Volcanoes and the Mantle in Rifts

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Albuquerque, Rio Grande Rift
Rio Grande Rift

Hydrated lithosphere during earlier subduction (60 Ma)

Crossey et al., 2010
Sine et al., 2008

Northern East African Rift

Mantle Plume

Bastow et al., 2010

Nature and Role of Mantle Fluids (melts, volatiles)
Importance of integrated studies (cross-discipline and geography)
QuickTime™ and a decompressor are needed to see this picture.
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Depiction of the Nyiragongo and Nyamuragira volcanoes, based on data from the Shuttle Radar Topography Mission, Advanced Spaceborne Thermal Emission and Reflection Radiometer, or Aster, and Landsat. Some lava flows (not all) from the 2002-01-17 eruption are shown in red.
Around 10:00 p.m. local time on November 27, 2006, Mount Nyamulagira erupted.
Stratospheric SO$_2$ emission during eruptions

TOMS group, NASA
Stratospheric SO$_2$ emission during eruptions

1 Mt

9 - 11 Mega tons of SO$_2$ per km$^3$ of erupted magma
(Carn & Bluth, 2003)

Iceland flood basalts:
5-9 Mega tons of SO$_2$ per km$^3$ of erupted magma
(Thordarsson & Self, 2003)
Great Variety of Rock Compositions!

Silicon Dioxide (wt%) vs. 

- Rio Grande Rift
- East African Rift
- Mid African Rift
- Antarctic Rift
- MORB
- Global nephelinites
- Aleutian Arc
- Central America

Alkaline and subalkaline rock compositions are indicated in the plot.
Spectacularly Active Volcanoes!

Active Volcanoes in Africa

Dallol, Nyamuragira, Nyiragongo, Ol Doinyo Lengai, Mount Cameroon, Addis Ababa, Cairo, Dar es Salaam, Cape Town
The East African Rift

~ 3000 km long

Western and Eastern Branch

Extensive volcanism (~20% rhyolites/ignimbrites)

Earliest Volc. 45 Ma (S-Ethiopia)

Huge Shield Volcanoes

Ethiopia Flood basalts (30 - 1 Ma)

Continental Flood Basalt Provinces are related to mantle plumes (e.g. White and McKenzie, 1995)

Tertiary volcanic rocks plate trajectories from 50 m.y. to 10 m.y.

S-Ethiopia was positioned over Kenya plume 50 m.y. ago

Two Plumes
Afar and Kenya (e.g. Ebinger et al., 1989)

George et al., 2010
Plume locations and eruption rates

George et al., 2010
Plume locations and eruption rates

Average Iceland, Hawaii

Afar Plume

George et al., 2010

Plume locations and eruption rates

Center of the Kenyan mantle plume
Onset of earliest magmatic event
Northern Ethiopian Flood Basalts

Eruption Rate (km$^3$/yr$^{-1}$)

RGR

~ 0.0002 km$^3$/yr

Southern NM Calderas
~ 33 - 28 Ma
Additional ~ 5000 km$^3$

0.01 km$^3$/yr

Southern Ethiopia

Northern Ethiopia

Turkana Depression

Central Kenyan Rift

Northern Kenya

Northern Tanzania

Onset of earliest magmatic event

Latitude

Age (Ma)

0
15°
10°
5°
0°
5°
10°
15°

Age (Ma)

0
50
10
40
30
20
15
10
5
0

Age (Ma)

30
40
50
0
The East African Rift

Enrichment in LILE compared to MORB -> similar to OIB or Plume

East African Rift System.
a. Pre-rift stage, asthenospheric mantle rises into the lithosphere. Decompression melting produces variably alkaline melts. Some partial melting of the metasomatized sub-continental lithospheric mantle (SCLM) may also occur.
b. Rift stage: development of continental rifting, eruption of alkaline magmas (red) mostly from a deep asthenospheric source.
c. Afar stage, in which asthenospheric ascent reaches crustal levels. This is transitional to the development of oceanic crust.

Anisotropy: Large-scale mantle flow in astenosphere associated with the superplume

Bastow et al., 2010
Plume location

Bastow et al., 2010
Geochemical/petrologic considerations

Rooney et al., 2007
Geochemical/petrologic considerations

Rooney et al., 2007
Geochemical/petrologic considerations

OIB-like REE

Rooney et al., 2007
Plume R/Ra > 9

Helium isotopes (phenocrysts, gas)
Pik et al., 2006

Deep Plume
“like Iceland”

Shallow mantle
upwelling
< 400 km

Plume R/Ra > 9

R/Ra 6-9
Aqueous Fluids from Slab in ARCS

FLUIDS??

SiO2 (wt%)
Melt inclusions: pre-eruptive melt volatile contents

Allow for assessment of pre-eruptive melt composition since they are assumed to be less susceptible to degassing and contamination than glasses
Melt inclusions: pre-eruptive melt volatile contents

H₂O (wt%) vs N-MORB

Volcanic Arcs

Fuego, Guatemala

Etna

Cerro Negro, Nicaragua

Open-system degassing

Georoc database and Roggensack et al., 2001
Melt inclusions: pre-eruptive melt volatile contents

'E' fields' from Wallace, 2005

Georoc database and Roggensack et al., 2001
In Arcs fluids come from the slab.

Slab dehydration.

Schmidt+Poli, 1998
Trace amounts of H₂O enhance melting.

\[ T_p = 1300 \, ^\circ C, \ [H_2O] = 0 \, \text{p.p.m.}, \]
\[ P_o = 1.3 \, \text{GPa}, F_B = 0.068, Z_c = 2.8 \, \text{km} \]

\[ T_p = 1300 \, ^\circ C, \ [H_2O] = 750 \, \text{p.p.m.}, \]
\[ P_o = 2.6 \, \text{GPa}, F_B = 0.043, Z_c = 3.7 \, \text{km} \]

Hirth & Kohlstedt, 1996;
Asimow & Langmuir, 2003

From: Hirschman’s MARGINS talk
WHOI 2006
CO$_2$ also enhances melting....

Dasgupta & Hirschmann (2006) - Nature

From: Hirschman’s MARGINS talk
WHOI 2006
Melt inclusions (Lavas-olivines) -not much data! (yet)

Kilauea
E-MORB

N-MORB

Mt. Cameroon

H₂O (wt%)

0 0.5 1 1.5 2

African Rifts

Suh, 2008 ‘fields’ from Wallace, 2005

Georoc MI data-base (last update 2010)
Rungwe-region, Southern Tanzania

Gas sampling
(fumaroles; springs; cold, pure CO₂ vents)
CO₂ (and Nitrogen) in Gas Emissions (Lengai and Rungwe)

Fischer et al. 2009
and Barry, Hilton et al., 2009 AGU
CO$_2$ and N$_2$ in Gas Emissions (Lengai and Rungwe)

- Mantle w/ CO$_2$
  - 1% CO$_2$
  - 100-300 ppm
  - 0.01% Non-mantle CO$_2$ N$_2$

- RGR (Crossey et al.)

- CO$_2$ and N$_2$ rich Sediments

- AIR

Fischer et al. 2009
and Barry, Hilton et al., 2009 AGU
Rio Grande Rift

B Laramide Orogeny (ca. 60 Ma)

Inactive Sierra Nevada magmatic arc
Inactive fold-and-thrust belt
Colorado Plateau uplift
Rocky Mountain uplift and magmatism in Colorado Mineral Belt

Crust
Melting
Lithospheric
mantle

Regionally widespread hydration (including CO$_2$) of lithosphere during flat subduction, but little addition of $^3$He

C Oligocene ignimbrite flare-up (35–25 Ma)

San Andreas Fault
Basin Range extension and volcanism

Uplifting Western U.S.
Colorado Plateau
Early Rio Grande rift extension and San Juan Volcanism

Pacific Plate
Farallon slab fragment

Focused magmatism due to delamination and addition of $^3$He in Basin and Range

Crossey et al., 2010
Melt inclusions (Lavas) - not much data! (yet)

Max solubility 4 kbar (NNO+4)

Sulfide solubility 4 kbar (NNO-2)

H₂O (wt%)
Melt inclusions (Lavas) - not much data! (yet)

Max solubility 4 kbar (NNO+4)
sulfide solubility 4 kbar (NNO-2)

Suh, 2008; Wilding, 1993; Lowenstern, 1997
### Oldoinyo Lengai Gas

<table>
<thead>
<tr>
<th>Component</th>
<th>OLD 1</th>
<th>OLD 2</th>
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</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>85.35</td>
<td>76.84</td>
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<tr>
<td>CO₂</td>
<td>14.13</td>
<td>22.80</td>
</tr>
<tr>
<td>Stotal</td>
<td>0.128</td>
<td>0.104</td>
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<tr>
<td>SO₂</td>
<td>0.060</td>
<td>0.039</td>
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<tr>
<td>H₂S</td>
<td>0.068</td>
<td>0.066</td>
</tr>
<tr>
<td>HCl</td>
<td>0.068</td>
<td>0.044</td>
</tr>
<tr>
<td>HF</td>
<td>n.m.</td>
<td>n.m.</td>
</tr>
<tr>
<td>He</td>
<td>0.0004</td>
<td>0.0001</td>
</tr>
<tr>
<td>H₂</td>
<td>0.2299</td>
<td>0.1633</td>
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<tr>
<td>Ar</td>
<td>0.0014</td>
<td>0.0003</td>
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<tr>
<td>O₂</td>
<td>0.0009</td>
<td>n.d.</td>
</tr>
<tr>
<td>N₂</td>
<td>0.0687</td>
<td>0.0276</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.0002</td>
<td>0.0001</td>
</tr>
<tr>
<td>CO</td>
<td>0.0242</td>
<td>0.0169</td>
</tr>
</tbody>
</table>

*in mol % total gas*
Oldoinyo Lengai Rocks

Volatiles analyzed by SIMS (DTM)
July 4 2005 Carbonatite Lava flow

<table>
<thead>
<tr>
<th>wt% H2O</th>
<th>CO2 (wt%)</th>
<th>S (ppm)</th>
<th>Cl (ppm)</th>
<th>F (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.022376</td>
<td>&gt; 9.69</td>
<td>8376</td>
<td>9909</td>
<td>4495</td>
</tr>
<tr>
<td>0.103099</td>
<td>&gt; 11.75</td>
<td>2242</td>
<td>5647</td>
<td>640</td>
</tr>
<tr>
<td>0.016047</td>
<td>&gt; 10.34</td>
<td>2255</td>
<td>5791</td>
<td>664</td>
</tr>
</tbody>
</table>

OLD.

N- MORB  0.1-0.5  0.01-0.03  800-1500  <100

Arcs  3.1-6.1  0 - 0.21  to 6000  to 4100

OLD Nephelinite 2009:  up to 0.8 wt% in glass and MI

Fischer et al., 2006
de Moor et al., AGU 2009

MORB glasses and arc melt inclusions  from Wallace, 2005
Sulfur Degassing Model -> estimate S content and $\delta^{34}$S in source

**Lengai**

2005 & 2009

Nepheline glass/MI

0.8 wt% S

$\delta^{34}$S -0.7 %

Mantle volatiles

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**de Moor et al. 2010 for Anatahan, Marianas**

**Fischer et al., AGU 2009**

de Moor et al., AGU 2009
Some Issues related to Volcanoes and the Mantle

- Connection between mantle volatiles (H$_2$O, CO$_2$, S) and melt production/composition/location in rifts
- Volatile fluxes into and out of rifts not constrained
- Is ‘big mantle plume’ below Afar expressed in volatile/fluid composition at surface (beyond Helium)?
- Role of mantle CO$_2$ (experiments vs. observations)
- Role of mantle sulfur in melt generation
- Nature and role of metasomatism in melt generation