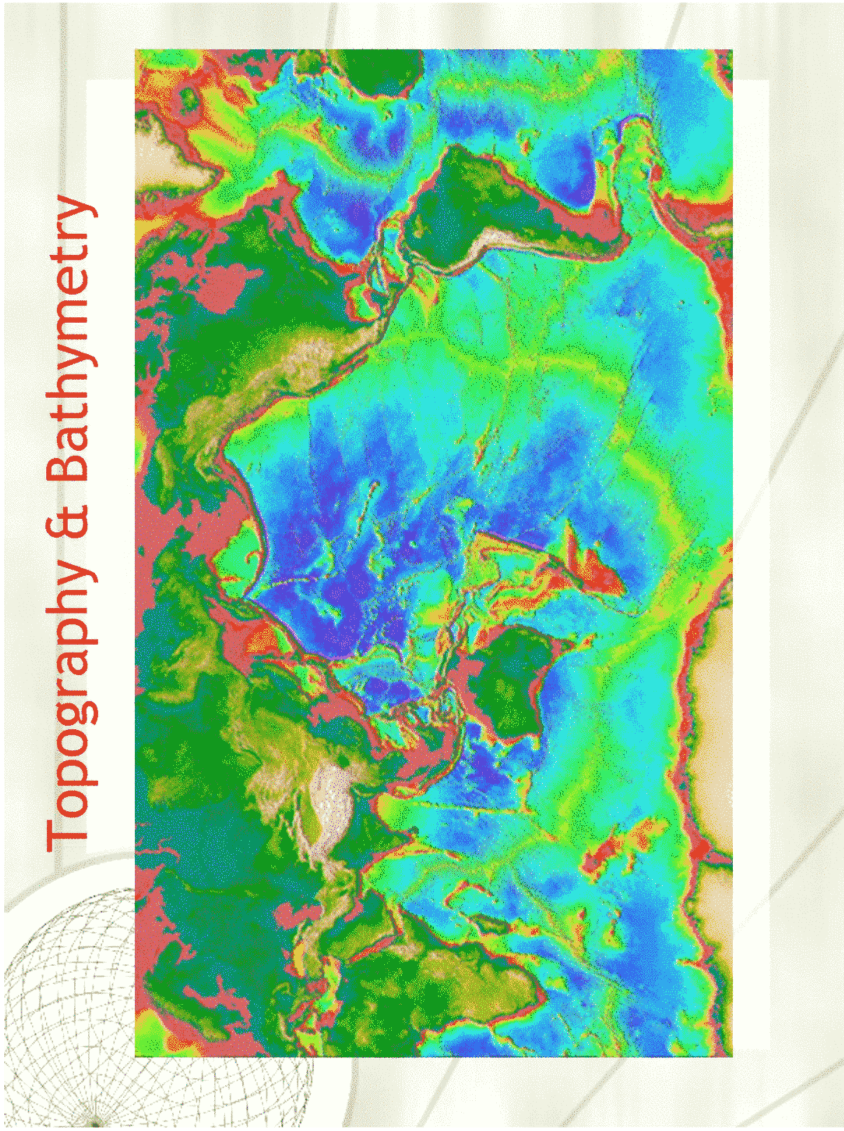
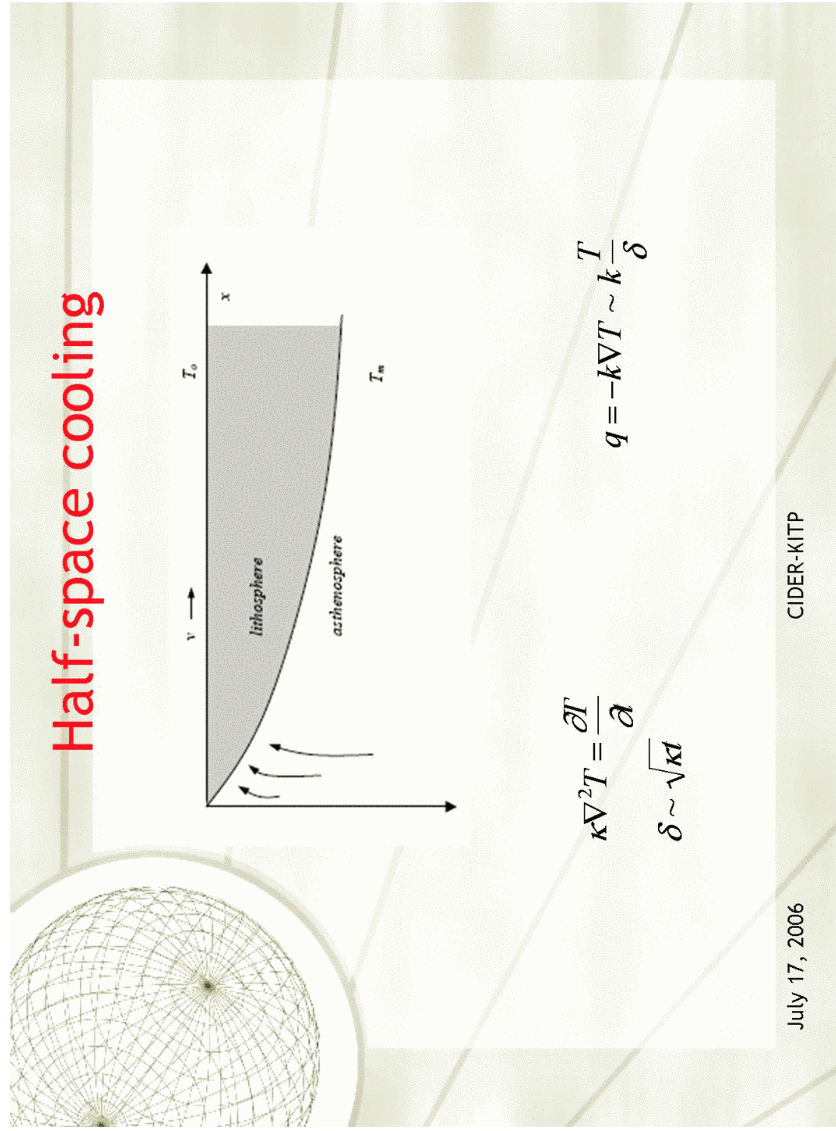

Slabs and Seismic Structure
[Grand, 1994]
1300-1450 km
2770 km depth
2700 km depth
A
B
FARALLON SLAB
[Grand et al., 1997]
0°
90°W
60°W
[Jordan & Lynn, 1974]
Caribbean Anomaly/Farallon- Jordan & Lynn (1974)
Marianas- Creager & Jordan (1986)
Farallon-Grand (1987, 1994)
Aegean-Spakman et al. (1993)
Western Pacific Slabs-van der Hilst et al. (various)


Direct Comparisons: Using Past Tectonics
Verkhoyansk
Early Cretaceous (95-135 Myr)
Late Jurassic (135 - 155 Myr)
Depth (km)
[Voo et al., 1999]
[Replumaz et al., 2004]


Slab dynamics and tectonics
Effect of changes in plate motion
Alter slab dynamics
dynamical (seismic ?)structure in areas of long-lived subduction
90 Ma
30 Ma
0 Ma
Temperature
[Tan et al., 2002]


Topography & Bathymetry


Half-space cooling
v
lithosphere
asthenosphere
T_o
T_m
x
$\kappa\nabla^2 T = \frac{\partial T}{\partial t}$
$\delta \sim \sqrt{\kappa t}$
$q = -k\nabla T \sim k\frac{T}{\delta}$
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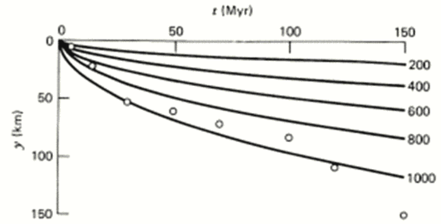


Figure 4-24 The solid lines are isotherms, $T - T_s$ (°K), in the oceanic lithosphere from Equation (4-125). The data points are the thicknesses of the oceanic lithosphere in the Pacific determined from studies of Rayleigh wave dispersion data. (From A. R. Leeds, L. Knopoff, and E. G. Kausel, Variations of upper mantle structure under the Pacific Ocean, *Science*, **186**, 141–143, 1974.)

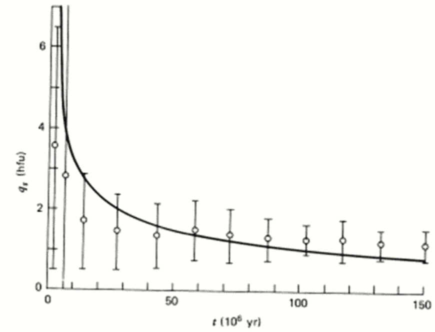
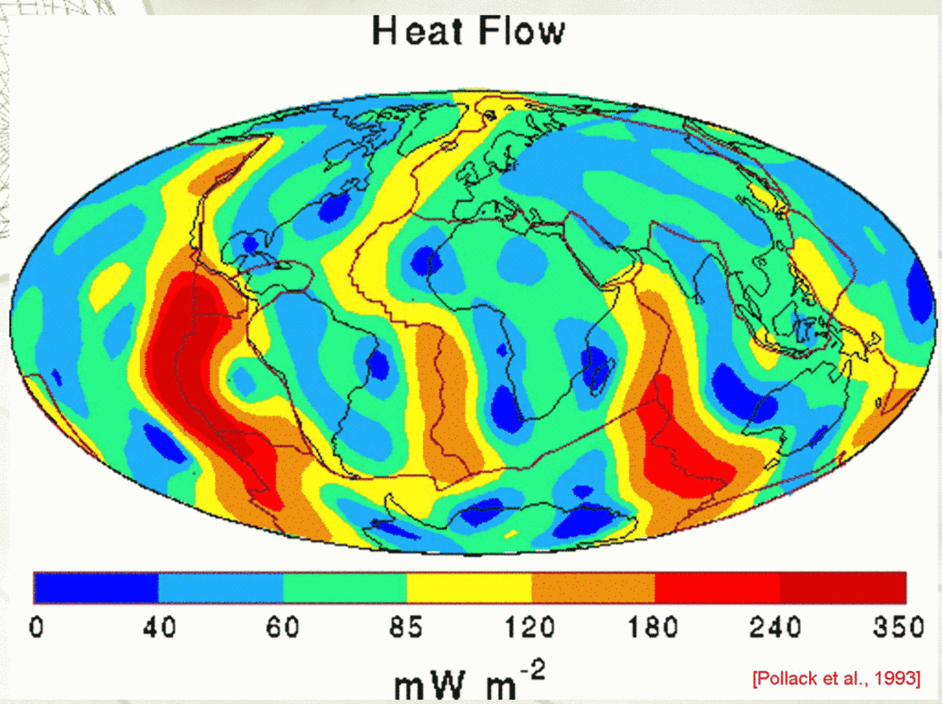
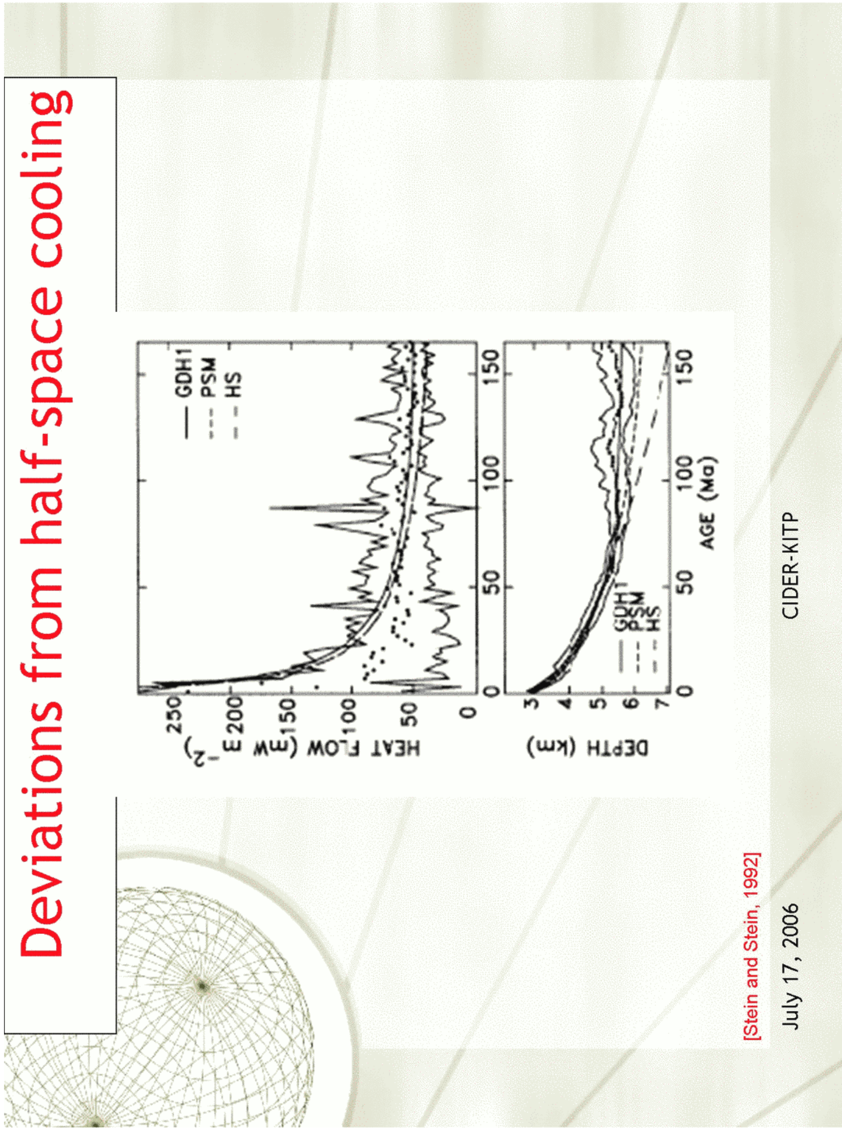


Figure 4-25 Mean values and standard deviations of ocean floor heat flow measurements as functions of age compared with Equation (4-127). Data from J. G. Sclater, C. Jaupart, and D. Galson, The heat flow through oceanic and continental crust and the heat loss of the Earth, *Reviews of Geophys. and Space Physics*, **18**, 269–311, 1980.

Global Heat Flow




Deviations from half-space cooling
HEAT FLOW (mW m^-2)
DEPTH (km)
AGE (Ma)
GDH1
PSM
HS
[Stein and Stein, 1992]
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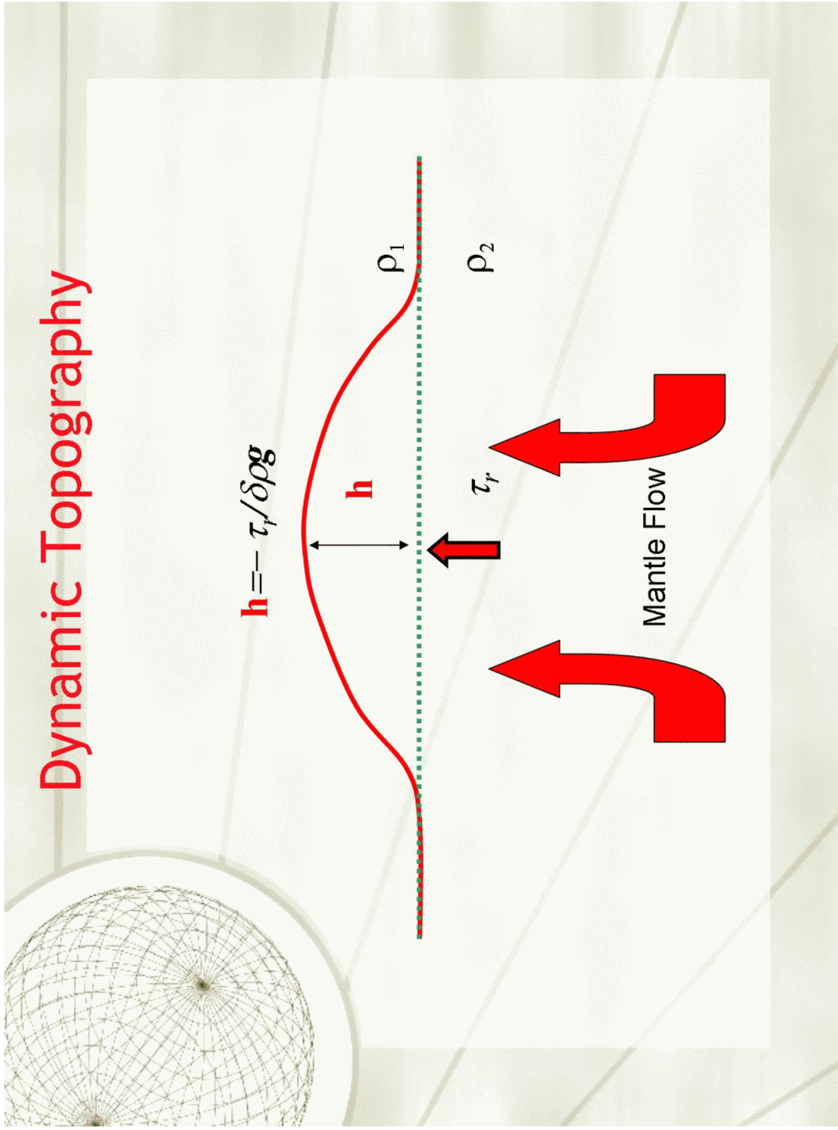
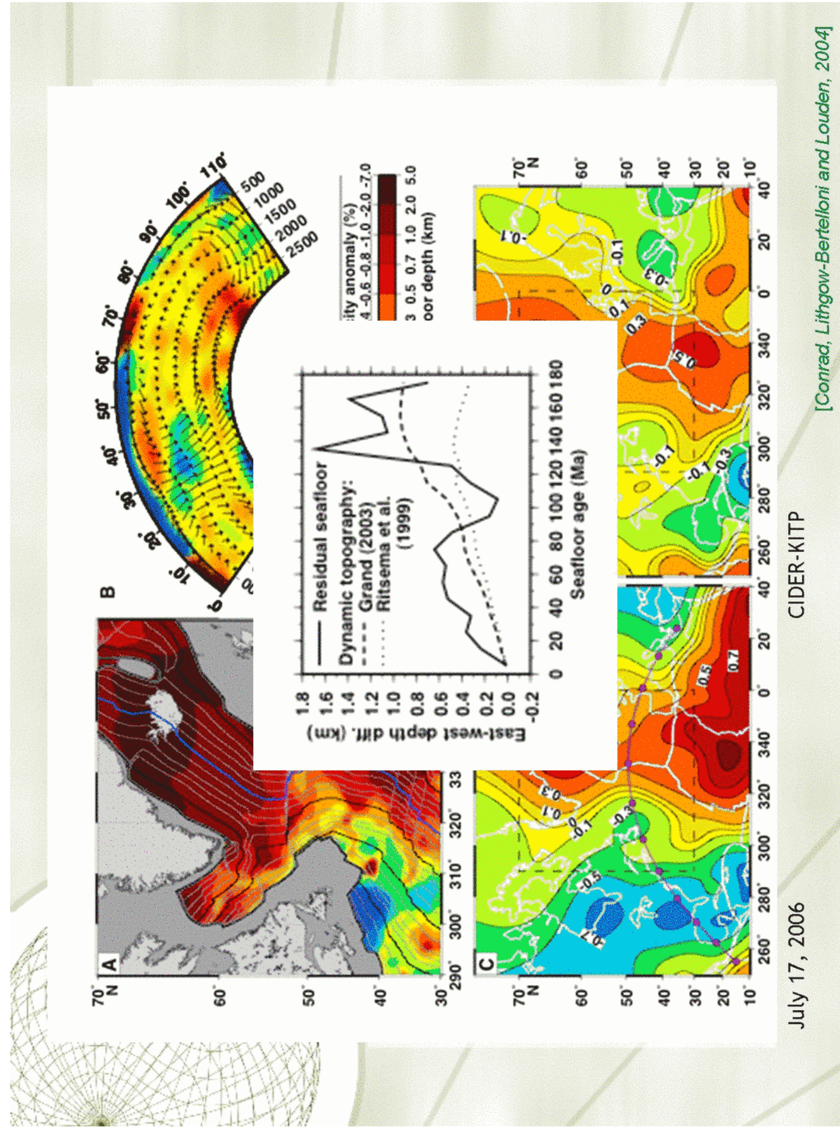
Contributions to Topography
τr
Mantle Flow
Factors:
Isostatic balance of crust
Orogenesis
short λ uncompensated
Epeirogeny
Long λ
Tectonic uplift; post-glacial rebound; dynamic topography (Mitrovica et al., 1989; Gurnis, 1993)


Dynamic Topography
h=− τr/δρg
h
ρ1
ρ2
τr
Mantle Flow


A
B
C
Residual seafloor
Dynamic topography:
Grand (2003)
Ritsema et al. (1999)
East-west depth diff. (km)
Seafloor age (Ma)
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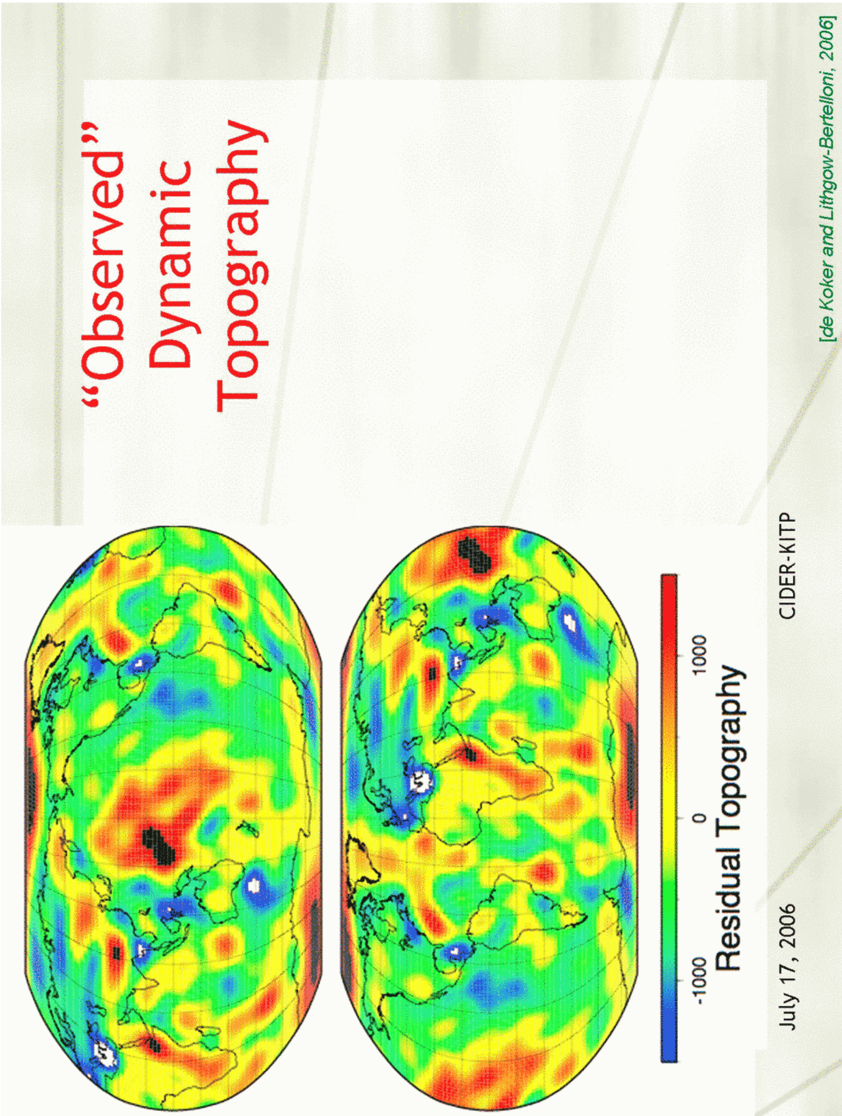
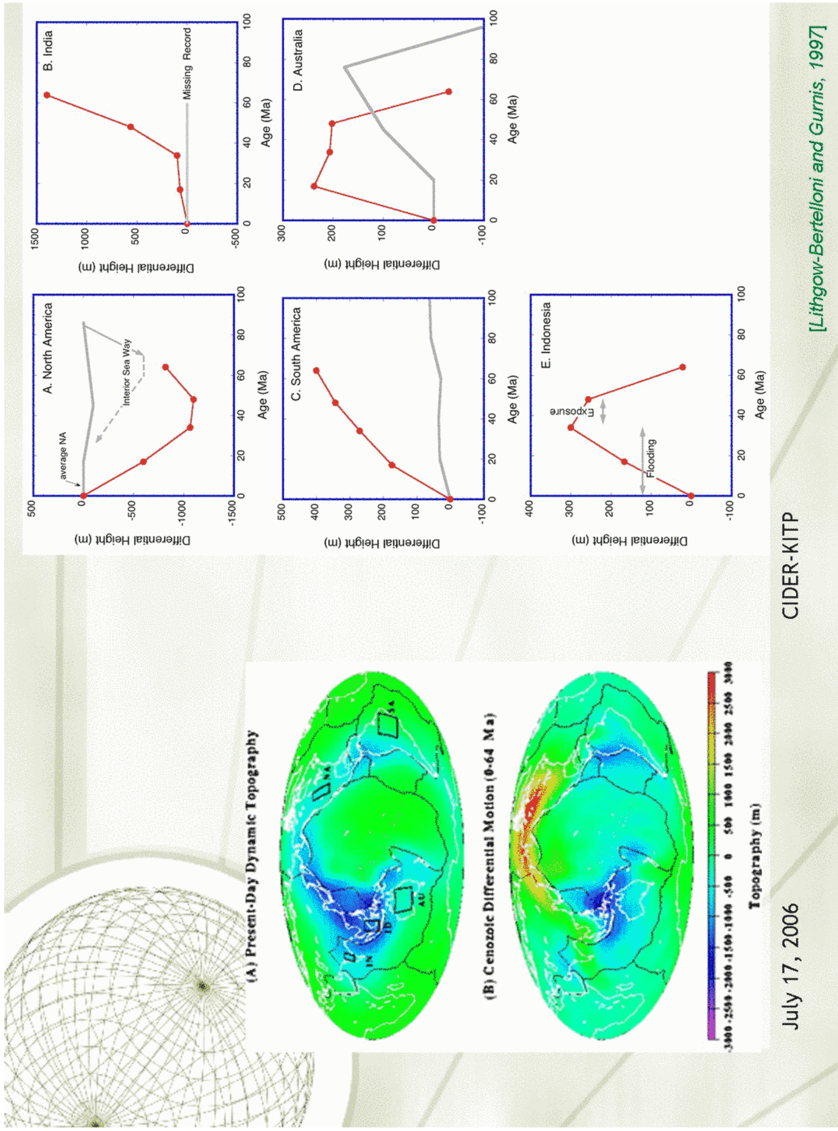
[Conrad, Lithgow-Bertelloni and Louden, 2004]

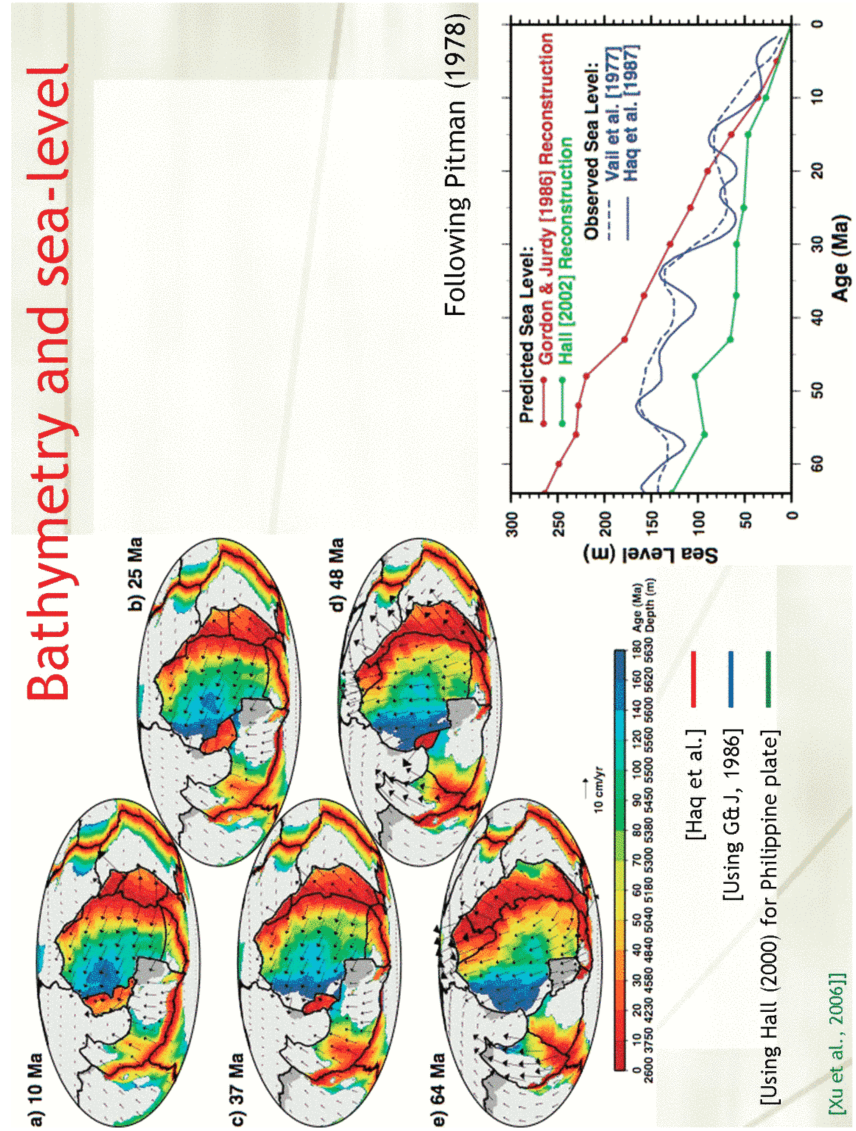


“Observed” Dynamic Topography
[de Koker and Lithgow-Bertelloni, 2006]
-1000
0
1000
Residual Topography
July 17, 2006
CIDER-KITP

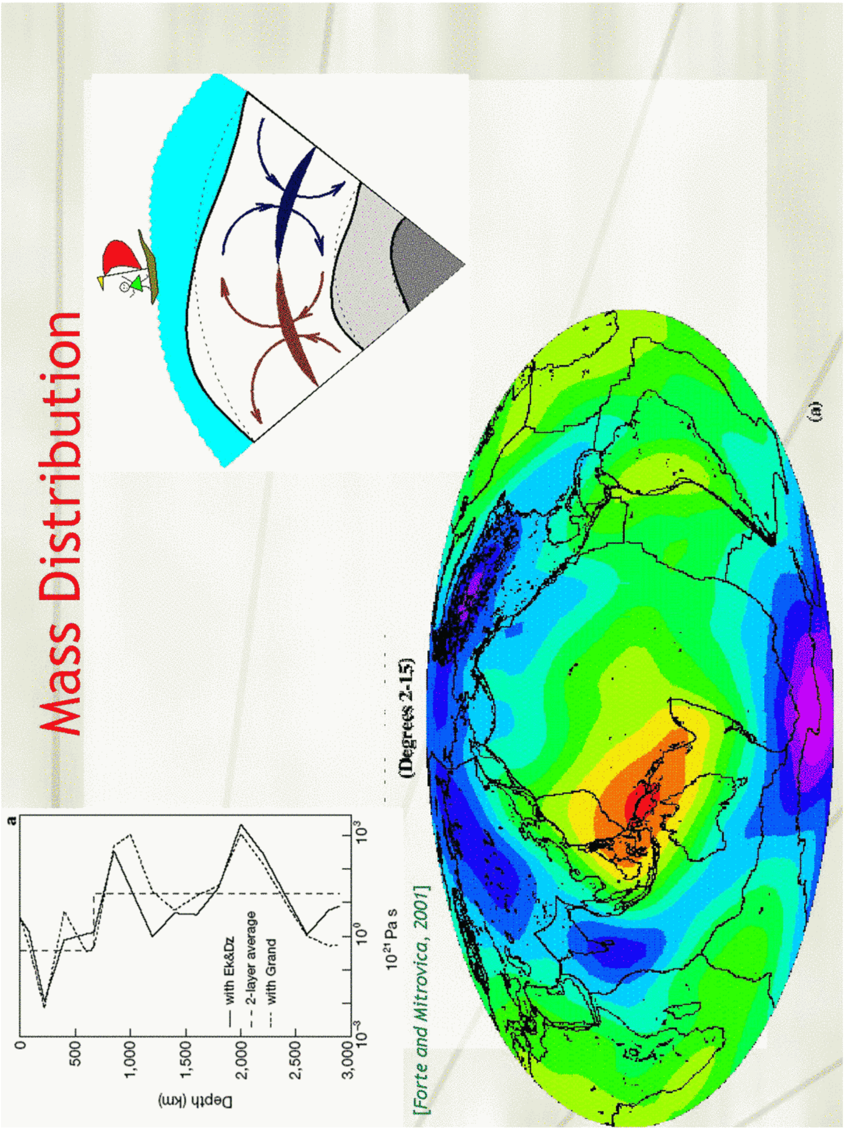
Continental flooding
•Ocean-volume variations
•ice cap melting
•Changes in volume of ocean basins
•spreading rates
•Isostatic balance of crust
•Orogenesis (short uncompensated λ)
•Epeirogeny
•long λ dynamic topography; tectonic uplift; post-glacial rebound

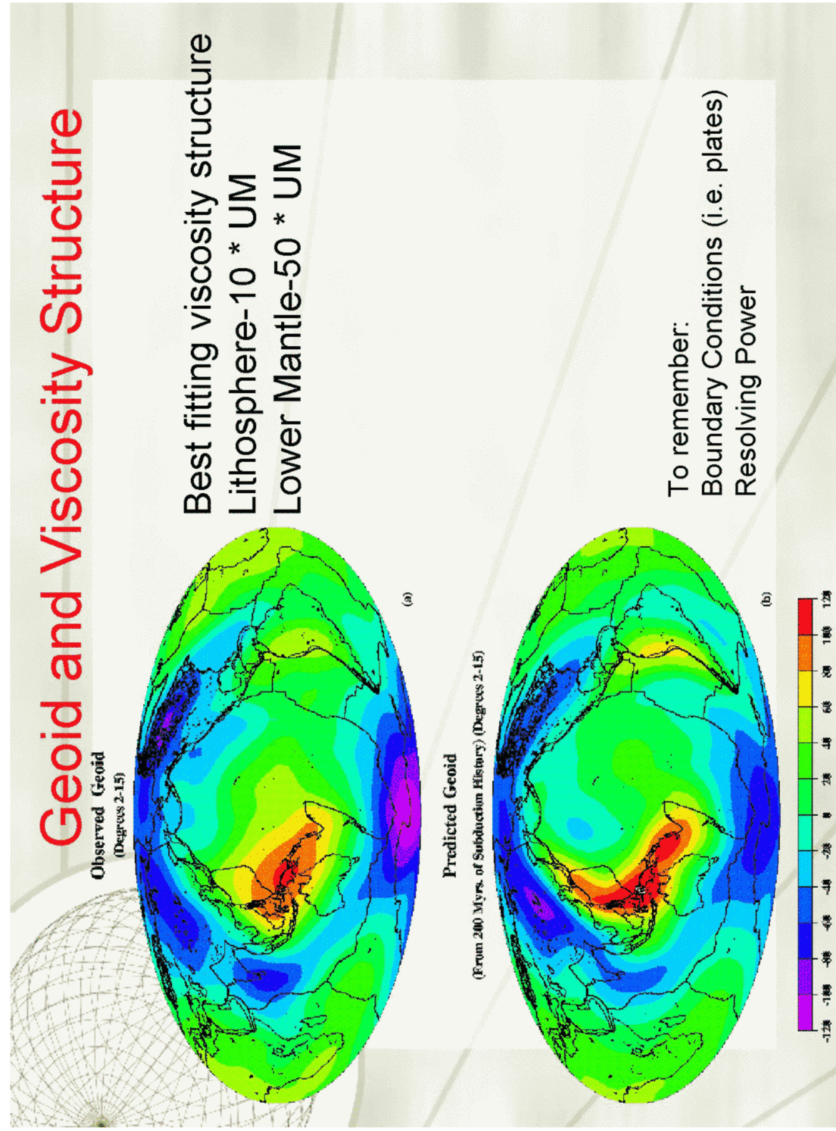


A. North America
B. India
C. South America
D. Australia
E. Indonesia
Differential Height (m)
Age (Ma)
average NA
Interior Sea Way
Missing Record
Exposure
Flooding
(A) Present-Day Dynamic Topography
(B) Cenozoic Differential Motion (0-64 Ma)
Topography (m)
[Lithgow-Bertelloni and Gurnis, 1997]
CIDER-KITP
July 17, 2006



Bathymetry and sea-level
Following Pitman (1978)
Predicted Sea Level:
Gordon & Jurdy [1986] Reconstruction
Hall [2002] Reconstruction
Observed Sea Level:
Vail et al. [1977]
Haq et al. [1987]
Sea Level (m)
Age (Ma)
a) 10 Ma
b) 25 Ma
c) 37 Ma
d) 48 Ma
e) 64 Ma
10 cm/yr
Age (Ma)
Depth (m)
[Haq et al.]
[Using G&J, 1986]
[Using Hall (2000) for Philippine plate]
[Xu et al., 2006]


Mass Distribution
a
Depth (km)
with Ek&Dz
2-layer average
with Grand
10^{21} Pa s
(Degrees 2-15)
(a)
[Forte and Mitrovica, 2001]


Geoid and Viscosity Structure
Best fitting viscosity structure
Lithosphere-10 * UM
Lower Mantle-50 * UM
To remember:
Boundary Conditions (i.e. plates)
Resolving Power
Observed Geoid
(Degrees 2-15)
(a)
Predicted Geoid
(From 200 Myrs. of Subduction History) (Degrees 2-15)
(b)
Geoid (m)

Geoid and Topography over subduction zones

-Broad local maxima (SH 4-9) [Hager, 1984]
-Back-arc geoid maxima at degrees > 9
-Requires large viscosity increase at 660 km [King, 2002] even accounting for phase transformations
-What about shorter wavelengths?

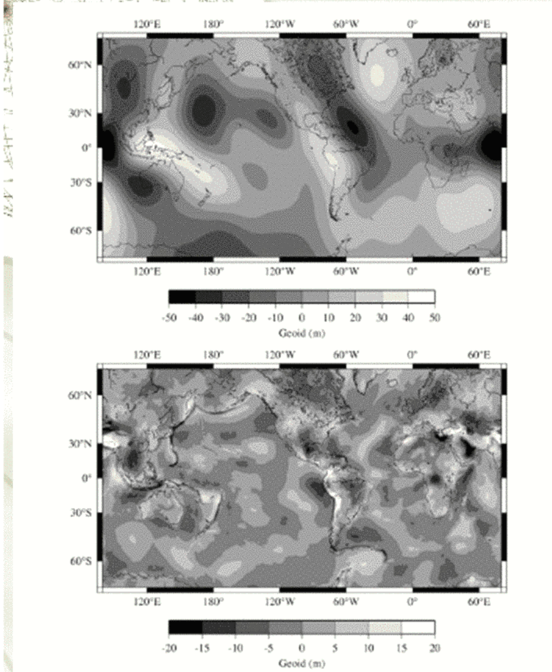
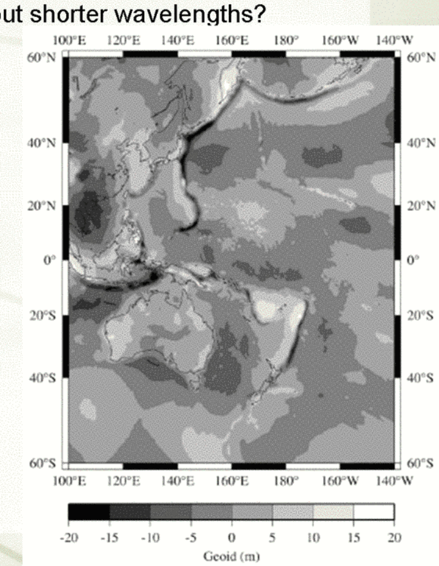


Figure 1. (top) Global geoid from EGM96 [*Lemoine et al.*, 1997] band-pass filtered passing wavelengths <15,000 km and cutting wavelengths >5000 km. These parameters are comparable to the degree 4–9 "slab" geoid used by *Hager* [1984]. (bottom) Global geoid from EGM96 [*Lemoine et al.*, 1997] band-pass filtered passing wavelengths <5000 km.

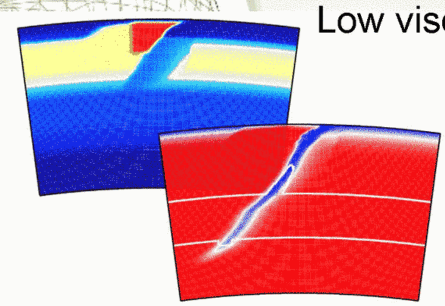


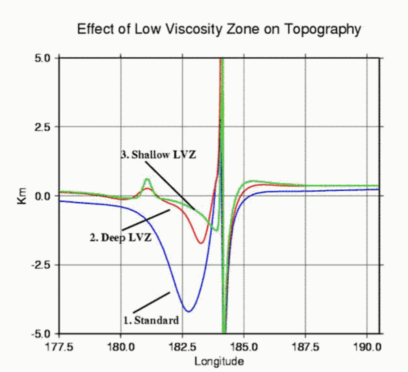
2. Geoid from EGM96 [*Lemoine et al.*, 1997] band-pass filtered passing wavelengths <5000 km , bottom) focused on the western Pacific.

[King, 2002]

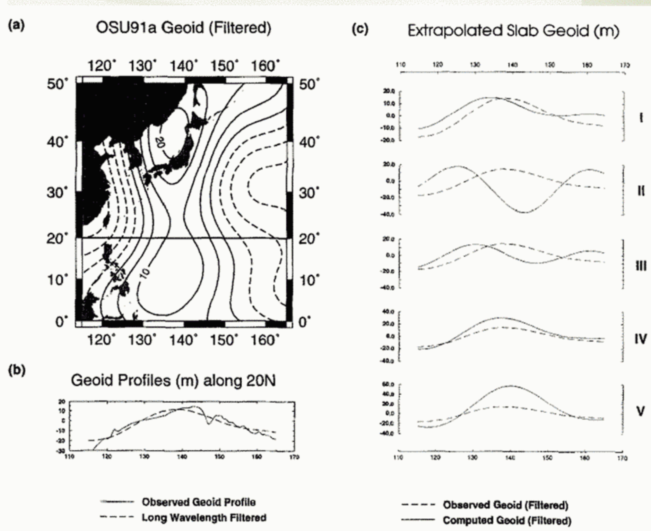
Geoid and Topography over Slabs

Low viscosity wedge above slab [Billen and Gurnis, 2001]]





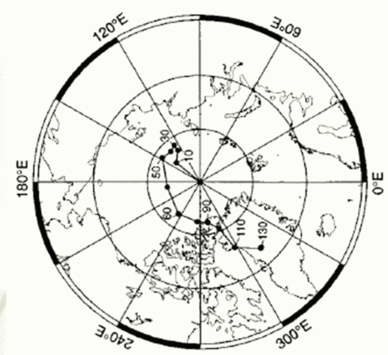
[Slabs weak?] [Moresi and Gurnis, 1996]

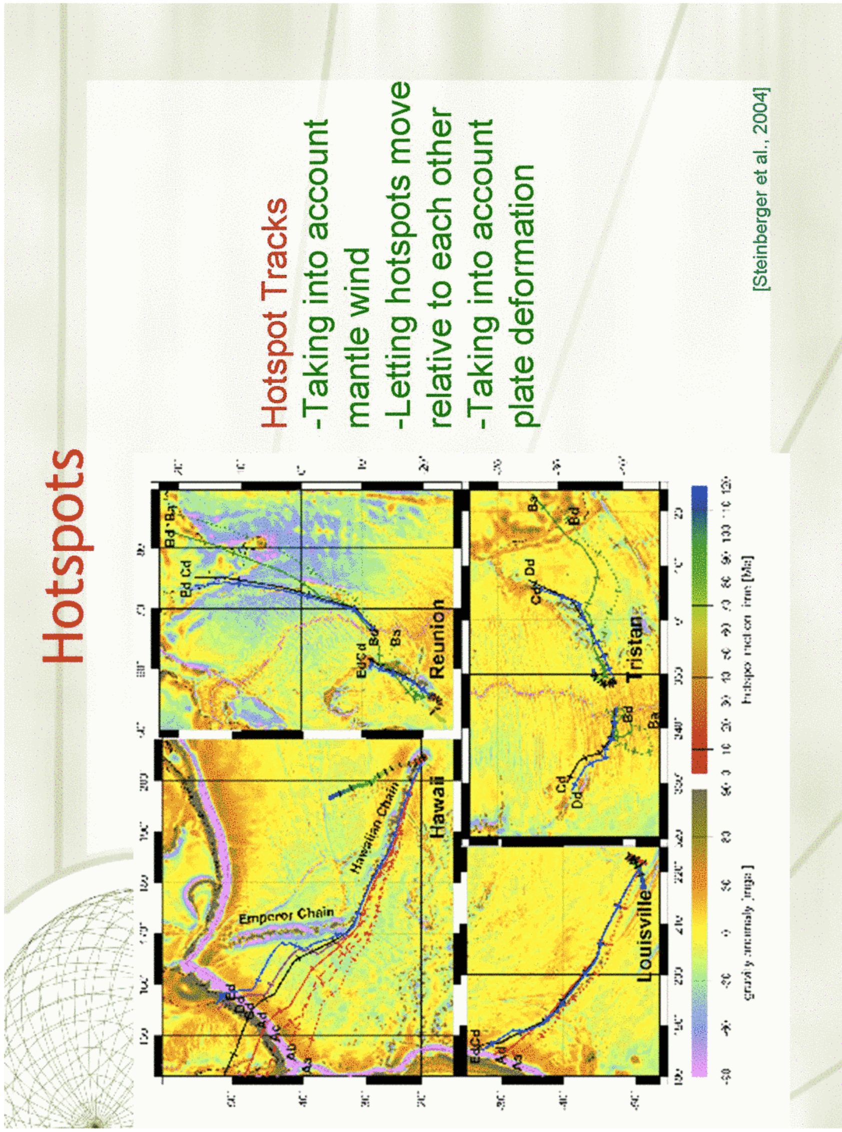


Changes in Mass Distribution: True Polar Wander

QuickTime™ and a Cinepak decompressor are needed to see this picture.

Inertial interchanges




Hotspots
Hotspot Tracks
-Taking into account mantle wind
-Letting hotspots move relative to each other
-Taking into account plate deformation
[Steinberger et al., 2004]
Emperor Chain
Hawaiian Chain
Hawaii
Reunion
Tristan
Louisville