Speed of Melt Extraction at Mid-Ocean Ridges

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Importance of Mid-Ocean Ridges

• Central component of Earth systems
  • Largest volcanic outpouring
  • Creation of “lithosphere”
  • Facilitates plates tectonics
  • Hydrothermal circulation
  • Biological communities

Magma plays a central role in mid-ocean ridge systems

Reynolds et al., Exploring Geology
Melting at Depth

- Wide region where 1 to 2% partial melt is present.
Simplified melt migration model

1) Rapid, subvertical melt extraction below the plate
2) Sub-horizontal migration along a permeability barrier at the base of the lithosphere
3) Subvertical extraction at tectonized plate boundary

Inspired by Sparks and Parmentier, EPSL, 1991

Gregg et al., 2012
U-series disequilibrium

- Decay chains reach equilibrium where generation exactly balances decay
- Melting can perturb equilibrium during partitioning
  - Needs melting deeper than 60 km
- Equilibrium recovered after a few half lives

Peate and Hawkesworth 2005
Disequilibrium at Mid-ocean ridge

- Excess of isotopes with half lives less than $10^5$ years.
  - $^{230}$Th: 76 kyr
  - $^{231}$Pa: 33 kyr
  - $^{236}$Ra: 1.6 kyr
- Rise from 60 km depth in less than 2000 years
  - 30 m/yr
  - $10^{-6}$ m/s
Required permeability

- Melt driven upward by buoyancy
  \[ \phi (v_f - v_s) = \frac{k}{\mu} \nabla P = k \Delta \rho g / \mu \]
  - Density contrast: 300 kg/m³
  - Gravity: 10 m²/s
  - Melt viscosity: 10 Pa s
  - Porosity: 10⁻²
  - Extraction velocity: 10⁻⁶ m/s

- Required permeability: \( k = 3 \times 10^{-11} \text{ m}^2 \)
  - Grain size: 10⁻² m

- What are the values of \( n \) and \( C \)?
Previous permeability estimates

- Quartz/calcite + H₂O NaCl analogues Wark and Watson (1998) and Liang et al., (2001)
  - \( n=3, \ C=270, \ k \approx 4 \times 10^{-13} \ m^2 \)
- Centrifuge experiments Connolly et al., (2009)
  - \( n=3, \ C=10, \ k \approx 10^{-11} \ m^2 \)
- Theoretical estimates (idealized networks, von Bargen and Waff, 1986; Cheadle et al., 2004)
  - \( 10^{-11} \ m^2 \)
Digital Rock Physics (DRP)

- **High pressure experiments**
- **Virtual experiments**

**microtomography**
Experimental charges

- **Starting materials**
  - San Carlos olivine
  - Oxide mixture to produce olivine ± orthopyroxene (0%, 18%, 40%)
  - Basalt (1%, 2%, 5%, 10%, 20%)

- **Procedure:**
  - Piston cylinder experiments
  - Pressure 15 Kbars (1.5 GPa)
  - Temperature 1350°C
  - Quenched for cylindrical cores
Imaging melt microstructure

- Experimental charges Olivine ± orthopyroxene + basalt (WHOI)
- Imaging at the Advance Photon Source (Argonne National Lab)
- Synchroton X-Ray microtomography

Miller et al., 2014
Microscale melt distribution

- Interconnected network along grain edges even at 2% volume melt fraction
- Importance of wetted grain faces at larger melt fraction

Zhu et al., 2011
<table>
<thead>
<tr>
<th>Digital Rock Physics</th>
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<tbody>
<tr>
<td>• Recognize melt and olivine</td>
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<tr>
<td>• Document interconnectivity of melt network</td>
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<tr>
<td>• Simulate fluid flow through the melt network (permeability)</td>
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<tr>
<td>• Simulate currents through olivine and melt (conductivity)</td>
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Permeability of melt/rock samples

- Compute permeability for each subvolume.
  - Finite-volume Avizo® XLab Hydro module

- Power law relation between melt fractions and permeability
  - Exponent 2.6 indicate an heterogeneous network dominated by melt at triple junctions

\[ k = \frac{\phi^{2.6} d^2}{58} \]

Miller et al., 2014; 2016
New Permeability Estimates

- $n=2.6$, $C=58$, $k \sim 10^{-11}$ m$^2$, $\phi=1\% \Rightarrow$ melt velocity: 10 m/yr
- Transport time from 60 km: 6000 yr.
  - $^{226}$Ra need other explanation

Peate and Hawkesworth 2005

$\frac{k}{d^2} = \frac{\phi^{2.6} d^2}{58}$
Dissolution Channel

- Interconnected channel network
  - Melt-rock reaction (incongruent melting)
  - Porosity/viscosity/grain size feedback
  - Surface tension

If porosity is $X\phi_0$ in channels, channels take $1/X$ of space

Velocity increases by factor $X^{n-1}$

- $^{226}\text{Ra}$: Rise in 2000 yr if $X=2$
- $^{310}\text{Pb}$: Rise in 100 yr if $X=40$

\[ v_f - v_s = \frac{k\Delta \rho g}{\mu \phi} \]
Channelization at mid-ocean ridges

Weatherley and Katz, 2006