Global and continent-scale tomography, and a stab at $\rho$, $T$, $X$

Meredith Nettles
Seismic imaging (tomography) with travel-time data

propagation speed of a seismic wave
e.g.,
\[ v_S = \sqrt{\frac{\mu}{\rho}} \]
\[ \leftarrow \text{rock shear strength} \]
\[ \leftarrow \text{density} \]

depends on rock properties

<table>
<thead>
<tr>
<th></th>
<th>( \rho )</th>
<th>( \mu )</th>
<th>( v_S )</th>
</tr>
</thead>
<tbody>
<tr>
<td>temperature decrease</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>temperature increase</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>iron removal (peridotite)</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
</tr>
</tbody>
</table>
seismic images:
elastic → velocity (@ f)
anelastic → shear Q

laboratory measurements →
V, Q, ρ @ P, T, f

thermal models →
temperature, heat flux

gravity → density

geothermobarometry →
pressure, temperature
Models that differ widely have different geodynamic implications
van der Lee, 2002

Godey et al., 2004

Model comparison
250 km depth

\( \frac{\delta v}{v} \)
Common tomographic flaws

- disagreement between models (different geodynamic implications)

- background structure unconstrained (long-wavelength heterogeneity dominates in the Earth)

- crustal corrections of dubious quality (the crust is important!)

- use one seismogram component only (anisotropy is important!)
PREM anisotropy

(Dziewonski and Anderson, 1981)
For this study:

- large, global dataset
- measure Rayleigh and Love waves to constrain $V_{SV}$ and $V_{SH}$
- correct for CRUST-2.0;
calculate sensitivity kernels in local crustal structure for better resolution of mantle structure
- hybrid global-local model
Data: Surface-wave dispersion measurements

Rayleigh wave dispersion:
Kermadec to Pasadena, $\Delta = 85^\circ$

Raw data

30-60 sec

80-120 sec

150-200 sec
Global velocity model

SV variations

SH variations

070 km

150 km

300 km

\( \delta c/c_0 \) (%)
Globally averaged profiles

- $v_{SH}$
- $v_{SV}$
- $v_{Voigt}$
- $v_{ref}$

$S$-velocity (km/s)

Depth (km)

Anisotropy $(V_{SH} - V_{SV})/V_{Voigt}$ (%)
Pacific cross section

Voigt average

Anisotropy

\( \frac{V_{SH} - V_{SV}}{V_{Voigt}} \)
**N. continental cross section**

**Voigt average**

**Anisotropy**

$$\frac{(V_{SH} - V_{SV})}{V_{Voigt}}$$

- Depth (km)
  - 0
  - 100
  - 200
  - 300
  - 400

- Distance (degrees)
  - 0
  - 5
  - 10
  - 15
  - 20
  - 25
  - 30
  - 35
  - 40
  - 45
  - 50
  - 55
Anisotropy
\( (V_{SH} - V_{SV})/V_{Voigt} \)

Voigt average
**GTR-1 oceans**

- Young oceans
- Mid-age oceans
- Old oceans
- GTR-1 oceans

**GTR-1 continents**

- Orogenic/magmatic Phan. platforms
- Phan. platforms
- p-C shields/platforms

![Graphs showing seismic wave velocities and the Voigt ratio for different types of ocean and continental regions.](image-url)
A test:

- Convert velocity model into density model
- Predict gravity field
- Evaluate for consistency with observed gravity field
Half-space-cooling model:

Predicted density of oceanic mantle

depth = 70 km
Digital age grid (Mueller et al., 1997)
Velocity-density scaling

(compare with 0.27 from laboratory results of Jackson et al., 1992, using same thermal-expansion coefficient)
Density kernels:

Sensitivity of free-air gravity to density perturbations

S.H. degree: 2 8 30 100 160

Depth:

0 km
200 km
400 km
600 km
Gravity anomalies predicted by seismic model

Thermal scaling only
Observed and predicted gravity anomalies

observed: EGM96

predicted: crust+mantle

mgal
Gravity anomalies $|\Delta g| > 50$ mgal

- crust only
- crust + mantle
Compositional derivatives (Lee, 2003)

![Graph A](image1)

**STP DENSITIES**

\[ \rho = -0.0144 \text{Mg}\# + 4.66 \]

\[ r^2 = 0.67 \]

![Graph B](image2)

**STP SHEAR VELOCITIES**

\[ V_s = (0.0143 \pm 0.0009) \text{Mg}\# + (3.53 \pm 0.08) \]

\[ R^2 = 0.71 \]
Assumption based on isopycnic hypothesis

lateral temperature gradients are
stabilized by compositional gradients

<table>
<thead>
<tr>
<th></th>
<th>$\rho$</th>
<th>$\mu$</th>
<th>$v_S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>temperature decrease</td>
<td>↑ ↑ ↑</td>
<td></td>
<td></td>
</tr>
<tr>
<td>temperature increase</td>
<td>↓ ↓ ↓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>iron removal (peridotite)</td>
<td>↓ ↑ ↑</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

at each depth, positive compositional buoyancy balances negative thermal buoyancy to maintain net neutral buoyancy (density)
Estimation of thermal and compositional effects on velocity and density

from Lee (2003): \[
\frac{\Delta \rho}{\Delta Mg\#} = -19.1 \text{ kg/m}^3 \quad ; \quad \frac{\Delta v_S}{\Delta Mg\#} = 14.3 \text{ m/s}
\]

At 100 km, average velocity and density are:
\[
v_S = 4.44 \text{ km/s} \quad ; \quad \rho = 3343 \text{ kg/m}^3
\]

yielding:
\[
\Rightarrow \frac{\Delta v_S/v_S}{\Delta Mg\#} = 0.32\% \quad \text{and} \quad \frac{\Delta \rho/\rho}{\Delta Mg\#} = -0.43\%
\]
\[
\Rightarrow \left( \frac{\Delta \rho/\rho}{\Delta v_S/v_S} \right)^c = -1.34\%
\]

from thermal scaling, we have:
\[
\left( \frac{\Delta \rho/\rho}{\Delta v_S/v_S} \right)^t = 0.25\%
\]

for a total perturbation to velocity \(X\):
\[
X = t + c
\]

an assumption of neutral buoyancy gives:
\[
t = 0.84X \quad \text{and} \quad c = 0.16X
\]

A velocity anomaly of +5% would thus imply a perturbation of \(~ -350 \text{ K} \) and +2.5 Mg#. 
- isotropic velocity correlates well with surface tectonics
- radial anisotropy shows strong continent-ocean signature
- craton dvS is ~85% thermal, ~15% compositional
Sensitivity kernels

**Rayleigh**

**Love**

- $V_{SV}$ sensitivity
- $V_{SH}$ sensitivity

Depth (km)

35 s

350 s
Dispersion due to attenuation
Experiment with 3 Q models

1-D avg. of 3-D model

“flat” Q

depth (km)
Preliminary 3-D Q model from Colleen Dalton

\[ Q_o = 95 \]

\[ Q_o = 93 \]

\[ Q_o = 146 \]

\[ Q_o = 216 \]
The diagrams illustrate the variation of V_p/V_s (Voigt) with depth for different ocean types: young oceans, mid-age oceans, old oceans, and GTR-1 oceans. The left panel shows the results for flat Q conditions, while the right panel depicts the average Q conditions. The depth is shown on the y-axis, and V_p (km/s) is on the x-axis.
Effect of 3-D Q structure

Basin & Range

Canadian Shield

depth (km)

$V_S$ (km/s)

A0Q_a
AAQ_b
ABQ_b

model comparison

100
200
300
-1 0 1 2 3 4 5

$(V_{SH} - V_{SV})/V_{Voigt}$ (%)

flat
1-D avg.
3-D
Extra slides
Attenuation-100 km

Attenuation-400 km

Velocity-140 km

Velocity-350 km

Gu et al. 2001

Megnin & Romanowicz 2000

dv/v (%)
This Study

Gung & Romanowicz 2004
Next steps:
- use thermobarometric data as constraints
- utilize oceanic geochemical data (?)
Voigt average velocity variations

70 km

100 km

\( \frac{\delta c}{c_0} \)
S-velocity variations, 070 km
(Voigt average)

S-velocity variations, 100 km
(Voigt average)

Craton boundaries from Abbott and Menke (1990)
Voigt average velocity variations

150 km

250 km

\( \frac{\delta c}{c_0} \ % \)
S-velocity variations, 150 km
(Voigt average)

S-velocity variations, 250 km
(Voigt average)

S-velocity variations, 300 km
(Voigt average)
Anisotropy
\( \frac{V_{SH} - V_{SV}}{V_{Voigt}} \)
Anisotropy \((V_{SH} - V_{SV})/V_{Voigt}\)
Anisotropy
\( \frac{V_{SH} - V_{SV}}{V_{Voigt}} \)
\[ \Delta g_{lm} = \int_{a_1}^{a_2} \left( \frac{\delta \rho}{\rho} \right)_{lm} K_l^\rho \, dr, \]

\[ K_l^\rho = -\frac{3g(l-1)}{2l+1} \left( \frac{\rho}{\bar{\rho}} \right) \frac{(r')^l}{a^{l+1}}. \]
Figure 13. Precambrian tectonic elements of the North American craton (platform cover removed) and Baltic shield. Upper case names are Archean provinces; lower case names are Proterozoic and Phanerozoic orogens. BH, Black Hills inlier; BL, Belcher fold belt; CB, Cumberland batholith; CH, Cheyenne belt; CS, Cape Smith belt; FR, Fox River belt; GP, Great Falls tectonic zone; GL, Great Lakes tectonic zone; GS, Great Slave Lake shear zone; KL, Kullarney magmatic zone; KP, Kapuskasing ultramafic; KR, Keweenawan rift; LW, Lapland-White Sea tectonic zone; MK, Makovik orogen; MO, Mistassini and Otish basins; MRV, Minnesota foreland; SG, Saglek terrane; TH, Thompson belt; TS, Trans-Scandinavian magmatic zone; VN, Volcanic tectonic zone; VT, Veterny tectonic zone; WR, Winooski River fault.

(Hoffman, 1989)
Figure 1. Simplified tectonic map of North America. BR - Basin and Range; BRO - Brooks Range; MK - Mackenzie Mountains; MA - Marathon uplift; OU - Ouachita Mountains; M.A.R. - Mid-Atlantic Ridge; E.P.R. - East Pacific Rise.
Voigt average velocity variations

Figure 3. Crust-formation provinces of the western United States. Provinces are distinguished on the basis of regional differences in the Nd isotopic evolution paths as determined by measurements of crustally derived samples of different ages (Fig. 4). The locations of Figure 2 are used to indicate the initial $\epsilon_{Nd}$ and $T_{DM}$ values of individual samples. Diamonds = Archean province ($T_{DM} > 2.7$ Ga), squares = province 1 ($T_{DM} = 2.0-2.3$ Ga), circles = province 2 ($T_{DM} = 1.8-2.0$ Ga), triangles = province 3 ($T_{DM} = 1.7-1.8$ Ga), inverted triangles = Grenville-age crust ($T_{DM} < 1.4$ Ga). Boundaries are drawn to group together samples of similar isotopic characteristics. SAF is the San Andreas fault; M.R. is the Mineral Range; G.C. is the Grand Canyon. Outlined areas are regions where Precambrian basement is exposed.

Figure 7. Map of North America, showing the distribution of Nd model age provinces on the basis of data from this study, Nelson and DePaolo (1985), Farmer and DePaolo (1983), Patchett and Arndt (1986), and Van Schmus and others (1987). M indicates the Mojavia terrane. The adjacent dashed curve is the inferred location of a Proterozoic shear.
STP DENSITIES

\[ \rho = -0.0144 \text{Mg\#} + 4.66 \]
\[ r^2 = 0.67 \]

Compositional derivatives
(Lee, 2003)
residual (observed − predicted), $|Δg| > 50$ mgal
Seismic imaging (tomography) with travel-time data

- measure travel times \( t \) of seismic waves from earthquake to seismograph
  \[ t = \frac{\Delta}{v} \quad (\Delta = \text{distance} ; v = \text{wave speed}) \]

- use variations in \( t \) to map variations in \( v \)
  \[ (t - t_{\text{ref}}) = \delta t \quad \rightarrow \quad \delta v = (v - v_{\text{ref}}) \]

- from \( v \) (plus auxiliary data) infer rock properties
Tectonic elements of the North American continent

(Williams et al., 1991)