Differentiation of the Continental Crust by Relamination

Bradley Hacker
Three Common Paradigms

- Lower continental crust is basaltic/mafic
- Continents are made in volcanoplutonic arcs
- Continents are recycled to the mantle
1. Lower Continental Crust is Mafic
2. Continents Made in Arcs
3. Continents Recycled to Mantle

http://plate-tectonic.narod.ru/

subduction erosion
Importance of Understanding the Evolution of Continents

- composition of continental crust
  - what minerals are where?
    - phase transformations
    - density & body forces
    - heat production
    - rheology, flow, elevation
  - interpretation of seismic wavespeeds
- crust–mantle mass exchange
  - evolution of crust & mantle
New Paradigms

- lower continental crust is mostly *not* mafic
- *raw* crust is made in arcs, but
- continents are refined by *relamination*
1. Lower Continental Crust is Mafic?
Why is lower crust said to be mafic?

1. xenoliths are dominantly mafic
2. $V_p = 6.7–7.3$ km/s
3. low inferred heat production

$\Rightarrow$ conclude lower crust is 80% mafic (underplated mantle melts)

Rudnick et al. [1990…2015]
Why might lower crust not be mafic?

1. ‘typical’ xenoliths may be atypical
   - many do not have garnet
   - most erupted in Phanerozoic crust
   - felsic xenoliths may be preferentially resorbed
Why might lower crust not be mafic?

2. $V_p = 6.7–7.3 \text{ km/s}$ not as diagnostic as claimed

(Hacker et al., 2015)
Why might lower crust not be mafic?

3. Low inferred heat production may be wrong

<table>
<thead>
<tr>
<th>Layer</th>
<th>Heat Flow</th>
<th>SiO₂ (wt%)</th>
<th>K₂O (wt%)</th>
<th>Th (ppm)</th>
<th>U (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Heat Flow</td>
<td>51 mW/m²</td>
<td>67</td>
<td>1.6</td>
<td>2.8</td>
<td>10.5</td>
</tr>
<tr>
<td>Upper Crust</td>
<td></td>
<td>67</td>
<td>1.6</td>
<td>2.8</td>
<td>10.5</td>
</tr>
<tr>
<td>Middle Crust</td>
<td></td>
<td>64</td>
<td>1.0</td>
<td>2.8</td>
<td>6.5</td>
</tr>
<tr>
<td>Lower Crust</td>
<td></td>
<td>53</td>
<td>0.2</td>
<td>2.8</td>
<td>12.5</td>
</tr>
<tr>
<td>Mantle Heat Flow</td>
<td>17 mW/m²</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Rudnick & Gao [2003]  
Hacker et al. [2011]  
Hacker et al. [2015]
2. Continents Made in Arcs?
Continents Made in Arcs?

‘Subduction Factory’: continental crust produced in intra-oceanic arcs from melting of mantle-wedge lithosphere.
Continents Not Made in Arcs

GeoRoc & Kelemen et al. (2006)

after Kelemen & Behn (2016)
Differentiation by **Delamination**

A) **Igneous differentiation**
[Arndt and Goldstein, 1989]

B) **Metamorphic differentiation**
[Herzberg et al., 1983; Kay & Kay, 1991]
Differentiation by Relamination

Hacker et al. (EPRL, 2011); Hacker et al. (Ann. Rev. Earth Planet. Sci., 2015)
Relamination refines ‘raw’ continental crust during convergence.

- Immature crust
- Buoyant (felsic) residue $\Rightarrow$ lower crust
- Dense (mafic) rock $\Rightarrow$ mantle
Subduction Factory + Relamination + ... = Continent Crust
3. Continents Recycled to Mantle?

1.4-2.0 km³/yr (Clift & Vannucchi, 2004; Scholl & von Huene, 2007)
Kramers & Tolstikhin (1997) ‘future Pb paradox’, based on secular increase in recycling rate, requires 60% of new crust currently be recycled into Earth’s mantle
I. Continent-Subduction Relamination

Hacker et al. (EPSL, 2011)
Buoyancy-Driven Differentiation of Subducted Continents Expected

~80% of continental crust buoyant [Hacker et al., 2015]

700 °C/ 3 GPa

sink $\bar{x} = 53$ wt% SiO$_2$

float $\bar{x} = 68$ wt% SiO$_2$

mantle

density (g/cm$^3$)

SiO$_2$

calculations by Mark Behn
Continent-Subduction Relamination Model

(Sizova et al., 2014)
Continent-Subduction Relamination

Examples: UHP Terranes

Hacker (2006)
UHP Terranes: Common, Some Giant

Variscan HP granulite massifs [Raumer et al., 2003]
Continent Relamination

Example: Bohemia

Schulmann et al. (2014)
II. Subduction-Erosion Relamination

Hacker et al. (EPSL, 2011)
Buoyancy-Driven Differentiation of Eroded Crust Expected

~80% of continental crust buoyant [Hacker et al., 2015]

~50% of arc crust buoyant [Kelemen and Behn., 2015]
Subduction-Erosion Relamination Model

Gerya & Stöckhert (2006)
Subduction Erosion Example?
Crustal Xenoliths from the Mantle

Hacker et al. (2005)
Crustal Xenolith Densities

1000° C/ 2.5 GPa

\( \bar{x} = 57 \text{ wt\% SiO}_2 \)

\( \bar{x} = 49 \text{ wt\% SiO}_2 \)

sink

float

mantle
III. Sediment Relamination

Hacker et al. (EPSL, 2011)
Buoyancy-Driven Differentiation of Subducted Sediments Expected

85% of trench sediments (Plank & Langmuir) buoyant expected to rise diapirically (Behn et al., 2011)
Sediment Relamination Model

(Gerya, 2011)
Sediment Relamination Example?

Pliocene domes of Cretaceous paragneisses hosting UHP eclogite; no young continent subduction

[Baldwin et al., 2004, 2012; Gordon et al., 2012; Little et al., 2011; Webb et al., 2008; Zirakparvar et al., 2012]
IV. Arc-Subduction Relamination

Hacker et al. (EPSL, 2011); Kellem & Behn (Nature, 2016)
Subducted Arc Lower Crust Unstable

Kohistan arc

Jagoutz & Behn (2013)

lowermost arc unstable when thick;
lower arc half unstable when subducted

~63 wt% SiO₂

~51 wt% SiO₂

volcanics

felsic plutons

mafic plutons

garnet granulite

pyroxenite

Density (kg/m³)

2600

3100

3600
Arc Relamination Example: Japan

Tamura et al. (2010): Tanzawa tonalites are 'remobilized' Izu–Bonin arc crust
Summary of Relamination

Relamination of buoyant, felsic rock

1. Sediment subduction
2. Subduction erosion
3. Continent subduction
4. Arc subduction
1. Lower Continental Crust is **Not** Mafic

- Rudnick & Gao (2014)
- Hacker et al. (2015)
2. Continents Are **Not** Made in Arcs

[Diagram showing various geological processes and features related to continental formation.]

*Image credits: Wikime.*
3. Continents Recycled & Relaminated
Relamination Could be Geodynamically/Geochemically Significant
Relamination Could be Geodynamically/Geochemically Significant

cycle time ca. 2 Gyr

continental crust
6 \times 10^9 \text{ km}^3
61 \text{ wt}\% \text{ SiO}_2
1 \times 10^{10} \text{ Tg SiO}_2

1.1-1.6 \text{ km}^3/\text{yr}
65 \text{ wt}\% \text{ SiO}_2
1.3-1.8 \text{Tg/yr SiO}_2

0.35 \text{ km}^3/\text{yr}
61 \text{ wt}\% \text{ SiO}_2
0.6 \text{Tg/yr SiO}_2

1.1-1.6 \text{ km}^3/\text{yr}
59 \text{ wt}\% \text{ SiO}_2
1.5-2.1 \text{Tg/yr SiO}_2

<0.09 \text{ km}^3/\text{yr}
63-66 \text{ wt}\% \text{ SiO}_2
<0.14 \text{Tg/yr SiO}_2

Hacker et al. (2011)
regardless of whether sediment, arc, forearc, or continental margin is subducted, if there’s buoyancy-driven differentiation—best aided by melting—the relaminated material added to the lower crust will be more felsic, i.e., differentiated
Identifying Potential Relaminants

- high-$P$ records (e.g., coesite, diamond) in granulites
- high-$P$ peridotite in granulites
- slowly exhumed UHP terranes
- low $V_p/N_S$ (i.e., felsic) lower crust
Melting Enhances Differentiation

Hacker et al. (2011)
**Delamination vs. Relamination**

**Delamination**
- removes isotopically primitive, mafic igneous rocks from crust
- \( P = 1 \) GPa
- \(~5\) Petagrams \( \text{SiO}_2 \) / yr new crust
- \(~3\) Petagrams \( \text{SiO}_2 \) / yr to mantle

**Relamination**
- adds isotopically evolved, felsic sedimentary & igneous rocks to base of crust
- \( P = 1–5 \) GPa
- \(<3\) Petagrams \( \text{SiO}_2 \) / yr relaminated
- \( >4\) Petagrams \( \text{SiO}_2 \) / yr to mantle