Fluid Fluxes and Crustal Dynamics: Insights from Rift zones

Cynthia Ebinger
University of Rochester, New York
Carbon flux –
Top – plausible carbonate melting zones (connected if mantle is oxidized)

Bottom – flux estimates
No continental rift flux?

Dasgupta and Hirschmann, 2010
Global water budget

No continental rift flux?

Contribution from mantle serpentinization during late rifting and rupture – increased flux during initial stages of collision?

Parai and Mukhopadhyay, 2012
Seismicity – short time scale response of elastic lithosphere

intraplate stress field changes
interseismic stress buildup, magma buildup
volcano recharge
seasonal stresses
diking
fault slip (aseismic)
fault slip (seismogenic)
Deep mantle to surface flux
Volcano plumbing systems = known conduits for volatile flux and magmas
Consider volcanic arc and rift systems, with emphasis on data from East African superplume province
What are fluxes, and implications for mass transfer?
What are implications for strain localization and rheology?

CO$_2$ degassing along faults
Locations of plumes detected in the lower mantle

Evidence for hydrous upwelling and melt layer above the lower mantle anomaly

Thompson et al., G-cubed, 2014; also seen in regional study of Nyblade and Julià, 2013
Lithospheric thickness variations surface wave analyses (prior to CRAFTI, SEGMeNT, PRIDE)

Contours - Red = positive FAA; Blue = negative FAA

Deeply rooted cratons dominate patterns (Tanzania craton outside resolution)

Surface wave model - Fishwick and Bastow, 2011
SKS, surface wave, and crustal shear-wave splitting measurements show strong rift parallel splitting – magma-filled cracks; constraints on depth distribution and crack dimensions

SKS, shear wave - Kendall et al. 2005, 2006; Crust - Keir et al., 2011
Extensional strain and magmatism beneath > 100 km-thick lithosphere widely distributed – what is stable?

Seismic moment release using NEIC (complete to ca M 4.5).

$$M_0 = \mu A s$$

where is shear modulus of rock at EQ source, and $A$ is area of fault plane, and $s$ is slip

$$\sim 10^2 \text{ y of } 10^3-10^5 \text{ y interseismic cycle}$$

Lindsey et al., submitted
Vola_les and lithospheric preconditioning–hints from xenoliths+ anisotropy

Vauchez et al., 2004
Rheologically layered lithosphere-plume interaction model

Koptev et al., Nature Geoscience, 2015
Natron-Magadi basin: < 7 My since onset of magmatism; developed in Archaean lithosphere

- Hypocentral depths > 15 km
- Gas sample site

Strain linkage between basins via magma intrusion

SEGMENT LINKAGE (STRAIN TRANSFER) VIA MAGMA INTRUSION

A

B

B'

Border fault

Monocline

Magma intrusion zone

Dike intrusion zone

Faulted shield volcano

Strain by magma intrusion and slip along border fault

NT=5

NL=12

NL=11

NL=4

NT=3

NL=10

Manyara basin

35.4 35.6 35.8 36 36.2 36.4 36.6

-3.4 -3.2 -3.0 -2.8 -2.6 -2.4 -2.2 -2.0 -1.8 -1.6

Ketumbeine

Gelai volcano

Uplifted flank

Border fault abandonment?
Box encloses depth range of Vp increase with elevated T – Guerri et al., 2015

Depth distribution similar to weakly magmatic crust in N Tanzania (Albaric et al., 2009; 2013)

Active intrusion into upper mantle or lower crust?

S. Tanganyika: amagmatic?

Natron-Magadi: < 7Ma magmatic
Initiation of magmatic segment?

Archaean craton

mantle lithosphere

CO$_2$

Intrusion zone?

S-wave velocities; ANT, body wave, gravity joint inversion –Roecker et al., in review.; RF – Plasman et al. in review
CO₂ flux along fault systems in Natron-Magadi basins highest measured worldwide. Mantle sourced fluids (metasomatic fluids, magma production). 71 ± 33 Mty⁻¹ - ca. 11 % of global budget and comparable to MOR 5-90 km³ km⁻¹ My⁻¹ for Eastern rift, Africa vs 82 km³ km⁻¹ My⁻¹ in Aleutians (Holbrook et al., 1999)

Working Model: Microseisms and saline fluids maintain permeable pathway for volatiles; lower crustal seismicity is caused by high pore pressures and magma intrusion
Large strain, steady-state rheological models for phyllosilicates allow for foliation development, cataclasis, pressure-solution - show velocity-dependent behavior

A = plastic flow in phyllosilicates
B = frictional slip over foliae
C = pressure solution controlled strength
D = dilatational cataclasis – sliding by dilatation

Niemeijer & Spiers, Geol Soc London 2005;
How does CO$_2$ change fault zone rheology?

- Simple answer – wish we knew

- CO$_2$ is supercritical fluid in lower crust – but no experimental data (experimental work by Pluymakers, Samuelson, Spiers applicable to shallow CO$_2$ reservoirs)

- High pore pressures from CO$_2$ fluid phases may reduce strength of cratonic lithosphere, facilitating early stage rifting
Rifts and return flux of water to mantle at subduction zones

Bayrakci et al., Nature Geosci. 2016
Modelling Directions

• Non-rigid plate behavior during cratonic delamination – wider range of rheologies considered
• Rapid rise of magma through thick lithosphere
• Organization of along-axis crustal intrusion zones = segmentation
• Less emphasis on strain via faulting and more on strain accommodation via magmatism with concomitant heating, volatile release
Basaltic melt volumes at incipient seafloor spreading centers in Afar

2D joint inverse models of transverse electrical data – with RF waveforms superposed

5-20 km depth
13% melt

(compares to 4-20% melt on MAR)

Desissa et al., Nature Geosci., 2013
Silicic melt volume - Altiplano Puno Volcanic Complex

MT > 18-19 km (20-80% melt)
Seismic: 4-25 km (10-25% melt); gravity (0-90% melt) Comeau et al. 2015; Ward et al. 2014, del Potro et al. 2013
East Africa rift system

Developed in Archaean to Proterozoic lithosphere – eastern areas deformed in Pan-African (ca. 500 Ma thermal event) and Permo-Triassic and enigmatic Palaeogene rifting episodes (blue faults)

New geochron documents synchronous development of MER, Eastern, Western rift ca. 17-25 Ma, but with diachronieity within each sector, regular re-arrangements
CO$_2$ flux in Eastern rift comparable to volcanic arcs worldwide

Lee et al., 2016
Inverse models of river profiles indicate rapid development of topography, consistent with shorter time scale fluid fluxes from more convecting mantle.

Nicky likens mantle to a ‘waterbed’

*Rundle, Roberts, White and Richardson, 2014*
Cross-sections: topography has $VE \sim 10:1; \sim 2$: below zero

Major faults from PROBE TPDC-Beach seismic reflection data; hypoDD depths

Lighter blue EQs have <20 km location error. Deepest EQs have dips 40° – soling into detachment?

D. Keir and students, Southampton, C. Ebinger and students, Rochester
Evidence for decompression melting and trapped melt at the LAB, above the hydrous upwelling =Sp and Ps receiver function analyses

Hammond et al. 2013; Bastow 2011

Rychert et al., Nat. Geo. 2012
Upward-migrating earthquake swarms in upper mantle and crust – Albert-Edward rift zone, Western rift

Ps, Sp RF constrain crust, mantle depths – Lindenfeld et al. Tectono, 2012
Topography at LAB controls adiabatic decompression melting and subsequent melt ponding

How do melt ponding and percolation through the plates influence plate rheology?

What is role of lateral heterogeneities in strain localization?

Role of magma and volatiles on fault zone rheology?
Stacked, multi-tapered waveforms

-Similar patterns seen beneath oceanic plates:

Pacific superplume—e.g., Hawaii, Galapagos

Rychert et al., 2013; Huckfeldt et al., 2013
Plate forces inadequate to initiate rifting. Magma buoyancy adds to tectonic stress and enables rifting in <100 km-thick lithosphere. Metasomatic - weaken plate to enable rifting of ca. 150 km-thick EAR lithosphere?

Buck 2004; Bialas et al., 2010; Bott, 1991
Active Solid Earth Summary

• Active and time-averaged patterns consistent
• High pore fluid pressures from magmatic degassing enable faulting, fluid migration from mantle to surface, yet raise new questions about lower crustal earthquakes and rock vs fault zone rheology
• Mantle xenoliths, petroleum & geothermal exploration reveals CO$_2$-charged systems in Western and Eastern rift.- widespread metasomatism above mantle plume?
• Rift zone magmatism and mantle degassing large contribution to global budgets (11% of C budget)
• Magma fluxes to crust comparable to volcanic arcs
• Fluids contribute to faster rates of topography formation
Big Wrap-Up Part

- Fluxes – comparisons with volcanic arcs
- Surface processes and orographic relief

Mt Doom
Burov, 2011

\[ q = 60 \text{ mWm}^{-2} \]

\[ z_{(1330^\circ C)} = 100 \text{ km} \]

\[ z_{(1330^\circ C)} = 200 \text{ km} \]