What are the relative roles of discrete & transient events in the breakup of continents and the onset of seafloor spreading?

And, hazard implications

Cindy Ebinger
Objectives

• Briefly review rift to rupture concepts. What part of the EQ + magma chamber overpressure cycles is captured in any study area?

• Highlight consensus and contention in terms of time-space patterns of strain accommodation in lithosphere

• Quantify strain accommodation during discrete events in magmatic and amagmatic rift zones, including faults above propagating dikes, and compare with classic ‘time-averaged’ deformation (10’s -1000’s of rifting cycles)?

• Role of fluids

• Emphasize critical need for space-based, drone, land, marine techniques and multi-disciplinary approaches to solve fundamental questions

• Broader Implications: Rifts provide key clues into tectono-magmatic triggering of eruptions
As rifting progresses to seafloor spreading, % strain accommodated by magma intrusion increases to ~100%. How does ’wet lithosphere’ deform?

Space-time response of plate depends on rheology

Questions – ask Fischer – Thursday AM
Rheology

• Elastic behavior in parts or all of crust, upper mantle, depending on geotherm; composition, hydration state
• Visco-elastic behavior – strong time dependence – post-seismic, post-intrusion deformation > steady plate motion.
• Where rock pores are filled with fluids, poroelastic effects are superposed - added complexity and added deformation (e.g., 1990 Dobi, Afar sequence)

Burgmann & Desen, 2008
Extensional strain and magmatism widely distributed in highly variable lithosphere—What is stable?

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

\[ M_0 = \mu A s \]

where \( \mu \) is shear modulus of rock at EQ source, \( A \) = area of fault plane, \( s \) is slip.
Geodetic and seismic evidence that strain has localized to narrow zone after < 15 My rift evolution in MER and Afar.

Ca. 150 km-wide plate boundary deformation zone vs 1000 km in magma-poor /initially thicker lithosphere.

East-directed velocity with distance from rift – Birhanu, Bendick, Fisseha, Lewi, Lloyd, King, Reilinger, GRL 2016.
< 5 Ma rift in at cratonic lithosphere edge. Evidence for edge-driven erosion of cratonic root? – suggested by short length scale of SKS splitting.

Tiberi et al., GJI, 2018; van Wijk, Currie, Ebinger & Reiss, almost submitted
- CO$_2$ flux along fault systems in Natron-Magadi basins. Mantle sourced fluids (metasomatic fluids, magma production). 71 ± 33 Mty$^{-1}$ - ca. 11% of global budget

- Fault zones penetrate to ~25 km and are permeable pathway for volatiles; lower crustal seismicity is caused by high pore pressures around magma intrusions; slip along border faults.

- Rates of crustal accretion 5-90 km$^3$ km$^{-1}$ My$^{-1}$ comparable to
Fault slip above sill on 17 July, dike intrusion on 26 July; eruption in August. At least 65% deformation occurred aseismically.
Dike intrusion occurs in between the large events detectable with satellite geodesy: Earthquakes in 2013 show large dilatational component and correlate with dike intrusion EQs from 2007. 30 similar events between 1995-2017 found using cross correlation of waveforms from permanent station KMBO - Sarah Jaye Oliva

Oliva et al., GRL, 2019 and poster
Upward-migrating earthquake swarms in upper mantle and crust – Albert-Edward rift zone, Western rift; Petrology, melt inclusions indicate pervasive CO₂-rich fluids.

Afar Depression

Zones of Holocene-Recent magma intrusion = volcanoes + dike intrusion zones

Boxes outline historic fissural eruptions and dike intrusion zones
Ca. 35 km-long, 8 m-wide dike induced unrest at Dabbahu volcano, and peralkaline eruption at small cone near Gab’ho volcano.
Fluid-filled cracks above magma bodies with ~20% melt (Desissa et al., 2013)
Comparison of MT and seismic imaging, and geoelectric and crust + mantle seismic anisotropy
Post-intrusion deformation – 'aftershocks'

NW-propagating and SE-propagating dikes from magma chamber at segment center Ayele et al. 2007

Figure 9, Ebinger et al.
Rifting at plate rupture:

Punctuated opening via dike intrusion: opening rates 2-3 times greater than interseismic cycle

Seismic moment << than geodetic moment – strain accommodated by frequent magma intrusions.

Poroelastic effects enhanced deformation in 1990 Dobi EQ sequence - Noir et al. 2011; Iceland – Jonsson et al. 2001
timescale $10^2$ to $10^5$ yr

period of tectonic quiescence

opening mainly by fault slip/creep

opening mainly by magmatic processes

timescale $10^{-2}$ to $10^2$ yr

d\rightarrow d\rightarrow d\rightarrow

d\rightarrow d\rightarrow d\rightarrow

Ebinger, van Wijk, Keir, 2013
3 Rift Fault-Dike Triggered Eruptions

• 2005 Afar – dike triggered pantellerite eruption and activity at Dabbahu volcano 2005 -
• 2007 Natron – Manyara – fault-dike-eruption at Oldoinyo Lengai
• Oranui, Taupo – 27 ka ??

New insights in lower crust and upper mantle rheology—all rifts with more mantle than crustal thinning

- SEGMeNT shows less activity
- No magma-involved (sills) earthquakes like CRAFTI
- No mantle earthquakes like TANGA

Blatant self-promotion to illustrate abundance of lower crustal EQs

Weinstein et al., 2017

In prep.

Lavayssiere, Drooff et al., 2019
Conclusions

• Magma intrusion aided by volatile release accommodates large % of lithospheric extension in EAR

• intrusive : extrusive ~ 10:1; 1/3 crust new igneous

Sectors with crustal magma reservoirs

• Strain is accommodated by magma intrusion, slow-slip, viscous relaxation; seismic energy release via dike-induced faulting

• Inter-seismic period is strongly dependent upon the magma replenishment cycle.

Sectors lacking active chambers

• Strain is accommodated by fault slip, creep – seismic 1/3 geodetic strain **Need more continuous GPS to evaluate role of aseismic deformation**

Both magmatic and amagmatic rifting events produce the long-term fault displacements, and maintain the along-axis rift architecture through repeated episodes of faulting, intrusion, and post-
March expedition to mid-segment. JRowland
Characteristic morphology created by faulting above dikes – short, large displacement faults - < 1 m/s propagation rate. Dike earthquakes $M_L < 5.6$

$M_0 = \mu L W s$ where $\mu$ is shear modulus of rock at EQ source, $L$ is length of fault plane, $W$ is fault width, and average fault $s$ is slip; $M_0 = 4 \times 10^{16}$ Nm

Dabbahu dikes: slip 1-3 m (0.5 expected from normal fault EQs worldwide)

- Mean fault length (lidar) = 2.5 km
- Width ~ 1 km (focal depths < 2.5 km)
- Some are low-frequency EQs (< 2 Hz) during intrusion cycle have normal fault mechanisms (<10% non-CLVD)
Fluids and Faulting III: Low-frequency earthquakes during and after dike intrusion.
Ancient example? 27 ka super-eruption; 530 km$^3$ lava; chemical mixing Allan et al., 2012; dike-triggering may explain Stop-start nature of eruptions

Burov, 2011

$z_{lith} = 100$ km

$z_{lith} = 200$ km
Confirmed magma intrusion and volcanic eruption events within the East African rift system: triangles, Holocene volcanoes ([www.si.edu](http://www.si.edu)).

2009 Lunayyir Harrat dike intrusion (Pallister et al., 2009); 2007 Jebal Al Tair eruption (Carn); 2008 Dallafilla rifting episode (Pagli et al., 2012); 2005-2011 Dabbahu rifting episode (e.g., Yirgu et al., 2006; Belachew et al., 2011); 2010 Gulf of Aden submarine rifting episode (Shuler and Nettles, 2010; Ahmed et al., 2012); 1978 Asal rifting episode (Abdallah et al., 1979); Main Ethiopian rift magma inflation episodes (Biggs et al., 2011); Eastern rift magma inflation episodes (Biggs et al., 2009); 2002 Nyiragongo eruption and dike intrusion (e.g., Tedesco et al., 2006; Wauthier et al., 2011); multiple Nyiragongo, Nyamuragira eruptions.