Subduction V
Multi-scale models and joint constraints

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Plate boundary forcing

- Can we use plate velocities to infer plate boundary strength?

Becker & O'Connell (2001)

Correlations are ambiguous what else can we use?

- Need to understand rheological properties of slabs and plates
  - Use absolute motion information (and not just correlations)
  - Use deformation, rather than rigid plate motion
- Better treatment of plate boundaries
Plate motions and reference frames
(slab pull contributes ~ 70% of driving force)

### Rigid Plate Model in HS2 Frame

- **Grippo & Gordon (1990)**

### Deforming Model in NNR Frame

- **Kreemer et al. (2003)**

#### Ocean/Continental RMS

- HS2: 2.9 cm/yr
- NNR-GSRM: 1.55 cm/yr

#### Plateness

- HS2: 1.0
- NNR-GSRM: 0.9

#### Toroidal/Poloidal Power (l > 2)

- HS2: 0.5
- NNR-GSRM: 0.6

#### Net Rotation

- HS2: 3 cm/yr
- NNR-GSRM: 0

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**Note:**

- *HS2* and *NNR-GSRM* refer to different rigid plate models used in the study.
Plate Mantle Coupling: Viscosity Structure

How do slabs drive plate motions?

Subducting Velocity  →  Overriding Velocity

Plate – Slab Attachment

Induced Mantle Flow

Gravitational Pull

Slide courtesy of C. Lithgow-Bertelloni

[Conrad and Lithgow-Bertelloni, 2004]
Plate Driving Forces

Observe Velocities (Present-Day)

\[ \frac{V_{\text{subducting}}}{V_{\text{non-subducting}}} = 3.9 \]

The Slab Pull Force:
Calculate excess weight of upper mantle slabs

\[ 10^{17} \text{ N/km} \]

Velocity / Average Velocity

0.00 0.25 0.50 0.75 1.00 1.25 1.50 2.00 2.50 3.00 3.50 4.00 4.50 5.00

Subducting Plate Motion
Strong Plate & Slab
Overriding Plate Motion
Weak Upper Mantle
Viscous Lower Mantle
Weak Lower Mantle Slab
Vicous Stresses
Gravity

Slab Pull from Upper Mantle Slabs
Slab Suction from Lower Mantle Slabs

[Conrad and Lithgow-Bertelloni, 2002; 2004]
Plate-Slab Coupling

Detached Slabs?

Which slabs must be detached to produce the best fit to plate motions?

Fully Attached Slab:
100% Slab Pull Force
0% Slab Suction

Completely Detached Slab:
0% Slab Pull Force
100% Slab Suction
Deep Seismicity (300-670 km)

Sum moments using the Harvard CMT Catalog (1977-2002)

Strong plate-slab attachment allows for more seismicity at depth.

[Bilek et al., 2005]
Global flow computations with LVVVs

- Use geologic information (cratons and seafloor ages) for lithosphere
- Infer temperature anomalies from seismic tomography
- Compute 3-D, spherical mantle flow with LVVVs
- Prescribe stiff cratons (cf. Conrad & Lithgow-Bertelloni, 2006)
- Solve with CitcomS (Zhong et al. 2000)

Becker (2006)
Rheology

A) use generic temperature and/or stress dependence of viscosity on top of radial variations

\[ \varepsilon_0 = \varepsilon_{\text{disl}} + \varepsilon_{\text{diff}} \]

B) use effective, olivine creep law with diffusion & dislocation creep

\[ \eta_{\text{eff}} = \frac{\eta_{\text{disl}} \eta_{\text{diff}}}{\eta_{\text{disl}} + \eta_{\text{diff}}} \]

\[ \eta = \left( \frac{d^m}{A'} \right)^{\frac{1}{n}} \dot{\varepsilon}_{II}^{\frac{1-n}{n}} \exp \left( \frac{E^* + pV^*}{nRT_r(T_c + T)} \right) \]
Global circulation models: Average mantle viscosities for dry olivine region of LPO formation

- Viscosity broadly consistent with geoid and post-glacial rebound
- Can match plate motions and other plate scores
- Depth range of dislocation creep consistent with anisotropy observations

Cadek & Fleitout (2003); McNamara et al. (2003); Podolevsky et al. (2005); Becker (2006)
Sub-oceanic vs. continental speeds
(LVV GCM @ 250 km)

Hager & O'Connell (1981); Ricard & Vigny (1989); Zhang & Christensen (1993); Cadek & Fleitout (2003); Becker (2006)
Fit to observed net rotations

- Stiff continental keels induce net rotations of the whole lithosphere wrt. the lower mantle (cf. Ricard et al., 1991; Ribe, 1992; Zhong, 2001)
- This is seen in hotspot reference frames; poles of HS2/HS3 matched well, amplitude too low
Prediction of plate scores with LVVs

Becker (2006)

new hotspot ref. frame (HS3)
geodesy model (GSRM)
viscosity depth dependent
viscosity temp. dependent
dry olivine creep law

Becker (2006)
\[ \eta_{\text{slab}} = 10^{20} \text{ Pa s} \]

\[ \eta_{\text{slab}} = 3 \cdot 10^{23} \text{ Pa s} \]

Gerault et al. (in prep)
How can we resolve the ambiguity between slab strength and lateral viscosity variations?
Fig. 5. Pointwise dissipation for models in cross section through small-circle at 17°S for case 6 (without lower-mantle structure) in (A) and through Case 8 (with lower-mantle structure) in (B). The Tonga area is denoted with the letter T, and the Northern Chile area with letters Ch. (C) Zoom-in on the Tonga area for case 6. (D) Same zoom-in for case 8.
Fig. 4. (A) Map of surface strain rate with plate velocities for plates in a NNR frame of reference for the New Hebrides-Tonga region. Predictions are in black and white arrows from Nuvel1-NNR (27), with micro-plate motions from (23). Plates are labeled Australian, AUS; New Hebrides, NH; Tonga, TO; Kermadec, KE; and Pacific, PAC. Cross-sections in (B), (C), and (D) denoted by red line in (A). (B) Predicted velocity and viscosity. (C) Down-dip compression (blue) and down-dip tension (red) from CMT solutions (22). (D) Predicted compressional axes for case 6.

Stadler et al. (2010)
Slab seismicity

Hager & O'Connell (1979); Bevis (1988); Vassiliou & Hager (1988); Billen and Gurnis. (2003); Bilek et al. (2005); Carminati and Petricca (2010); Alpert et al. (2010)
Alpert et al. (2010)
“observed” dynamic topography

Boschi et al. (2010)
Trench dynamics

- Back-arc deformation
- Relative trench motions
Back-arc deformation

- Distinguish between
  - absolute motion of trench and
  - back-arc deformation (shortening or extension) with respect to overriding plate

Uyeda and Kanamori (1979)
Relative trench motions

Becker & Faccenna (2009), based on Funiciello et al. (2007)
Back-arc kinematics

- Velocities:
  - Over. plate $V_{OP}$
  - Subduct $V_S$
  - Trench $V_T$
  - (Oc.) plate $V_P$
  - Back-arc $V_D$

- $V_S = V_P + V_{OP}$

Heuret et al. (2007)
Back-arc kinematics

- Less net rotation will shift values to \( v_P > 0 \)
- \( x \) and \( y \) axes depend on reference frame

Heuret et al. (2007)
V_s is roughly constant, ~ independent of reference

If \( V_s > 5 \), back-arc shortening

If \( V_s < 5 \), back-arc extension

Slab anchoring effect

\[ V_s = 5 \text{ cm/yr} \]

Heuret et al. (2007)
Back-arc dynamics

- Similar behavior found in lab for stiff slab experiments
- Compressional and extensional response of back-arc determined by $V_s$ compared to subduction (modified Stokes) velocity $V'$

Heuret et al. (2007)
What controls trench motions?

Becker & Faccenna (2009), based on Funiciello et al. (2007)
Instantaneous slab flow field

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

Piromallo et al. (2006)
The role of slab width for toroidal flow

- Inverse relationship between slab width and retreat rate Dvorkin et al. (1993) and Bellahsen et al. (2005)
- Royden & Husson (2006) provide analytical approximation for effect of slab width on the pressure due to toroidal flow

\[ P_{\text{visc}}(x, 0) = \frac{12 \mu a}{\lambda^2} \left[ v_R - \left( \frac{v_t + v_m}{2} \right) \right] e^{-0.9(x/a)^{0.8}} \]

Royden & Husson (2006)
$V_T = f(W)$ applied to nature

Schellart et al. (2007)
Fig. 3 Regional subduction zone kinematics and slab geometry parameters. We assume that all intra-plate deformation is localized in the back-arc deformation rate, $V_b$ (positive for extension), and all velocities are trench-normal components. Plate ($V_p$), trench ($V_T$, positive for rollback) and overriding plate ($V_{OP}$, positive toward the trench) velocities are all computed in an absolute reference frame. The convergence rate at the trench, $V_c$, is given by $V_p + V_{OP}$ with this sign convention, and the sinking velocity of the slab, $V_s$, is partitioned between $V_p$ and $V_T$. (We assume $V_T = V_{OP} + V_B$, so $V_s = V_p + V_{OP} + V_B$). We also indicate the width of the slab and plate, $h$, and the approximate bending radius at the trench, $R$, as well as the slab dip angle, $\delta$. For more elaborate dip angle descriptions, see Jarrard (1986) and Lallemand et al. (2005).
Most (but probably not all) trenches retreat away from the overriding plate

Funiciello et al. (2008)
$V_p - V_t$ scaling in nature as $f(\text{ref. frame})$

Funiciello et al. (2008)
Fig. 12 Laboratory model behavior for free ridge models with different slab/mantle ratios $\eta'$ and normalized subduction velocities ($V'$ of eq. 7, divided by a normalized Stokes velocity to remove the effect of buoyancy changes at constant mantle viscosity). Models are from Bellahsen et al. (2005), Funiciello et al. (2008) (diamonds), and Schellart (2004b) (circles). Dashed lines are approximate divisions of model behavior; figure is modified from Funiciello et al. (2008)
\( V_p - V_t \) scaling in the lab as \( f(\text{slab viscosity}) \)

\( \eta' \sim 280 \)

Funiciello et al. (2008)

\( \eta' \sim 3,600 \)

\( \eta' \sim 2,000 \)

\( \eta' \sim 18,000 \)
Let's turn it around

- Assume free slab, fluid experiments are meaningful models for the Earth
- Assume that subduction velocity (balance of slab pull, bending and viscous drag) is useful
- Assume $V_p \sim 1/V_T$ relationship holds as $f(\eta')$
- Assume that net rotation of the lithosphere is at least partially related to regional slab dynamics
Let's turn it around

- Range of best-fit scaling for $V_T \sim 1/V_p$ corresponds to viscosity ratios $\eta'$ of $\sim 150 \ldots 350$
- This is borderline in the advancing/retreating regime (or maybe not, according to Ribe, 2010)
Seismic anisotropy
FIGURE 3-1
Combined data from Hawaii region showing velocity anisotropy given as deviations from the mean velocity of 8.159 km/sec plotted as a function of azimuth.
(From Morris, Raitt, and Shor, 1969, with permission. Copyright American Geophysical Union.)
Shear wave splitting

garnero.asu.edu
Shear wave splitting in anisotropic media

(After Crampin, 1981)
Causes of seismic anisotropy

Predicted elastic anisotropy

- individual minerals
- aggregates: lattice preferred orientation (LPO)
  - build up by dislocation creep
  - lines up with flow (most of the time)
Effect of water/stress

Long and Becker (2010)
Long and Becker (2010)
See also Buttles and Olson, EPSL, 1998
Along-arc flow

- Flow -> FSE -> LPO
- LPO -> 3D $C_{ij}$
- $C_{ij}$ -> waveforms
- Waveforms -> split

Hall et al. (2000)
3D flow due to trench geometry (curvature, slab dip changes)

Splitting: Pozgay et al., GJI, 2007
Contours: Syracuse and Abers, G-cubed, 2006

Figure 1 | Thermo-mechanical two-dimensional model of a spontaneously bending oceanic plate.  

**a.** Compositional map. Serpentинized faults are trenchward dipping but sets of antithetic and seaward-dipping faults are occasionally visible. Light green is gabbroic oceanic crust; basalt and sediments are shown in dark green.  

**b.** Strain rate map. Fault activation due to the bending of the plate occurs mainly at the trench in the upper layer of the slab. Arrows indicate the direction of material displacement. White lines are isotherms in °C (see Methods for details of the numerical model).
Schematic diagram of the anisotropic components and estimates of delay time. 

**a.** Thin layering of dry (blue) and hydrated (green) mantles results in an SPO-induced anisotropy for long-wavelength SKS waves. 

**b.** CPO$_{\text{hydr}}$ formed by hydrated minerals parallel to the layering in the hydrated mantle and by perpendicular olivine and enstatite grains in the dry mantle (destructive interference). 

**c.** Contours of delay time for an anisotropic plate dipping at 30$^\circ$ with strong transverse isotropic antigorite, as a function of the volume fraction of antigorite-filled fractures and fault length, with a fracture aspect ratio of 100:1 (see Methods for details of the anisotropy model). Delay times: circles, 0.5 s; triangles, 1.0 s; squares, 1.5 s. The horizontal dashed line indicates a 50-km-thick antigorite layer.
**Figure 4 | Summary of SKS fast directions and fault set orientations.**
Question marks indicate that no data are available. See Methods for data sources.

Faccenda et al. (2008)
Hypotheses for formation of trench parallel anisotropy

- Lithosphere and crustal structure
- Fluid filled cracks in crust
- Anisotropy within incoming slab
- Deviation from 2D cornerflow
- Crustal foundering
- Olivine fabric transitions in the cold nose
- Flow beneath slabs and around slab edges
- Melt related anisotropy
The sub-slab splitting signal

Fig. 7. Sketch of constraints on subduction zone anisotropy from shear wave splitting measurements from the compilation of Long and Silver (2008, 2009b). The anisotropic signals of the wedge and sub-slab regions are shown separately. Red arrows indicate average fast directions for the sub-slab splitting signal from SKS, local S, and source-side teleseismic S splitting measurements. The associated average sub-slab delay times are shown in red. Blue arrows indicate average fast directions for wedge anisotropy from local S splitting. In regions where multiple fast directions are shown, splitting patterns exhibit a mix of trench-parallel, trench-perpendicular, and oblique fast directions.

Long and Becker (2010)
Can we explain the global trend in sub-slab splitting with $|V_t|$?

3D flow caused by trench migration

Russo & Silver, 1994
Some open questions

- Slab strength and “plate coupling”
- Interactions between continental and oceanic plates/slabs
  - Tectonics
  - Earth evolution
- Relationship between subduction, volatile transport, upper mantle, small-scale convection with tectonics and magmatism
- Long-term pass transport between upper and lower mantle