Seismological constraints on the nature of cratonic lithosphere and Phanerozoic lithosphere

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Global Seismic-Velocity Models

Regional averages SEMum2 (French et al., 2013)

Crustal classification (after Laske et al. 2013)
Effects of Temperature and Pressure

![Diagram showing the effects of temperature and pressure on depth and shear-wave velocity.]

- Depth (km)
- Temperature (°C)
- Shear-Wave Velocity (km/s)

**Mantle Xenoliths**
- South Africa
- Siberia
- Tanzania

**L. Thickness**
- 0.4 \(\mu\)W/m³
- 0.5 \(\mu\)W/m³
- 0.6 \(\mu\)W/m³
- 0.7 \(\mu\)W/m³

**Mantle Adiabat**

**Baltic Shield observations**

**Geotherm predictions:**
- 1-3: xenolith peridotites
- 4,5: wehrlite, websterite
- 6-9: exotic compositions

*(Bruneton et al., 2004)*

Refereed by Rudnick et al. (2008)
Surface-Wave Observations of Cratonic Lithosphere

Lebedev et al. (2009)

Pedersen et al. (2009)
Effects of Composition

218 cratonic mantle xenoliths
3 GPa, 800°C

Mg # = 100*MgO/(MgO+FeO)

Archean & Proterozoic xenoliths

Phanerozoic xenoliths

Lee et al. (2011)

Celnick, Dalton, Faul (2010)
Effects of Composition

Baltic Shield observations

Shear-Wave Velocity (km/s)

1-3: xenolith peridotites
6: peridotite + 4% amphibole
7: peridotite + 10% amphibole
8: peridotite + 13% phlogopite
(Bruneton et al., 2004)

Selway et al. (2015)
Status of Global Attenuation Models as of 2015

Attenuation (1/Q): 100 km

Shear Velocity: 100 km

QRLW8
Gung and Romanowicz 2004

SW02
Selby and Woodhouse 2002

QRFS12
Dalton et al. 2008

S362ANI
Kustowski et al. (2008)

SEMum
Lekic & Romanowicz (2011)

S40RTS
Ritsema et al. (2011)

travel times more straightforward than amplitudes
Composite Fields of Observations of 50-s Rayleigh Waves

3 events to southwest (Samoa Islands)

3 events to west (Solomon Islands)

\[ A_{ij}(\omega) = A_i^S(\omega)A_j^R(\omega)A_{ij}^F(\omega)A_{ij}^Q(\omega) \]

- **Source**: \( A_i^S(\omega) \)
- **Focusing**: \( A_j^R(\omega) \)
- **Receiver**: \( A_{ij}^F(\omega) \)
- **Attenuation**: \( A_{ij}^Q(\omega) \)
Wavefield Simulations

SPECFEM3D_GLOBE (Komatitsch and Tromp, 2002a; 2002b)
42 shallow events, 134 global stations

3-D elastic model

1-D anelastic model

measurements of synthetic seismograms

Dalton et al. (GJI, 2014)
Wavefield Simulations: Focusing Effects

50 s: input map

50 s: output map

GCRA: great-circle ray approx.
ERT: exact ray theory
FFT: finite-frequency theory

Dalton et al. (EPSL, 2017)
2-D Attenuation Maps

Dalton et al. (EPSL, 2017)

CRUST1.0 (Laske et al., 2013)

Ma et al. (2016)

van Heijst & Woodhouse (1997)

Ekström et al. (1997)

Dalton et al. (EPSL, 2017)
Thermal Structure

1. Construct geotherms by systematically varying:
   - Potential temperature ($T_P$) of adiabat (1100°C, 1150°C, 1200°C, ..., 1600°C)
   - Layer thickness (5 km, 10 km, 15 km, 20 km, ..., 400 km)

2. Convert temperature into shear attenuation and seismic velocity using Jackson and Faul (2010)

3. Predict Rayleigh wave attenuation and phase velocity using Mineos
Thermal Structure

Fit to 2-D Rayleigh wave attenuation maps: 40-200s

Dalton et al. (EPSL, 2017)
Thermal Structure

**cratonic phase velocity**

- Observed
- Geotherm-predicted
- Geotherm-predicted + reduction 60-80 km + increase 200-250 km

**cratonic shear velocity**

- Perturbed
- Geotherm
- PREM
Single-Station Sp Profiles from Global Cratons

Mancinelli, Fischer, Dalton (in revision)
CCP Sp Profiles from USArray Stations

Depth (km)

West
- Transverse Ranges
- SAF
- Basin and Range
- Mojavia
- Yavapai
- Jemez Lineament
- Rio Grande
- Mazatzal
- Granite-Rhyolite Province
- Appalachian

East
- Oklahoma-Auolocagen
- Ouachita Mtns
- Reel Foot Rift
- Mississippi Embayment

RF Amplitude

Hopper & Fischer (in prep.)
Rayleigh Wave Phase Velocity Maps

Superior

**province boundaries from Andrew Schaeffer**
Areas of Anomalous Attenuation

Attenuation: 50 s, az.-avg. approach

Phase velocity: 50 s

Bao et al. (GJI, 2016)

1/Q, az-avg approach: SELECTED

Regional 1/Q map
Regionally Averaged Attenuation Maps

Bao et al. (GJI, 2016)

40 s

50 s

60 s

50 s phase velocity

Bao et al.
(GJI, 2016)
Conclusions

1. New global degree-16 attenuation maps
   • strong agreement using different amplitude data sets and focusing corrections
   • clearly image very low attenuation associated with specific continental cratons.

2. Frequency-dependent attenuation values at periods < 200 s are fit by a simple thermal boundary layer.
   • global variations in cratonic LAB depth
   • allows the compositional effects on shear velocity to be isolated

3. USArray attenuation maps
   • high attenuation west
   • low attenuation interior
   • elevated attenuation in northeast

4. Anomalous features in attenuation maps demand future investigation
   • focusing effects underestimated?
   • other wave-propagation phenomena?
Wavefield Simulations: Source and Receiver

source excitation calculation (50 s)

receiver term calculation (50 s)

42 events

134 stations

Dalton et al. (GJI, 2014)
Effects of Composition

Depth (km)

Temperature (°C)

Pressure (GPa)

MLD

LAB

Solidi
- Saturated
- Anhydrous
- Oxidized
- Reduced
- Metasomatized

90 mW/m²
80 mW/m²
70 mW/m²
60 mW/m²
55 mW/m²
50 mW/m²
45 mW/m²
40 mW/m²
35 mW/m²
800 900 1000 1100 1200 1300
Surface-Wave Focusing and Sensitivity

Dunn & Forsyth (2003)

Surface-wave focusing

Rayleigh wave sensitivity

Depth (km)

Sensitivity to shear attenuation

0 10 20 30 40 50 60 70

0 100 200 300 400 500

-300 -200 -100 0 100 200 300

West - east, km

N

3.5 3.6 3.7 3.8 3.9 4 4.1 4.2 km/s
Effects of Composition

Lee et al. (2011)
Pure-Path Regionalized Inversion

A: oceans < 25 Myr
B: oceans 25-100 Myr
C: oceans > 100 Myr

P: platforms
Q: orogenic continents
S: exposed shields & platforms

GTR1
Jordan (1981)

no focusing correction

with focusing correction

van Heijst & Woodhouse (1997)
Ma et al. (2016)
Ekstrom et al. (1997)
SPECFEM input
Pure-Path Regionalized Inversion

attenuation (amplitudes from Ma et al. 2016)

$1/Q$

phase velocity (travel times from Ma et al., 2014)

$c$ (km/s)

<table>
<thead>
<tr>
<th>Period (s)</th>
<th>$1/Q$</th>
</tr>
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<tbody>
<tr>
<td>50</td>
<td>0.012</td>
</tr>
<tr>
<td>100</td>
<td>0.010</td>
</tr>
<tr>
<td>150</td>
<td>0.008</td>
</tr>
<tr>
<td>200</td>
<td>0.006</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Period (s)</th>
<th>$c$ (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>3.8</td>
</tr>
<tr>
<td>100</td>
<td>4.0</td>
</tr>
<tr>
<td>150</td>
<td>4.2</td>
</tr>
<tr>
<td>200</td>
<td>4.4</td>
</tr>
</tbody>
</table>

A: oceans < 25 Myr
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Dalton et al. (EPSL, 2017)
Thermal Structure

- Construct geotherms: vary potential temperature ($T_P$) of adiabat & layer thickness
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**Fit to pure-path regionalized Rayleigh wave attenuation**

![Graph showing variance reduction vs period for GTR1 values and TBL models.](image1)

![Graph showing attenuation vs period for observed and predicted values.](image2)
\[
\frac{2 \nabla \beta \cdot \nabla \tau}{\beta} - \frac{2 \alpha}{c} = \frac{2 \nabla A \cdot \nabla \tau}{A} + \nabla^2 \tau
\]
Curve-Fitting Approach

50-s Rayleigh waves

unsmoothed

Gaussian smoothing (400 km)
Azimuthal-Averaging Approach

unsmoothed

Gaussian smoothing (400 km)

Comparison: Curve-Fitting Approach
Independent Constraints on Local Site Amplification

amplitude ratio approach of Eddy and Ekström (2014)

amplitude ratio approach applied to our data set

Beta

from curve-fitting approach

Eddy and Ekström (2014)
Independent Constraints on Local Site Amplification

amplitude ratio approach of Eddy and Ekström (2014)

amplitude ratio approach applied to our data set

curve-fitting approach

azimuthal-averaging approach
• 882 earthquakes from January 2, 2006 to March 3, 2015
• 1966 seismic stations

• travel time and amplitude measured using Automated Surface Wave Phase Velocity Measuring System (Jin & Gaherty, GJI, 2015)

• 389,552 Rayleigh waves measured
Helmholtz Equations

\[ A_{ij}(\omega) = A_i^S(\omega)A_j^R(\omega)A_{ij}^F(\omega)A_{ij}^Q(\omega) \]

Use wavefront-tracking approach of Lin et al. (2012) to determine:

**attenuation maps**

\[
\frac{2\nabla \beta \cdot \nabla \tau}{\beta} - \frac{2\alpha}{c} = \frac{2\nabla A \cdot \nabla \tau}{A} + \nabla^2 \tau
\]

- receiver effects
- attenuation
- focusing effects

**phase-velocity maps**

\[
\frac{1}{c^2} = \nabla \tau \cdot \nabla \tau - \frac{\nabla^2 (A / \beta)}{\omega^2 (A / \beta)}
\]

**observations**
- \( \tau \) = travel times
- \( A \) = amplitudes

**unknowns**
- \( c \) = phase velocity
- \( \alpha \) = attenuation coeff.
  - \( \alpha = \omega / 2UQ \)
- \( \beta \) = site amplification

receiver effects
attenuation
focusing effects