Insights into mid-ocean ridge magma chambers from volcanic eruptions

- Compositional variations in sub-axial magma reservoirs and the processes that are responsible
- The geometry of magmatic plumbing beneath and within magma reservoirs
- How reservoirs are tapped during eruptions
Mid-Ocean Ridge Magma Chambers

70’s-80’s view of MOR magma chambers

Reservoir about as wide as the Mid-Atlantic Ridge inner rift valley

Different parts of the reservoir tapped during different eruptions

Hekinian et al. (1976)
Seismic imaging and petrological study required a revision to size, longevity and internal constitution of MOR magma chambers

**fast-spreading ridge**

**slow-spreading ridge**

Quasi-steady state shallow magma chamber with thin, eruptible melt lens overlying a much thicker region of partially crystalline mush

Intermittent, deeper magma chamber, mostly smaller, deeper or less persistent than seismic resolution. Less eruptible magma

Most mid-Ocean ridge magma chambers are mostly small and mostly mush (lots of crystals), most of the time.

*Sinton & Detrick, 1992*
Along-axis; fast-spreading ridge

How much mixing along axis?
What is geometry of injection (recharge) to the shallow crust?
How are magma reservoirs tapped during eruptions? - over what along-axis distances?

Sinton & Detrick, 1992
Mid-Ocean Ridge Eruptions in North Iceland

1725-1729 Mývatn Fires near Krafla caldera
Late 1975 a new earthquake swarm caused rifting extending ~20 km south and 60 km north of the caldera.

Followed by a brief (20 min) outbreak of lava inside Krafla caldera.
20 events; 9 eruptions

Total erupted volume ~0.25 km² from reservoir ~2.5 km below surface

Erupted volume increased in each successive eruption; last one by far the largest

Erupted lava volume ~1/4 that determined to have moved through the magma system based on deformation modeling (~1 km³)
Krafla and Mývatn are the latest two of five major rifting events in the last 2800 years.

### Hverfjall Period

- **Krafla Fires:** 1975-1984
- **Mývatn Fires:** 1725-1729
- **Dalseldar:** ~900 A.D.
- **Hólseldar:** ~2300-2500 yrs. B.P.
- **Hverfell:** ~2600-2800 yrs B.P.

### Lúdent Period

- **Lúdunt, Námafjall, Kröfluháls**
- **7500 -11,000 yrs B.P.**

Eruptions grouped into episodes

Episodes grouped into periods
Lessons from Krafla

1. Rifting events and associated eruptions in Iceland are episodic.
2. Major rifting episodes comprise several events, some of which have associated eruptions.
3. Eruptions can re-occupy vents from earlier events and episodes.
4. Lava can flow back into pre-existing fissures.
Contemporaneous sampling during Krafla eruptions

Sample maps and chemical data from Karl Grønvold and Sæmundur Halldórsson

March, 1980
October, 1980
November, 1981
September, 1984
More Lessons from Krafla

1. The combined episode flow field can be readily distinguished from the products of earlier episodes (flow fields); individual lava flows are not easily discernible once the episode is completed.

2. Two chemically distinct magma reservoirs tapped in single eruptions
   Caldera lava basically the same as the Mývatn lava erupted 250 yrs earlier

1977 Photo by S. Thorarinsson
Afar Rifting: 2005 - present also is episodic

Krafla rifting episode 1975–1984

Afar rifting episode 2005–present

Annu. Rev. Earth Planet. Sci. 38:439–66
### A catalogue of known submarine MOR lava flow fields (by eruption age)

<table>
<thead>
<tr>
<th>Flow Field</th>
<th>Discovery</th>
<th>Age (method)</th>
<th>References</th>
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<tbody>
<tr>
<td>Axial Smt (JdF)</td>
<td>accidental</td>
<td>early 2011</td>
<td>Chadwick et al., 2011</td>
</tr>
<tr>
<td>9°50'N EPR</td>
<td>accidental</td>
<td>2005-6 (seismic, $^{210}$Po)</td>
<td>Tolstoy et al., 2006; Soule et al., 2007</td>
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<tr>
<td>10°45'N EPR</td>
<td>exploration</td>
<td>2003 ($^{210}$Po)</td>
<td>McClain et al., 2004; van der Zander et al., 2004</td>
</tr>
<tr>
<td>Axial Smt (JdF)</td>
<td>seismic event</td>
<td>1998 (seismic)</td>
<td>Chadwick et al., 1999; Dziak et al., 1999</td>
</tr>
<tr>
<td>N. Gorda</td>
<td>seismic event</td>
<td>1996 (seismic)</td>
<td>Chadwick et al., 1998; Rubin et al., 1998</td>
</tr>
<tr>
<td>JdF CoAxial</td>
<td>seismic event</td>
<td>1993 (seismic)</td>
<td>Dziak et al., 1995; Embley et al., 2000</td>
</tr>
<tr>
<td>9°50'N EPR</td>
<td>exploration</td>
<td>1991-92 (geology, $^{210}$Po)</td>
<td>Haymon et al., 1993; Rubin et al., 1994</td>
</tr>
<tr>
<td>17°25'S EPR (Aldo-Kihi)</td>
<td>exploration</td>
<td>Late-80s - 1993 (geology/paleointensity)</td>
<td>Auzende et al., 1996; Sinton et al., 2002; Bergmanis et al., 2007</td>
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<tr>
<td>JdF Cleft Mounds</td>
<td>megaplumes</td>
<td>1985 (megaplumes; differential seabeam)</td>
<td>Chadwick &amp; Embley, 1991</td>
</tr>
<tr>
<td>Animal Farm, SEPR</td>
<td>exploration</td>
<td>1915 ± 35 A.D. (paleointensity)</td>
<td>Auzende et al., 1996; Carlut et al., 2000; Sinton et al., 2002</td>
</tr>
<tr>
<td>SEPR Pillow mounds</td>
<td>exploration</td>
<td>1870 ± 70 A.D. (paleointensity)</td>
<td>Sinton et al., 2002; unpublished</td>
</tr>
<tr>
<td>S. Hump (2 flows)</td>
<td>exploration</td>
<td>1865 ± 45; ~1617 A.D. (paleointensity)</td>
<td>Sinton et al., 2002; unpublished</td>
</tr>
<tr>
<td>Moai (SEPR)</td>
<td>exploration</td>
<td>1785 ± 115 A.D. (paleointensity)</td>
<td>Sinton et al., 2002; unpublished</td>
</tr>
<tr>
<td>FAMOUS (Mars, Pluto, Venus)</td>
<td>exploration</td>
<td>??</td>
<td>Ballard and van Andel (1977)</td>
</tr>
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</table>
Seismo-acoustically detected eruption on the Gorda Ridge - 1996

Chadwick et al., 1998
1996 North Gorda Ridge

Chemically variable lava eruption

Systematic variation with sample (eruption?) location
1993 Co-Axial

1.6
1.65
1.7
1.75

Mg #

47 48 49 50

65

50.0
49.5
49.0
48.5
48.0
47.5
46.51 46.52 46.53 46.54 46.55

Degrees N. Latitude

Mg #

TiO₂ wt %

4.7 4.8 4.9 5.0

1.65 1.7 1.75

47 48 49 50

Degrees N. Latitude

Mg #
Is vertical diking necessary to explain the chemical variations along axis?

What is the relationship between magma transport and seismic propagation?

• Seismic propagation indicates migration of stress release, which may or may not track dike propagation

• Along-axis migration of epicenters is expected for “unzipping” during vertical rise of inclined dikes

• Correlations between seismic migration and deformation are consistent with lateral dike migration

Migration rates for various seafloor seismic “events” in the NE Pacific and Krafla

[after Dziak et al., Geology, 2007]
Southern EPR

Relatively “young” lava fills the floor of a narrow axial graben in the S. Hump

- First discovered in 1993 (ND-11)
- Later revisited in 1999 (Alvin dives 3347 and 3348)
But the northern and southern parts of the flow field have very different compositions, which cannot be related by fractionation.
And the two different lava compositions differ in age by ~150 yrs

Magnetic paleointensity data of Bowles (2006)
The relationship between lava composition and the AMC discontinuity requires (?) near-vertical (<1 km lateral) transport of lava from the AMC to the surface, at least for the younger lava eruption.

“Boundary” between the two lava flows coincides with discontinuity in underlying AMC reflector and layer 2A structure.
Compositional heterogeneity EPR eruptions near 9°50’ N

Chemical data from Rubin et al. (2001) and Goss et al. (2009)

2005-6 flow field map from Soule et al. (2007)
Note:
- Significant along-axis compositional variation, and
- change in Mg# across the tiny 9°52.5’N axial discontinuity for both eruptions
EPR near 17°30’ S

4 (maybe 5) eruptive episodes in last ~500 yrs
- Last one in late 80’s to early 90’s

Bergmanis et al., 2007
For last two eruptions:
- Center of eruptive activity where the magma lens is shallow and relatively low temperature; not at the hottest part of the magma lens
- MgO and magma temperature generally correlate with AMC depth

After Bergmanis et al., 2007
Step in MgO content south of the long-lived small axial discontinuity at 17°29’S.

South of 17°29’S, erupted volume and hydrothermal venting are less, and the AMC is deeper and narrower.

-This relationship strongly suggests vertical diking from a magma reservoir characterized by long-lived chemical heterogeneity.

After Rubin et al., 2010
Chemical variations within the two youngest lavas are dominated by mixing:

- a low-MgO, low-$^{206}\text{Pb}/^{204}\text{Pb}$ magma residing in the magma reservoir, and

- magma with high MgO and $^{206}\text{Pb}/^{204}\text{Pb}$ that was injected within 20 years prior to 1993 (collection date).
See-saw pattern of isotopic variation along axis

- Variation in amount of newly arrived, high \(^{206}\text{Pb}/^{204}\text{Pb}\) magma that is progressively mixed with resident low-\(^{206}\text{Pb}/^{204}\text{Pb}\) magma in the shallow melt lens.
- In this interpretation, the high \(^{206}\text{Pb}/^{204}\text{Pb}\) regions represent locations (concentrations) of recent magma injection to the shallow lens.
Lava flow fields (from isolated eruptive episodes) can be chemically heterogeneous.

- Some are; some aren’t

- Where present, heterogeneity unlikely to be produced during eruptions; rather it likely reflects variation in underlying magma reservoirs.

- suggests limited mixing in subaxial magma reservoirs, either because of their shape (road-kill-cigar-shaped melt lens), inhibited mixing in crystal-rich mush zones, or because frequency of recharge exceeds the time scales for mixing
Evidence for Vertical Diking during Mid-Ocean Ridge Eruptions

1. Preservation of crustal reservoir properties in surface lava flow fields
   Requires vertical rise of magma to the surface with limited along-axis mixing, either within dikes or in surface lava after eruption
   Examples: EPR 17.5°S, S. Hump

2. Correlations of along-axis chemical variations with ridge axial discontinuities or other structures
   Axial discontinuities reflect deeper level variations in magma chamber or thermal structure
   Examples: EPR 17.5°S; 9°50’N; Krafla

3. Along-axis variations in magma temperature and chemistry
   Most likely correspond to similar gradients in reservoir chemistry and temperature
   Examples: EPR 17.5°S; 9°52’N; N. Gorda, Co-Axial

Eruptions represent only one (last) part of a rifting event. Considerable lateral migration possible prior to eruption
Flow fields without chemical heterogeneity provide little information about nature of subaxial reservoirs or magma transport processes