Dynamic Model of Lithospheric drip Magmatism in western arm of EARS and its Implication for Geothermal Occurrences

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Research accepted for publication in Geochimica et Cosmochimica Acta (Furman et al. 2016)
East African Rift System - Today

- Eastern “Kenya” Rift (Tanzania)
- Main Ethiopian Rift valley floor
- Oldoinyo Lengai (Tanzania)
East African Rift System - Today

Nyiragongo Volcano (D.R.C.)

Ertā ‘Ale Volcano (Eritrea)
Mantle Plumes and EARS volcanism

- Plume models vary
  - One “runny” plume (Ebinger & Sleep, 1998)
  - Two completely separate plumes – one with a HIMU signature (e.g. George et al., 1998)
  - Two shallow plumes the merge into one plume with depth (e.g. Furman et al., 2006)
Plume Mantle Fingerprinting: $^3\text{He}/^4\text{He}$

- **Afar Plume:**
  - $^3\text{He}/^4\text{He} > 9\text{Ra}$
  - Up to 19.6Ra
  - Note: Baffin Island max = 49.5Ra (Stuart et al 2003)

- **Depleted MORB Mantle**
  - $8 \pm 1\text{Ra}$

- **Subcontinental Lithospheric Mantle**
  - 5-7Ra
Mantle structure beneath Africa and Arabia from adaptively parameterized P-wave tomography: Implications for the origin of Cenozoic Afro-Arabian tectonism

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“Flavors” of Volcanism

- Highly sodic volcanism
- Alkaline to Highly potassic volcanism
- Transitional to Alkaline lavas
Classic Mechanisms for Melt Generation

Bastow et al. (2011)
Geochemical Conundrums

- 30 Ma high-Ti “Mantle Plume” flood basalts and picrites
  - Why do they record radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ (~0.704)?

![Geochemical Diagram]

Western Branch Technical Workshop

Kigali, Rwanda. March 10, 2016
Geochemical Conundrums

- 30 Ma high-Ti “Mantle Plume” flood basalts and picrites
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  - Why are there significant $\text{K}_2\text{O}$ depletions and $\text{TiO}_2$-enrichments?

(Pik et al. 1998)
Geochemical Conundrums

- 30 Ma high-Ti “Mantle Plume” flood basalts and picrites
  - Why do they record radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ (~0.704)?
  - Why are there significant $\text{K}_2\text{O}$ depletions and TiO$_2$-enrichments?
  - Why are lithospheric mantle $^{187}\text{Os}/^{188}\text{Os}$ isotopes similar to flood basalt values?

<table>
<thead>
<tr>
<th>187Os/188Os</th>
<th>Basalts: 0.1247-0.1323</th>
<th>Xenoliths: 0.1261-0.1295</th>
</tr>
</thead>
</table>

(Rogers et al., 2010; Nelson et al., 2012; Nelson, unpublished data)
Geochemical Conundrums

- 30 Ma high-Ti “Mantle Plume” flood basalts and picrites
  - Why do they record radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ (~0.704)?
  - Why are there significant $\text{K}_2\text{O}$ depletions and $\text{TiO}_2$-enrichments?
  - Why are the $^{187}\text{Os}/^{188}\text{Os}$ isotopes mildly unradiogenic, similar lithospheric peridotite xenoliths in the region?

- 26-20 Ma pre-rifting volcanism
  - Why does is there a widespread have a HIMU-flavor (elevated $^{206}\text{Pb}/^{208}\text{Pb}$) that is absent in younger volcanism?
Additional Mechanism for Melt Generation

Continental magmatism, volatile recycling, and a heterogeneous mantle caused by lithospheric gravitational instabilities
Linda T. Elkins-Tanton\textsuperscript{1,2}

Mantle melting beneath the Tibetan Plateau: Experimental constraints on ultrapotassic magmatism
Eva S. Holbig\textsuperscript{1,2} and Timothy L. Grove\textsuperscript{1}

Mantle-drip magmatism beneath the Altiplano-Puna plateau, central Andes
M.N. Ducea\textsuperscript{1,2}, A.C. Seclaman\textsuperscript{1,2}, K.E. Murray\textsuperscript{2}, D. Jianu\textsuperscript{1}, and L.M. Schoenbohm\textsuperscript{2}

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\textsuperscript{2}University of Arizona, Department of Geosciences, Tucson, Arizona 85721, USA
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Geology, 2013 v. 41, 915-918

Continuing Colorado plateau uplift by delamination-style convective lithospheric downwelling
A. Levander\textsuperscript{1}, B. Schmandt\textsuperscript{2}, M. S. Miller\textsuperscript{3}, K. Liu\textsuperscript{1}, K. E. Karlstrom\textsuperscript{4}, R. S. Crow\textsuperscript{4}, C.-T. A. Lee\textsuperscript{1} & E. D. Humphreys\textsuperscript{2}

LETTER

doi:10.1038/nature10001
Drip vs. Adiabatic Melting

HOLBIG AND GROVE: TIBETAN PLATEAU MANTLE MELTING

JGR, 2008 v. 114, B04210
Why Would Lithosphere Drip?

- Dry, peridotitic continental lithosphere is
  - Rigid
  - Stable

- Metasomatizing the mantle changes stability.
  - Reintroduce fluids (e.g. phlogopite, amphibole, carbonate).
  - Alter mineralogy to highly fusible minerals (e.g. pyroxene).
  - Pyroxene-rich (pyroxenite) lithologies are more dense than peridotite lithologies.
  - New mineralogy is more ductile.
Lithospheric Drip Melting

- Lithosphere
- Convecting Asthenosphere
- Metasomatized "dense" lithosphere
Lithospheric Drip Melting

- Dominated by pyroxenite melt

Increasing heat with depth $\rightarrow$ melting pyroxenitic material
Lithospheric Drip Melting

- Dominated by pyroxenite melt
  - Adiabatic
  - Flux Melting

- Dominated by peridotite melt
  - Adiabatic
  - Flux Melting

Peridotite “fills in” space left by drip, allowing peridotite to melt adiabatically.

Devolatilization of descending drip can flux-melt surrounding peridotite.
Lithospheric Drip Melting

- Dominated by pyroxenite melt
- Dominated by peridotite melt
  - Adiabatic
  - Hydration
- Combination of both – pyroxenite then peridotite
Pan-Africa: 900-500 Ma

Modified after Stern (2002) and Küster & Harms (2011)
Drip Magmatism: Geochemical Test

(Furman et al, accepted)
30 Ma Flood Basalts
30Ma Flood Basalts

Furman et al. *accepted* (GCA)
(Data sources: Pik et al., 1998; Beccaluva et al., 2009)
26-16 Ma Mafic Lavas
26-16 Ma Mafic Lavas

Furman et al. *accepted* (GCA)
(Data sources: Furman et al. 2006; George & Rogers, 2002; Kieffer et al., 2004)
< 10 Ma Mafic Lavas
< 10Ma Mafic Lavas

Furman et al. *accepted* (GCA)
What is melting?

![Graph showing the relationship between Mn/Zn and 1000*Zn/Fe for different samples labeled as HT2, HT1, and LT, with two regions labeled as Pyroxenite and Peridotite.]

Furman et al. *accepted* (GCA)
What is melting?

Furman et al. *accepted* (GCA)
What is melting?

Furman et al. *accepted* (GCA)
Lithospheric Drip Magmatism: Flood Basalts

Future Afar Margin
ETHIOPIA ← YEMEN

LT  HT-1  HT-2  HT-1

Asthenosphere

Lithosphere

Crust

Plume-metasomatized mantle; generates low-Ti (LT) basalts

Plume-metasomatized mantle; generates high-Ti (HT) basalts, some with amphibole

Furman et al. accepted (GCA)
Drip Melting and the Western Rift

- If lithospheric drip melting is a processes that occurs across the EARS,
  - What are the implications for magma production?
  - How does this affect the formation of crust-level magma chambers necessary for productive geothermal reservoirs?
Western Rift – New Localities

Bufumbira & Virunga

Katwe-Kikorongo
Western Rift – New Localities

Virunga, Bufumbira, and Katwe Kikorongo lavas

Normative olivine (%) vs. Cr ppm

(Pitcavage et al., 2015)
Lithospheric Foundering and Magma Production

- Lithospheric drip magmatism
  - Is finite
  - Is low volume
  - Is limited to the size and speed of descending lithosphere
  - Can be a mixture of peridotite and pyroxenite end members, which will affect
    - Major element compositions
    - Isotopic ratios
Depth of Melting

(Rosenthal et al, 2009)
Summary

- Lithospheric drip melting may play an important role in localized magma production.
- Evidence for lithospheric drip is found in:
  - Oligocene high-Ti (HT2) flood basalts
  - Miocene and Quaternary Turkana basalts
  - Quaternary Chyulu Hills
  - Eastern Virunga, Bufumbira, and Katwe-Kikorongo
- Little to no evidence for drip magmatism in Kivu and Rungwe
- The low-volume, highly alkaline magmas are not likely to stall in the crust and, therefore, are unlikely to form long-lived magma chambers.