A seismological view of the lithosphere-asthenosphere boundary

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Zaranek (2006)
Questions

- Is the seismological LAB a rheological LAB?

- Why is the lithosphere strong vs. the asthenosphere - temperature, water, melt?

- Do the properties of the lithosphere-asthenosphere boundary vary between oceans, young continents and cratons?

Fischer et al. (Ann. Rev., 2010)

*Assumes dry, depleted lithosphere
Is the seismological LAB a rheological LAB?

Yuan et al. (GJI, 2011)
Ford et al.

\[ \varepsilon = 10^{-15} / \text{s} \]
Ford et al.
Viscosity (Pa*s)

Depth (km)

\[\dot{e} = 10^{-13} / \text{s}\]

\[\dot{e} = 10^{-15} / \text{s}\]

Ford et al.
Ford et al.
• Why is the lithosphere strong vs. the asthenosphere - temperature, water, melt?
• Do the properties of the lithosphere-asthenosphere boundary vary between oceans, young continents and cratons?

Surface wave tomography

Ps receiver functions

Lekic & Romanowicz (EPSL, 2011)

Rychert & Shearer (Science, 2009)
Sp or Ps “receiver functions”

1) Decompose the wavefield into its incident P and S components using a free-surface transform (Kennett, 1991).

2) Deconvolve S from P (Sp) or P from S (Ps) using a simultaneous frequency-domain approach (Bostock, 1998) or an iterative time-domain approach (Ligorria and Ammon, 1999) and migrate to depth in 1D with corrections for lateral heterogeneity.
Measuring velocity gradients with Ps and Sp

Ps and Sp synthetic seismograms

Rychert et al. (JGR, 2007)
Oceans

Oceanic LAB \(<\sim 100\) km

PA5: Gaherty et al. (1999)
Tan & Helmberger (2007)

ScS reverberations:
Bagley & Revenaugh (2008)

Ps and Sp receiver functions:
Collins et al. (2002)
Li et al. (2004)
Kumar et al., (2007)
Rychert & Shearer (2009)
Kawakatsu et al. (2009)
Kumar & Kawakatsu (2011)

SS precursors:
Schmerr (2011)
Rychert & Shearer (2011) \(<130\) km

Nettles & Dziewonski (JGR, 2008)
Phanerozoic continents

North America
Sp Discontinuity Depth
Abt et al. (JGR, 2010)
Ford et al. (in prep)
Abt et al. (JGR, 2010)
Basin and Range / Colorado Plateau

Levander et al. (Nature, 2011)
Sp receiver functions: Eastern Australia
Ford et al. (EPSL, 2010)
Australia and North America

- Dominant Sp period $\sim 10$ s
- Sharp LAB beneath younger continent: $\Delta H < 30-40$ km, best fits $\leq 20$ km
How sharp is the LAB velocity gradient?

Combined inversions of Ps and Sp:

Rychert et al. (Nature, 2005 & JGR, 2007)

- 5.3-7.4%
- 6.0-9.6%
- <5-11 km

5.3-7.4%
NE U.S. Ps and Sp:
> 5-6 % velocity drop in 5-11 km
> 20 °C/km temperature gradient

Phanerozoic U.S. and Australia:
> 6% velocity drop in < 30-40 km
> 5 °C/km temperature gradient

*T to Vs scaling from Faul and Jackson (2005)

• Inconsistent with temperature gradients at base of lithosphere in mantle flow models (e.g. King and Ritsema, 2000; Cooper et al., 2004; Zaranek, 2006)

• Velocity gradient is too sharp or localized in depth to be defined by temperature alone

Zaranek (2006)

Cooper et al. (2004)
Sharper velocity gradients with composition or melt

- Hydration of the asthenosphere with respect to a drier, more depleted lithosphere?
  
  Chemical depletion < 2.5% (Lee, 2003)
  
  < ~1% (Schutt & Lesher, 2006)

  Volatile enrichment in asthenosphere < 3.8%
  (following Karato and Jung, 1998; Karato, 2003)

  Depletion+hydration may be sufficient if T permits

- Partial melt in the asthenosphere?
  
  Velocity drop large enough with 0.5 - 1.5%
  (Hammond and Humphreys, 2000; Kawakatsu et al., 2009) or ~2% melt (Takei and Holtzman, 2009a)
Salton Trough

Sp CCP Stack
Lekic et al. (Science, 2011)

Shear wave velocity from Rayleigh wave tomography
Rau and Forsyth (Geology, 2011)
• ~30 km of lithospheric thinning beneath Salton Trough and Inner Borderlands
• LAB topography very well-correlated with surface geology/deformation; varies over small length-scales
• High viscosity mantle lithosphere and localized strain

Lekic et al. (2011)
Cratons

North America
Sp Discontinuity Depth
Abt et al. (JGR, 2010)
Ford et al. (in prep)
North America
Sp Receiver Functions
Ford et al. (in prep)

No phase in LAB depth range
Do see discontinuity internal to lithosphere
North American Craton
Miller & Eaton (GRL, 2010)

Weak phase in LAB depth range at some stations
Also see discontinuity internal to lithosphere
Cratons:
No phase in LAB depth range
Do see discontinuity internal to lithosphere

Rychert & Shearer (Science, 2009)
Sp receiver functions: Northern Australia
Ford et al. (EPSL, 2010)

Craton:
No phase in LAB depth range
Do see discontinuity internal to lithosphere
Australia and North America (Ford et al., Abt et al.)

- Dominant Sp period ~ 10 s
- Sharp LAB beneath younger continent: $\Delta H < 30$-$40$ km, best fits $\leq 20$ km
- No cratonic LAB phase: $\Delta H > 50$-$60$ km

Synthetic Sp phases from LAB velocity gradients

10% velocity drop
Cratonic lithosphere-asthenosphere boundary

- If no LAB phase beneath cratons:
  $\Delta H > 50-60 \text{ km}$
  - Consistent with purely thermal gradient
  - Gradual gradients in composition or melt cannot be ruled out
- If LAB phase beneath cratons:
  $\Delta H < 30-40 \text{ km}$
  - Not consistent with purely thermal gradient
  - Sharper gradients in composition or melt indicated

Zaranek (2006)
Origin of mid-lithospheric discontinuity at 60-120 km?

• **Observed globally**
  - North America and Australia Sp: Abt et al., Ford et al.
  - Global Ps, Sp: Rychert & Shearer, Rychert et al., others
  - Shear velocity from tomography: Yuan & Romanowicz, Lekic et al.
  - Active source profiles: Thybo et al.

• **North America**: MLD lies within transition between cratonic lithospheric layers defined by azimuthal anisotropy (Yuan & Romanowicz, 2010)
Origin of mid-lithospheric discontinuity at 60-120 km?

• Hypothesis 1: Relict of cratonic mantle formation - base of original dry, depleted lithosphere?
  • MLD depth correlates with boundary between anisotropic layers
  • Do the MLD and anisotropic boundary reflect the same structure?

• Hypothesis 2: Reflects lithospheric alteration by upward melt percolation - top of melt cumulate layer?
  • No + phase from lower layer boundary; layer either thin (< 10 km) or lower boundary gradual (> 50 km)
Conclusions

The seismological LAB is a rheological boundary

Oceans & Phanerozoic Continents
  • LAB velocity gradient sharp (< 30-40 km in depth): volatiles and/or melt in asthenosphere
  • Salton Trough/Inner Borderlands: strong lithosphere and localized strain in mantle

Cratons
  • Debate over LAB phase at depths comparable to base of fast lid
  • If no phase, LAB velocity gradual (> 50-60 km in depth): consistent with purely thermal boundary
  • Velocity drop internal to lithosphere at 60 to 120 km (MLD)