Seismic anisotropy: enough already?

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Nope.

CIG? ... gotta love it thanks to the people who contribute software and geoframework.org
Goal of this talk

- provide a brief review of seismic anisotropy as a constraint for mantle convection and lithospheric deformation
- discuss some of the previous modeling efforts on global and regional scales
- present work in progress on evaluating the remaining problems
**Message**

- *applied geodynamics* useful for understanding plate tectonics (AGUPT)
- need to widen the realm of quantitative model predictions to reduce ambiguities (QUMRA)
- seismic anisotropy can yield a useful measure of flow and tectonic deformation (SAMFT)
- improved grip on many modeling issues, but imperfect data remains a big limitation (IHMBID)
Collaborators

- Donna Blackman (UCSD)
- Jules Browaeys (USC)
- Sebastien Chevrot (CNRS)
- Boris Kaus (USC)
- Jamie Kellogg (UCLA)
- Rick O'Connell (Harvard U)
- Vera Schulte-Pelkum (CU Boulder)
USC HPCC

- 1716 nodes, 1.4TB
- 7th fastest academic supercomputer as of 2004
- I haven't been able to properly edit files for six months now
- Hunters and farmers
Roadmap

- data
- anisotropy (azimuthal, $2\phi$) modeling
- mantle flow modeling
- combining the two
  - previous work
  - regional tectonics
  - global statistics
  - global specifics
Applied geodynamics

- construct “realistic” (i.e. best-guess) models of mantle flow to make predictions for our Earth
- buoyancy forces $\sim$ viscous flow
- stress $= \text{viscosity} \times \text{strain-rate}$
- examples of constraints:
  - velocities: plate motions, past and present
  - strain-rates: GPS, earthquakes, uplift
  - stress: WSM, geoid
  - integral of strain-rates: anisotropy, geochemistry
Data and models
Constraints on mantle structure from seismic waves

\[ \delta t > 0 \]
\[ \delta t' > 0 \]
\[ \delta t' < 0 \]

Isotropic anomalies

Seismology

Anisotropic anomalies

Temperature, composition

Geodynamics

Strain-rates
Isotropic tomography: upper mantle

vox3p05, $z = 290$ km

mndm04p, $z = 254$ km

ngrand, $z = 288$ km

s20rts, $z = 300$ km
Azimuthal anisotropy: Rayleigh wave phase velocity maps


100 s  150 s
Shear wave splitting

after Crampin (1981), from garnero.edu
SKS splitting data coverage

\[ \delta t_{SKS} = 1.5 \text{ s} \]

data compilation from Matt Fouch's ASU database
Regional anisotropy: splitting at trenches

- water?
- arc-parallel flow?
At what depths do we detect seismic anisotropy?


dislocation creep (high $\sigma$, low $T$) needed for LPO (what about climb?)
Laboratory studies:
LPO in the multi-anvil

- subcrustal anisotropy likely caused by lattice preferred orientation (LPO) of intrinsically anisotropic olivine crystals in flow
- for olivine, the seismically fast, slow, and intermediate axes are $a [100]$, $b [010]$, $c [001]$, respectively
- $a$ and $b$ align with the largest and smallest axes of the finite strain ellipsoid (FSE) for small strains
- for large strains, $a$ rotates into the shear plane by dynamic recrystallization (subgrain rotation and grain boundary migration)
Pole figures

uniaxial compression experiment by Nicolas et al. (1974)
High $\tau$ and high $H_2O$ regime

- type A: normal anisotropy, $a [100]$ in shear plane
- type B: High $\tau$ and high $H_2O$ regime, $a [100]$ normal to shear plane (Jung & Karato, 2001)
Plate-tectonic anisotropy

• in a simple world, both ridges and trenches should show $a$ in plate motion direction
• ridges: ridge-parallel fast $a$
  • due to melt/crack alignment (Kendall et al., 1994)
  • due to melt segregation (Holtzman et al., 2003)
  • small scale, so far not observed
• subduction zones: arc-parallel alignment of $a$
  • arc-parallel flow (e.g. Hall et al., 2000; Mehl et al., 2003)
  • presence of water (Mitsukami et al., 2004)
Quantitative links between LPO and flow: theories

- Kinematic constraint theory of Ribe (1991): grains rotate to minimize the mismatch between local and global strain rate
  - Predicts alignment of \(a, b, c\) with FSE
  - Critical \(\xi = \log (e_1/e_2) \sim 0.5\) overprints texture

- VPSC theory of Wenk & Tome (1999)
  - Computationally intensive
  - Six free parameters

- Kinematic theory of Kaminski & Ribe (2001, 2002); DREX (Kaminski et al., 2004) (freely available...)
Kinematic recrystallization

- Kaminski & Ribe (2001, 2002) method includes stress dependent recrystallization
  - volume fraction of grains controlled by dislocation density, $\rho$
  - non-recrystallized fraction of grain = $\exp (-\lambda \rho^2)$
  - large (small) strain energy grains shrink (grow) by grain boundary migration
- two free parameters from lab:
  - strain-free subgrain nucleation $\lambda$
  - grain boundary mobility $M$
KR and the lab: a axes

Zhang & Karato lab

KR method

simple shear

uniaxial compression

Kaminski & Ribe (2001); Kaminski et al. (2004)
Saturation of LPO anisotropy under simple shear: olivine

- \( C \) tensor norms
- anisotropy
- \( d\ln \nu \sim \frac{1}{2} d\ln C \)

![Graph showing saturation of LPO anisotropy](image)
Saturation of LPO anisotropy: GBS, olivine and enstatite

- $C$ tensor norms anisotropy
- $d\ln v \sim \frac{1}{2} d\ln C$
LPO: an integral measure!

- red: fast $a$
- blue: velocities
- red $\neq$ blue!
- need mantle flow as $f(t)$

Kaminski & Ribe (2001)
\( \xi = 2 \) texture for simple, sub-Pacific streamlines

- Regular slip system
- Water slip system

Directions: [100], [010], [001]
Trench LPO

- simple flow model
- LPO not so simple
Advection rules for global models

- here: assume steady-state flow (backward convection was used in Becker et al., 2003)
- follow tracers backward until $\xi = \log (e_1 / e_2) \sim 0.5$ (OK for FSE) or $\xi \sim 2$ (OK for LPO)
- erase texture if tracers rise from below 410km, maximum advection time $\sim 43$ Ma
- compute full elastic tensor (21 components) at each depth layer
From LPO to wiggles, how?
Surface wave anisotropy: Rayleigh wave phase velocities

\[ D^2 \phi = \frac{B_{C,S}(C_{ij})a(z)}{A} + \frac{H_{C,S}(C_{ij})f(z)}{F} + \frac{G_{C,S}(C_{ij})l(z)}{L} \]
Body wave anisotropy: SKS splitting, for example

- can compare largest FSE axes with best-fit transverse anisotropy (TI) axes for the hexagonal component of stiffness tensor
- any tilt will lead to back-azimuth dependence of fast splitting axes, so will non-hexagonal tensors

Schulte-Pelkum & Blackman (2003)
From flow to SKS splitting

- compute elastic tensors from LPO fabrics using the Kaminski et al. (2004) method for olivine/enstatite mix using \textit{DREX} (with fixed enstatite handling)
- compute elastic tensors (using $dP$ and $dT$ derivatives, both $P$ and $T$ are here $f(z)$ only)
- compute synthetic seismograms using reflectivity method
- measure splits by cross-correlation
Back-azimuth variations
Global flow models
What's going on?

- solve conservation of mass, momentum, (& energy)
- infinite Prandtl number, incompressible fluid
- constitutive relationships: \( \tau = 2 \eta \dot{\varepsilon} \)
  
  1) \( \eta = f(z) \)
  
  2) \( \eta = f(z) \exp(E(T_0 - T')) \)
  
  3) \( \eta = A f(z) \exp(E(T_0 - T'))^{n} \dot{\varepsilon}^{n}_{II} \)  

  (only for upper 410 km, should use mixed rheol.)
Numerical tools

- finite elements:
  - Citcom (Moresi, Tan, Conrad, Gurnis, ...)
  - CitcomS (Zhong, Moresi, ...)
  - all old versions from geoframework.org, slightly modified
- Hager & O'Connell (1981) semi-analytical, spectral method is used for comparison
Some details on code

“development”

- Citcom and CitcomS modifications:
  (thanks to Allen, Eh, and Jeroen)
  - surface velocities and $T$ from GMT grd files
  - regional model side-velocities from recoded, modular spectral method (not quite done...)
  - multi-grid and CG solver issues
  - power-law implemented with new, damped iteration scheme, clipped viscosities ($10^4$ range)
  - VTK output conversion
  - tested double/single precision
Resolution and accuracy

- global CitcomS:
  - 12 CPU x 64 x 64 x 64 (~ 3,100,000) elements, ~50km resolution
  - this is probably not enough, but fast
- can easily improve resolution for instantaneous computations, long simulations problematic
- some benchmarking done, more to do
- power-law rheology work in progress
Choices and input models

- present-day plate velocities prescribed on top
- seismic tomography for density structure
- need viscosity profile, and $R = \frac{d\ln T}{d\ln \nu}$
- typically: $smean$ or $ngrand$, constant $R$
Present-day surface velocities in no-net-rotation reference frame
Viscosity profiles
Input structure at 290 km
(ngrand tomography)
Viscosity at 290 km for $\eta = f(r, T)$
Viscosity at 290 km for $\eta = f(r, T, \sigma)$, power-law oceanic asthenosphere
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
Previous work on nested flow models: some examples

- Tan, Gurnis, *et al.* on plumes: coupled Citcom and CitcomS
- Mihalffy, Marquart, & Schmeling on plumes: side flow boundary conditions from Hager & O'Connell code
- *PYREZed* CitcomS
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
Puttin' it all together
SKS splitting in trenches

- 2.5D flow, FSE, and seismic synthetics: Hall et al. (2000)
- poster by Lassak et al. (here)
- work by Liverpool group

Hall et al. (2000)
California splitting

GPS and rigid plate flow: Silver & Holt (2002)

African splitting

mantle flow, instantaneous strain-rates

Behn et al. (2004)
Pacific surface wave anisotropy

mantle flow,
instantaneous strain-rates

Gaboret et al. (2003)
Phase velocity maps explored

$T = 50\text{ s Rayleigh waves, FSE, smean tomography model}$  Becker et al. (2003)
Phase velocity maps explored

- FSE better than APM
- active upwellings better than slabs
- NR degrades fit
- changes in plate motions improve fit
- LPO ~same as FSE

Becker et al. (2003)
Some loose ends

- LPO means dislocation (power-law) creep, yet all models use diffusion (Newtonian) creep
- FSE is not the whole story, should use LPO
- lateral viscosity variations important (cratons, asthenosphere, $\eta(T)$,...)
- time-dependence of mantle flow
Surface wave anisotropy revisited: radial $\eta(z)$, low strain, FSE

Rayleigh wave
at 100 s (~150 km depth)

$\langle \Delta \alpha \rangle_{\text{ocean}} = 37.7^\circ$

(best models in Becker et al., 2003, have $\langle \Delta \alpha \rangle_{\text{ocean}} \sim 24^\circ$)

ngrand tomography, plate motions, Ekstrom (2001) tomography
Surface wave anisotropy revisited: power-law $\eta(z, T, \sigma)$, low strain, FSE ngrand tomography, plate motions, Ekstrom (2001) tomography

Rayleigh wave at 100 s (~150 km depth)

$\langle \Delta \alpha \rangle_{\text{ocean}} = 41.9^\circ$
Surface wave anisotropy revisited: radial $\eta(z)$, low strain, KR LPO

Rayleigh wave at 100 s (~150 km depth)

$$\langle \Delta \alpha \rangle_{\text{ocean}} = 38.7^\circ$$

ngrand tomography, plate motions, Ekstrom (2001) tomography
Surface wave anisotropy revisited: radial $\eta(z)$, high strain, KR LPO

Rayleigh wave at 100 s (~150 km depth)

$\langle \Delta \alpha \rangle_{\text{ocean}} = 37.8^\circ$

ngrand tomography, plate motions, Ekstrom (2001) tomography
Radial $\eta(z)$, high strain, KR LPO, different anisotropic model

Rayleigh wave at 100 s (~150 km depth)

$\langle \Delta \alpha \rangle_{\text{ocean}} = 31.9^\circ$

ngrand tomography, plate motions, Trampert & Woodhouse (2003)
Surface wave findings

- effect of LPO vs. FSE moderate, but LPO allows for amplitude predictions
- lateral viscosity variations less important than radial structure
- strong effect of input density (bad & good)
- surface wave models have global coverage, but patterns are of uneven robustness
Westcoast: different $\xi$

low strain

high strain

\[ \delta t_{SKS} = 1.5 \text{ s} \]

$\frac{\text{r}_\text{ID} \text{ s} \text{mean}_\text{n}_\text{t} \xi_C}{\text{r}_\text{ID} \text{ s} \text{mean}_\text{n}_\text{t} \text{ ol}_\text{only} \xi_C} = 0.5 $
Westcoast: density models

slabs only

tomography

$\delta t_{SKS} = 1.5 \text{ s}$
$\eta_D^{\text{stein}} \xi_C = 0.5$

$\eta_F^{\text{smean nt}} \xi_C = 0.5$
Regional anisotropy

conclusions

• can explain observed variety in splitting
• can use variation in fast axes and delay time to constrain depth dependence of anisotropy
• can explain amplitudes of splitting (kindof)
• there's a hint of a crustal deformation signal (to be explored with better models)
• slab models (with induced return flow) lead to better model fits
Open questions for seismic anisotropy modeling

- What are the length scales of heterogeneity, and how are they imaged?
- What is the best theoretical description of LPO formation?
- How important is the crust for shear wave splitting ($S$ and $SKS$)?
- How do we constrain $H_2O$, so that we can comprehensively model alternative slip systems?
need to evaluate the robustness of mantle flow estimates with respect to rheology
further exploration of convection, and tectonophysics, reconstructions is crucial
a lot of progress will come from joint (seismology and geodynamics) models
data quality (coverage) is a problem and...
Some suggestions for CIG

(mostly harmless)

- keep it simple (in the beginning)
  - modularize and document existing codes, at a low level, without framework commitment
  - create a repository of cleaned-up subroutines
  - facilitate utilization of CS developments
  - assist in I/O handling and interpolation

- long term goals
  - coupled lithospheric/mantle codes
  - nested models