Subduction dynamics and Mediterranean mantle flow

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Collaborators

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Purpose of this talk

• Provide overview of a (somewhat biased) subset of geodynamic subduction models
• Present some of the current modeling efforts by USC and collaborators
• Point out potential avenues of interdisciplinary research to address the Hellenic tectonics in the MEDUSA framework
Constraints on time-dependent system evolution: examples

- rates \((du(t)/dt)\)
  - velocities \(v_{\text{GPS}}\)
  - strain-rates \((dv/dx)\)
  - trench rollback (petrology)

- flow and strain: \((du(t))\)
  - LPO fabrics (seismic anisotropy)
  - offsets of faults and geologic provinces
  - slab morphology (tomography)
Goals of MEDUSA geodynamics
(as I see them)

• Understand the physics of slab dynamics for a fully developed subduction system, particularly the causes and consequences of trench motion and back-arc tectonics

• Construct quantitative models whose predictions (e.g. slab morphology, rates, temperatures, strain etc.) can be tested

• Create unifying interpretative framework for the Hellenic subduction system
Roadmap

- Subduction: recent observations and models
- 2-D models of free trench rollback
- Some comments on 3-D subduction
- Mantle circulation models
- Mediterranean mantle flow and constraints
Global systematics?
Absolute trench motion and back-arc deformation

Heuret & Lallemand (2005)
Conceptual models

(1) Upper plate controlled
(2) Slab pull controlled
(3) Mantle wind controlled

Heuret & Lallemand (2005)
Correlations: Trench motion and oceanic plate age

Heuret & Lallemand (2005)
The real world

... is complicated. Some effects that may be important for evaluating trench migration

- plate motion reference frames
- viscous slab bending at the trench
- viscous slabs affected by deep flow
- mantle wind (e.g. Sunda arc)
- mantle wedge dynamics
- overriding plate topography
Reference frames

Gripp & Gordon (1992)

NNR
The viscous slab

Karason (2001)
P wave tomography
Viscous slab bending

\[ F = \frac{\text{slab pull}}{\text{slab stiffness}} \]

e.g. Conrad & Hager (1999); Becker et al. (1999); Faccenna et al. (2001)
Other effects: mantle wind

- Slabs may be relatively weak (e.g. tomography, seismic strain rates)
- Slabs may be significantly affected by large scale mantle flow
- Hypocenters indicate deformed slabs, in a few cases (Sunda arc; Becker et al., 1999) even backward-bent slabs as expected from flow
Subduction zone forces

Becker & O'Connell (2001)
Predicting plate motions to invert for forces

Slab pull versus viscous drag I

Becker & O'Connell (2001)
Slab pull versus viscous drag II

Ambiguity of plate forces

Becker & O'Connell (2001)
Idealized models
Dynamically consistent ("free") rollback models

- Numerical work:
  - Zhong & Gurnis (1996)
  - Tetzlaff & Schmeling (2000)
  - Enns et al. (2005) and new results
  - Royden & Husson

- Lab work:
  - Kincaid & Olson (1987)
  - Faccenna, Funiciello et al. (2000)
2.5-D trench motion models

Figure 13. Schematic diagram showing gravitational and viscous forces that act on the subducted slab. The slab moves to maintain force balance between gravitational forces and viscous forces.

Royden and Husson
2D models with Newtonian rheology and no thermal effects

- Solve the conservation equations with FDCON: finite difference stream function formulation, use markers to trace material and viscosity contrasts
- Buoyancy due to the density contrast between the lithosphere and mantle (fixed, no thermal effects), no overriding plate
- Stratified viscosity, jump at 660 km, plus Byerlee at shallow depths (the surface boundary condition is crucial for fluid slab models)
- Test the effect of reflective or periodic, free-slip boundary conditions (BCs)

Enns et al. (2005)
Parameters of the models with a weak lithosphere

- Lithosphere: $\eta_{lith} = 100 \cdot \eta_{um}$, $\rho_{lith} = 3250 \text{ kg/m}^3$
- Upper mantle: $\eta_{um} = 10^{20} \text{ Pa} \cdot \text{s}$, $\rho_{um} = \rho_{lm} = 3200 \text{ kg/m}^3$
- Lower mantle: $\eta_{lm} = 50 \cdot \eta_{um}$

Enns et al. (2005)
BC 1, reference:
Reflective boundary conditions, fixed slab

Enns et al. (2005)
2) Periodic free slab

3) Reflective free slab

Enns et al. (2005)
Subduction parameters: reference model

Enns et al. (2005)
Subduction parameters: stiff slab

Enns et al. (2005)
Periodic BC, free slabs are able to induce relative motion between upper and lower mantle (net rotation, reference frame!)

Flow confinement leads to stronger folding of slabs

After interaction with 660, the trench retreat velocity decreases for reflective boundary conditions

Free, stiff slabs show trench advance after 660-interaction, periodic weak slab shows no significant changes in $v(\text{trench})$

Fixed slabs can only retreat, their retreat velocities in the initial subduction stage are higher than those of the free slabs
2D models with power-law rheology and thermal effects

- Bouyancy due to “realistic” thermal structure
- Initial temperature profile with an error function in the lithosphere and an adiabatic gradient in the mantle
- Constant viscosity in the lower mantle
- Power-law (e.g. Tetzlaff and Schmeling, 2000) or Newtonian rheology in the upper mantle and lithosphere, plus Byerlee weakening as before
- Reflective, free-slip boundary conditions
Model parameters

Model with power law rheology

time=0 Myr

- Lithosphere
- Upper mantle
- Lower mantle ($\eta_{lm}=50\eta_0$)

$z$ in km

Model with Newtonian rheology

time=0 Myr

- Lithosphere ($\eta_{lith}=150\eta_0$)
- Asthenosphere ($\eta_{asth}=0.1\eta_0$)
- Upper mantle ($\eta_{um}=0.2\eta_0$)
- Lower mantle ($\eta_{lm}=50\eta_0$)

$x$ in km

$C_p = 1250 \, \text{J/(kgK)}$

$\alpha = 2.4 \times 10^{-5} \, \text{K}^{-1}$

$\rho = 3200 \, \text{kg/m}^3$

$\eta_0 = 10^{21} \, \text{Pa s}$
Power law model

Newtonian model

T [°C]

Graphs showing temperature distribution over time for both models.
Subduction parameters

![Graph showing trench migration velocity over time with power law and Newtonian rheology](image)

- **Trench advance**
- **Trench retreat**

**Axes:**
- Y-axis: Trench migration velocity in cm/a
- X-axis: Time in Ma (million years ago)
Summary for power-law models

- Thermal models behave similar to the Stokes model (expected)
- Initially, the weak bending region of the power-law slab leads to stretching and high trench retreat velocities (also possible for Newtonian slab for weak Byerlee yielding)
- The Newtonian slab shows more regular folding than power-law
- A decreased folding-tendency due to the high viscosity of the power-law slab allows trench-retreat in late subduction stage
- Folding of the weak Newtonian slab causes alternating trench migration velocities
What about three dimensions?

- trench retreat induces toroidal flow
- this requires a significantly stiff slab
- large scale mantle flow will likely affect the slab shape
3-D lab models: flow as $f$ (prescribed trench motion)

Kincaid & Griffith (2003)
3-D numerics, flow as $f(\text{viscosity})$

\[
\frac{\eta_{\text{slab}}}{\eta_{\text{mantle}}} = 1
\]

\[
\frac{\eta_{\text{slab}}}{\eta_{\text{mantle}}} = 500
\]
Time-dependent plate motions: funny slabs

Tan et al. (2001)
Back to the Med

Piromallo & Morelli (2002)
Mantle circulation models: applied geodynamics

- construct estimates of mantle flow at present-day and within last few 10s of Ma
- FE code by Moresi, Zhong, Tan, Gurnis et al., from geoframework.org (Citcom)
- plate motions prescribed on top
- temperature inferred from tomography $\delta v$
- parameters as in Becker et al. (2003)
Global flow models

global reference model
ggrand tomography,
NNR reference frame
Effect of rheology: Newtonian, $\eta = f(r)$
Effect of rheology:
Newtonian, $\eta = f(r, T)$
Effect of rheology: power-law, $\eta = f(r, T, \sigma)$
Nested circulation models
Nested models, $\eta = f(r, T)$, only density driven using large scale, $S$ wave tomography
Nested models, $\eta = f(r, T)$, density and top plate flow
Nested models, $\eta = f(r, T)$, density and large scale flow
Flow, fabric, and seismic anisotropy: quantifying the coherency of tectonic strain
Splitting observations

Schmid et al. (2004)
Regional splitting

Splitting, fast $\phi$

Mean $\phi$ vs. $\varepsilon$ from GPS

Hatzfeld et al. (2004), see also Kreemer et al. (2004)
GPS tectonics: importance of “arc pull”

Flerit et al. (2004) models based on McClusky et al. (2000) geodesy
From flow to SKS splitting

- compute *present-day*, upper mantle flow field, assume steady state
- follow tracers until logarithmic strains of ~2 are reached at observation points
- compute elastic tensors from LPO fabrics using the Kaminski *et al.* (2004) method
- compute synthetic seismograms using reflectivity method, measure splits by cross-correlation
LPO fabrics

- Log strains of ~2 generally "sufficient" for LPO
- ~9, 7, 1, 0.7% total, hexagonal, orthorhombic, monoclinic anisotropy (tensor norms)
- Fast [100] typically aligns with $e_1$ of FSE
Back-azimuth variations

e.g. Saltzer et al. (2001), Schulte-Pelkum & Blackman (2003)
Predictions for Greece

FE $\eta(z)$ model

Schmid et al. (2004) SKS splitting
Predictions for Greece

FE $\eta(z)$ model

Hatzfeld et al. (2004) SKS splitting
Predictions for Greece

FE $\eta(z, T, \sigma)$ model

Hatzfeld et al. (2004) SKS splitting
Anisotropy conclusions

- back-azimuth dependence of SKS splitting may yield improved information on anisotropy at depth
- very preliminary flow models match splits away from trench (back-arc spreading?) and NAF (crustal deformation signature?)
- quantitative exploration of model fits seems promising
General conclusions

- Nested flow models yield improved estimates of large scale flow, results may be useful for smaller scale models.
- Need to resolve the importance of mantle wedge and deep dynamics for rollback.
- Together with geodynamic models, seismic anisotropy can yield information about vertical coherence of deformation.