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

And, hazard implications

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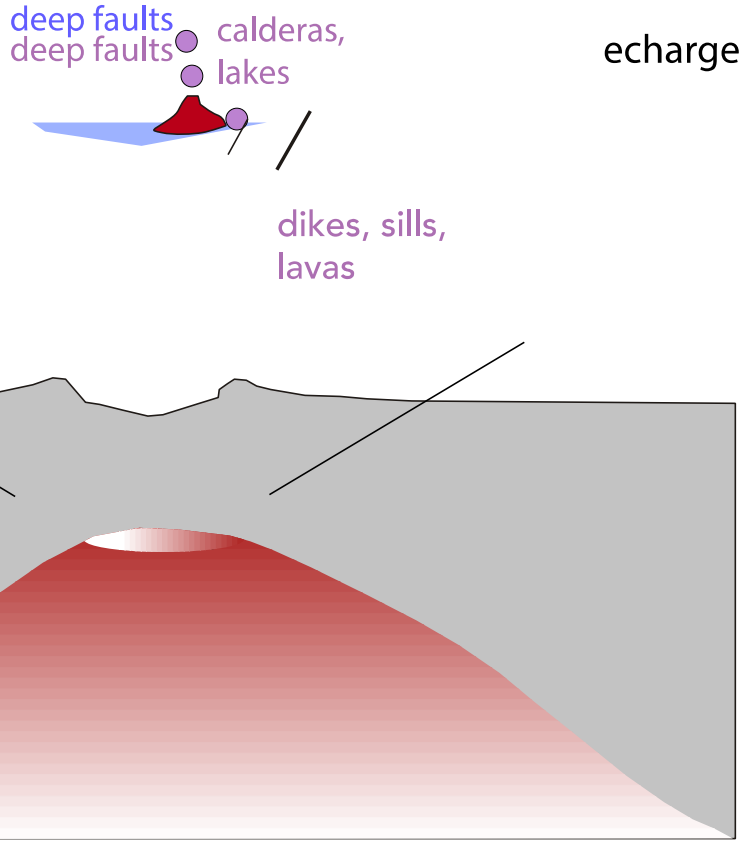
Geodynamic Processes at Rifting and Subducting Margins

GeoPRISMS

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**



echarge

As rifting progresses to seafloor spreading, % strain accommodated by magma intrusion increases to ~100%. How does 'wet lithosphere' deform?

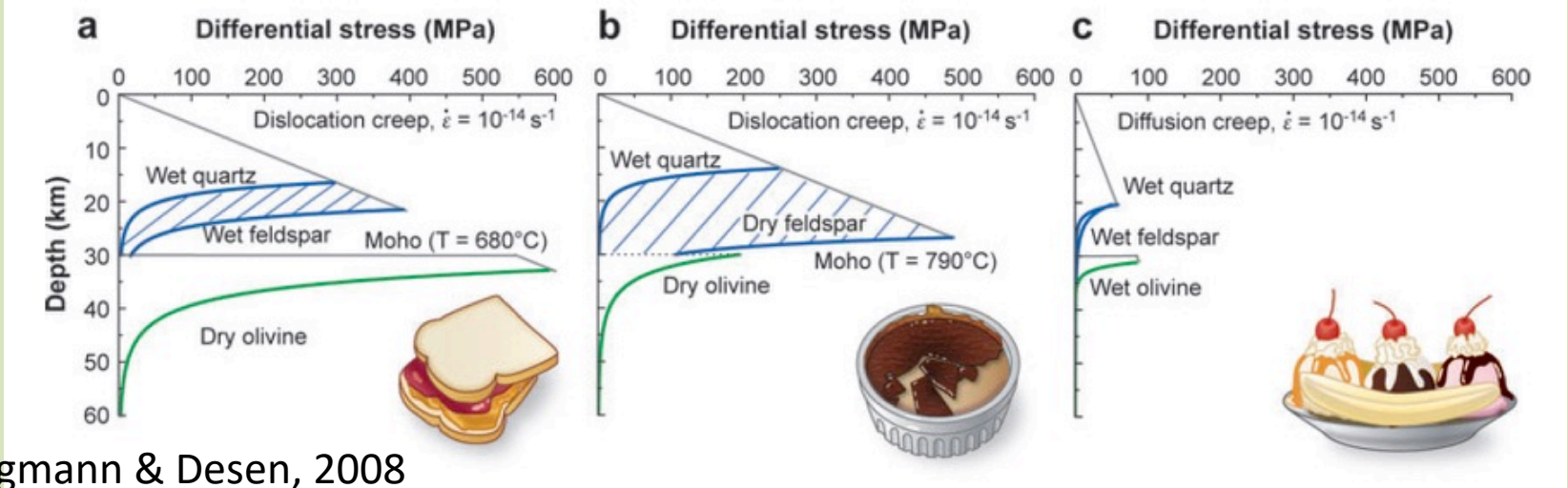
Space-time response of plate depends on rheology

cial unloading

Questions – ask Fischer – Thursday AM

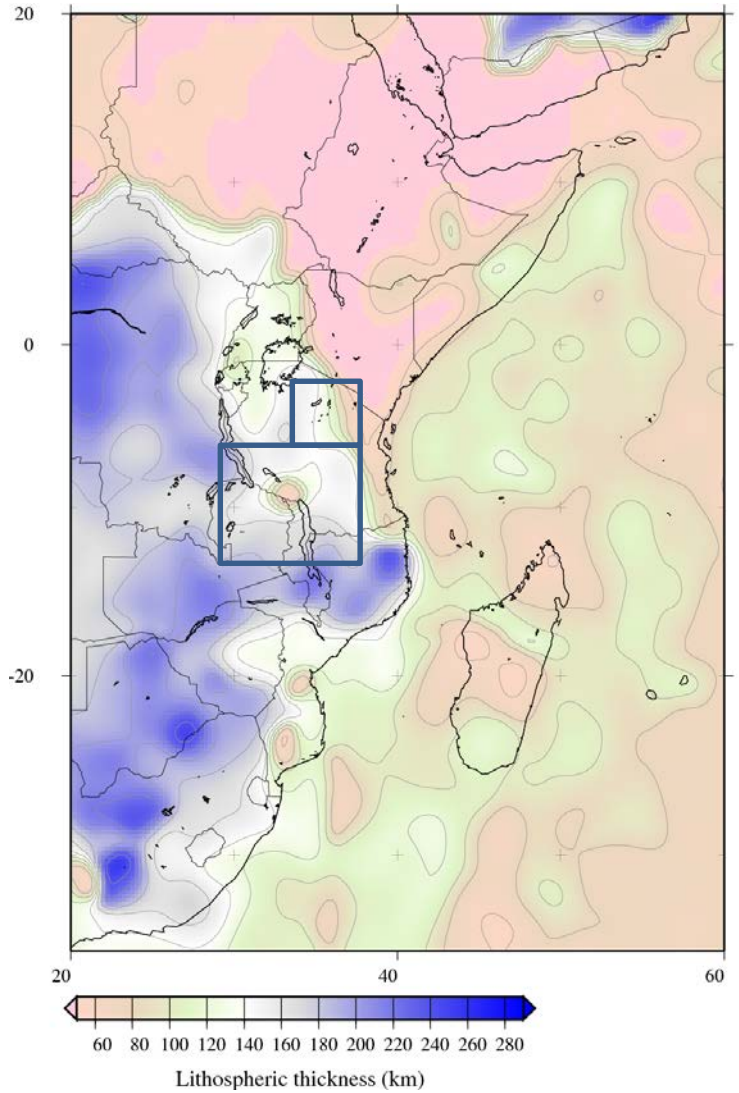
Rheology

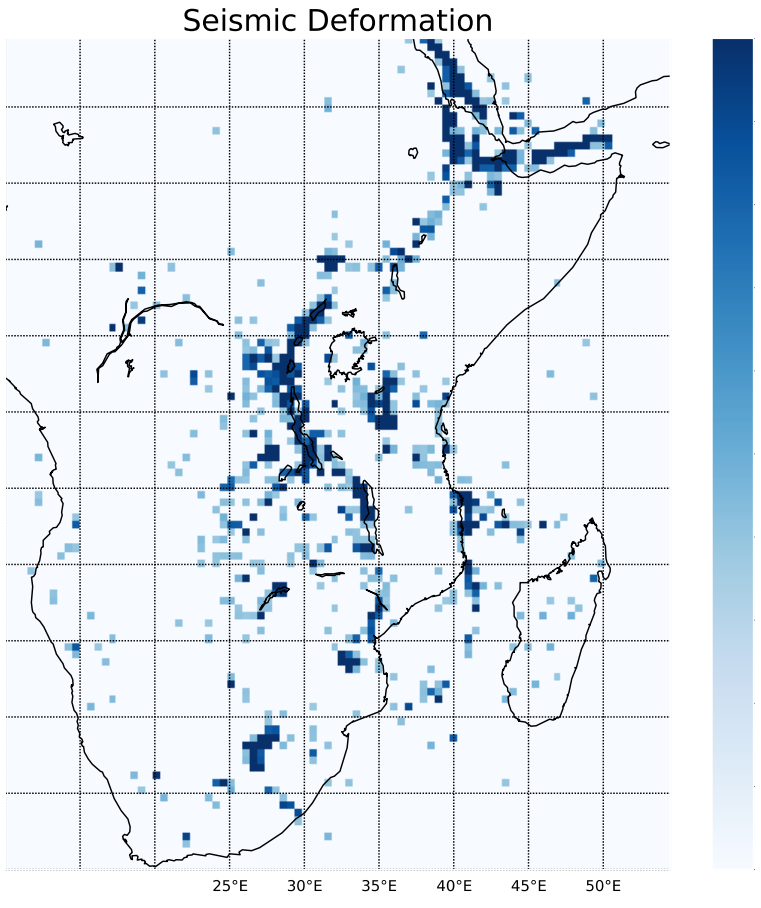
- Elastic behavior in parts or all of crust, upper mantle, depending on geotherm; composition, hydration state
- Visco-elastic behavior – strong time dependence – post-seismic, post-intrusion deformation > steady plate motion.
- Where rock pores are filled with fluids, poroelastic effects are superposed - 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?





Surface wave model - Fishwick et al., in review

GPS – sparse, E side: Saria, Bendick, Stamps, Floyd, King, Birhanu, Elliott

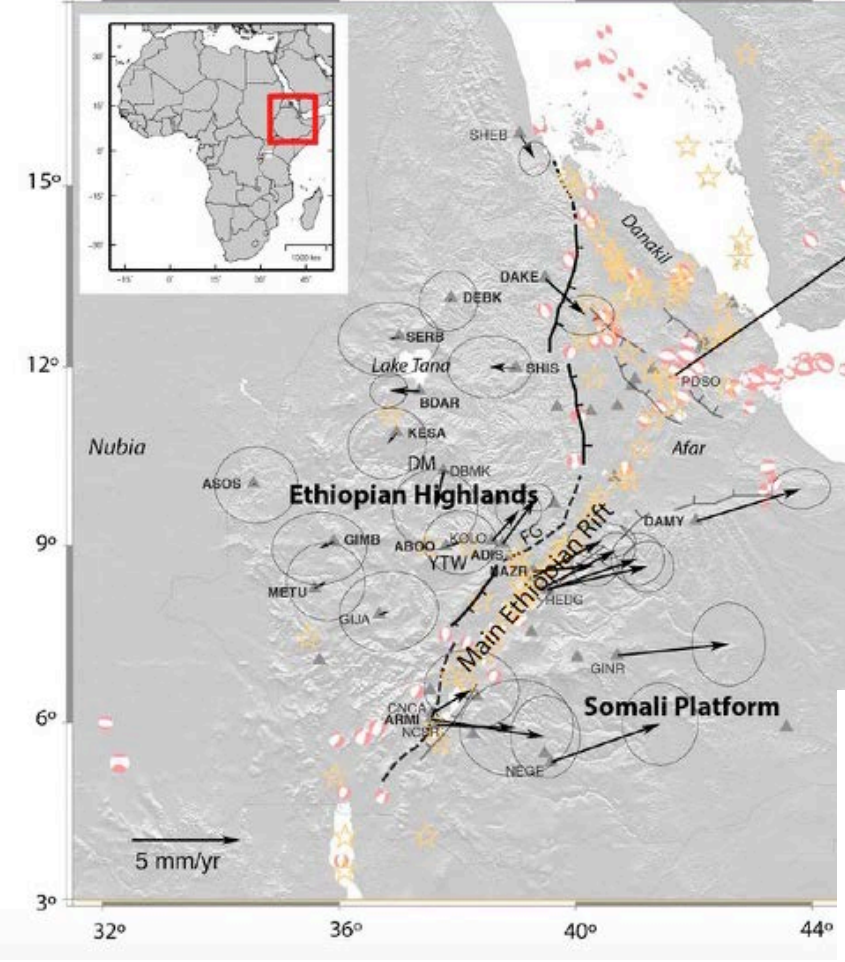
Seismic moment release: NEIC catalogue; 1973-7/2017

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

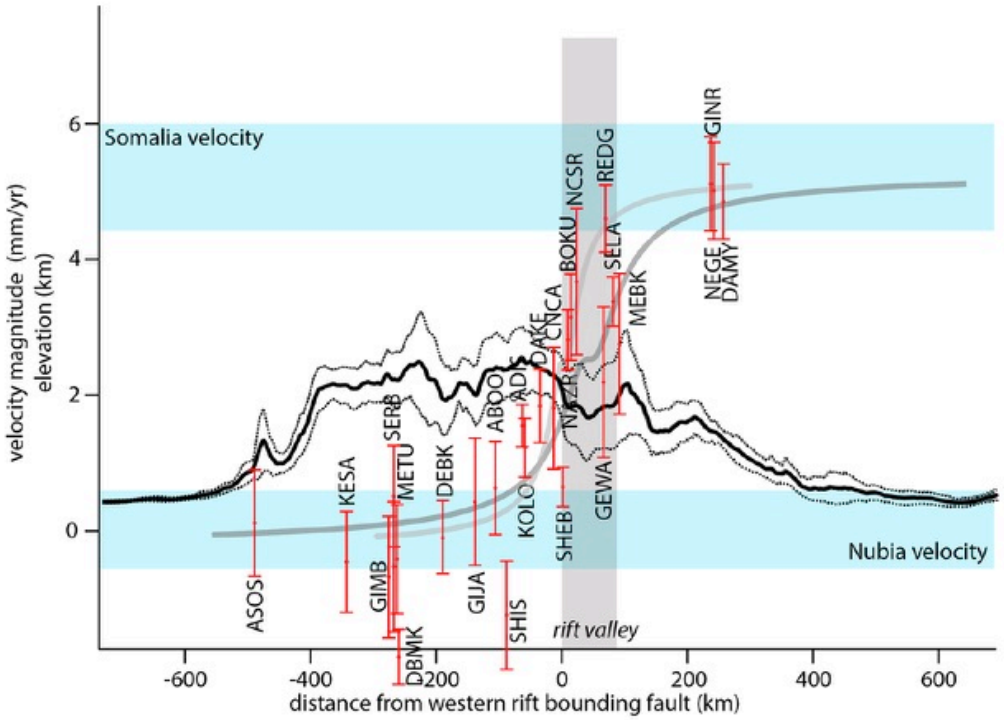
$M_0 = \mu A s$ where μ is shear modulus of rock at EQ source, A = area of fault plane, s is slip

Geodetic and seismic evidence that strain has localizaed 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

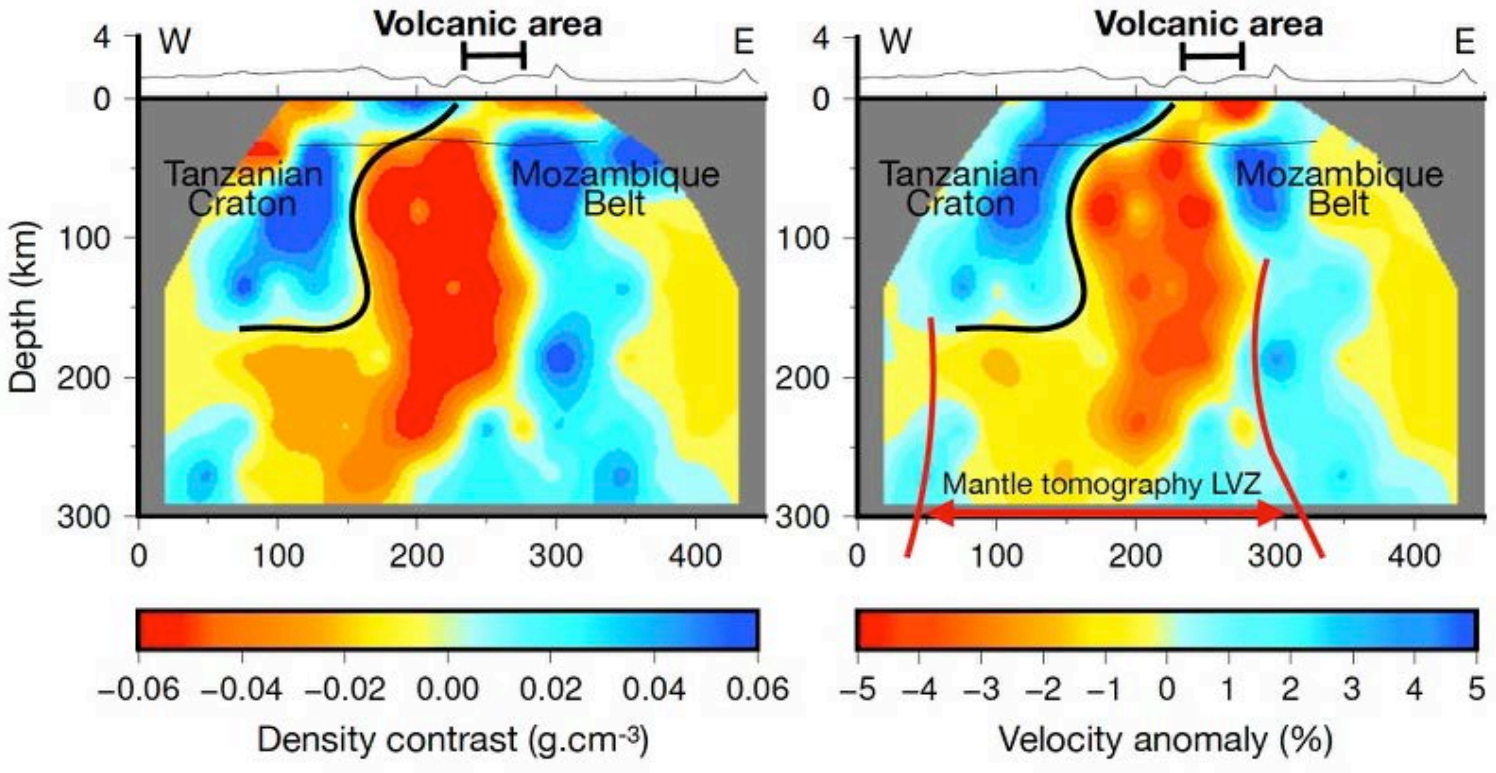


East-directed velocity with distance from rift – **Birhanu, Bendick,Fisseha, Lewi, Lloyd, King, Reilinger, GRL 2016**



< 5 Ma rift in at cratonic lithosphere edge. Evidence for edge-driven erosion of cratonic root? – suggested by short length scale of SKS splitting.

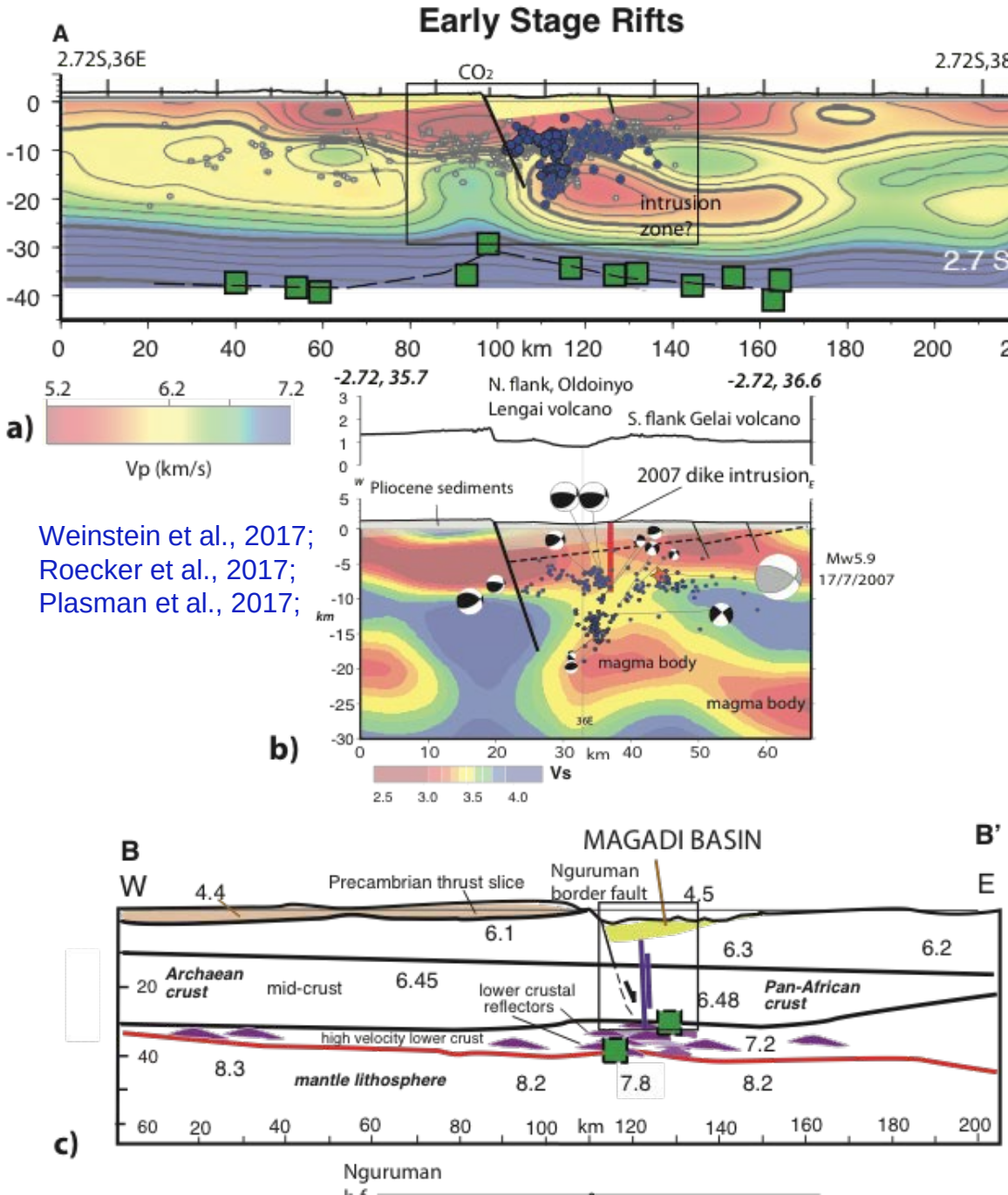
Tiberi et al., GJI, 2018; van Wijk, Currie, Ebinger & Reiss, almost submitted



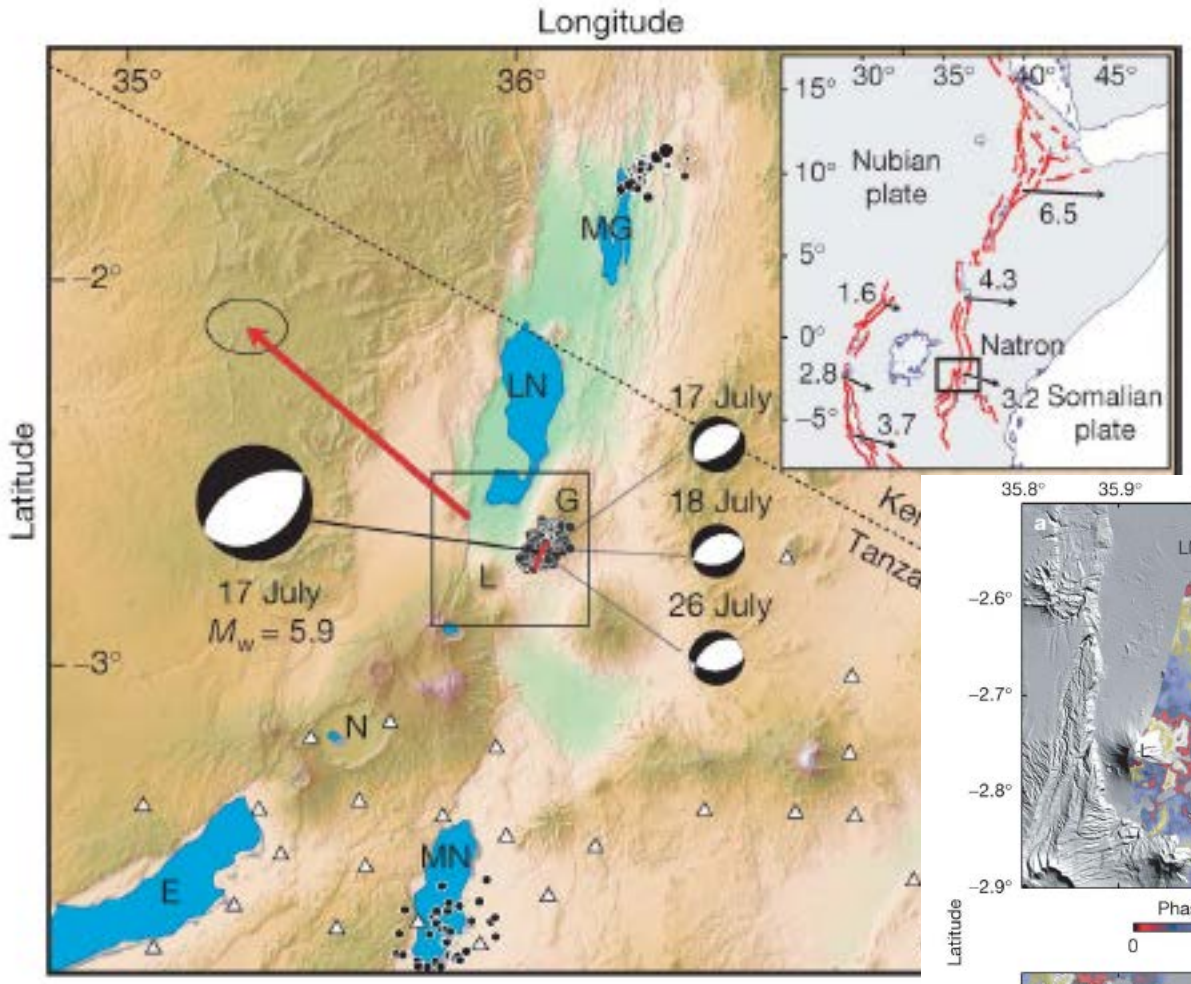
- **CO_2 flux along fault systems in Natron-Magadi basins. Mantle sourced fluids (metasomatic fluids, magma production). 71 ± 33 Mty^{-1} - ca. 11 % of global budget**

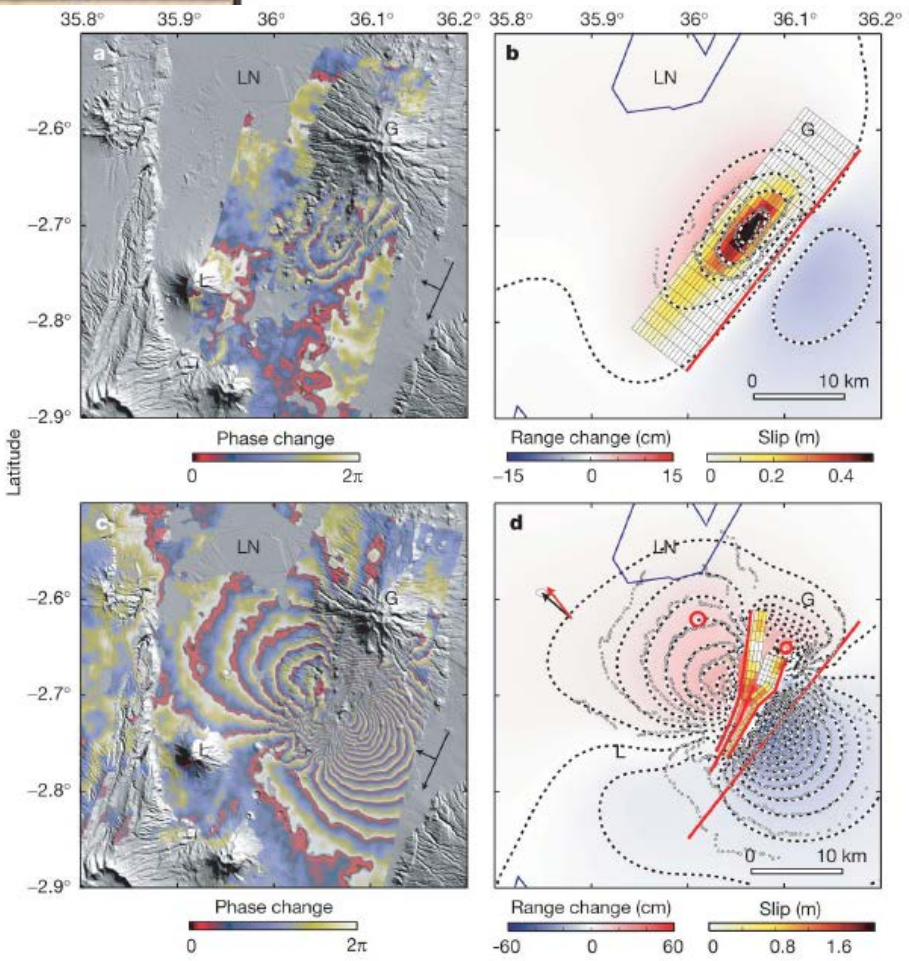
- **Fault zones penetrate to ~ 25 km and are permeable pathway for volatiles; lower crustal seismicity is caused by high pore pressures around magma intrusions; slip along border faults.**

- **Rates of crustal accretion 5-90 km^3 km^{-1} My^{-1} comparable to**

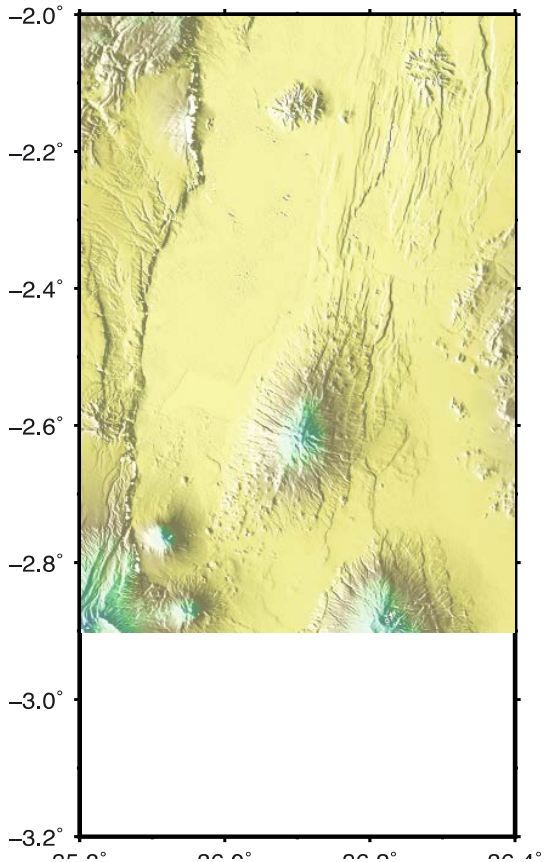


Calais et al., Nature,2008; updated in Oliva et al., GRL, 2019

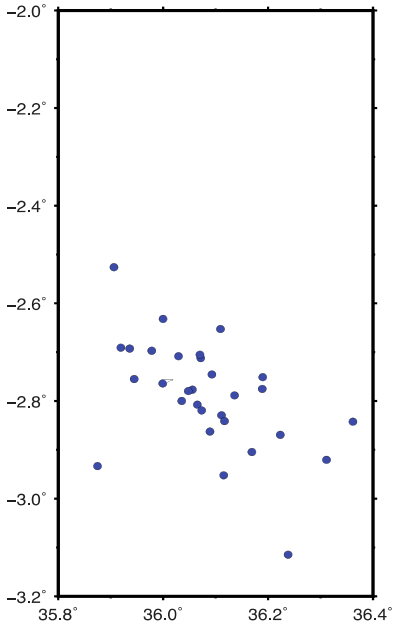


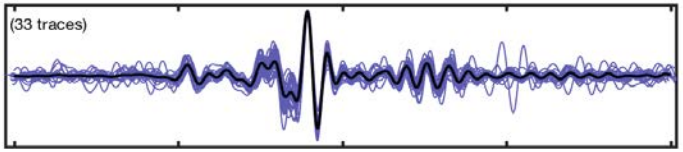


Fault slip above sill on 17 July, dike intrusion on 26 July; eruption in August. At least 65% deformation occurred aseismically.



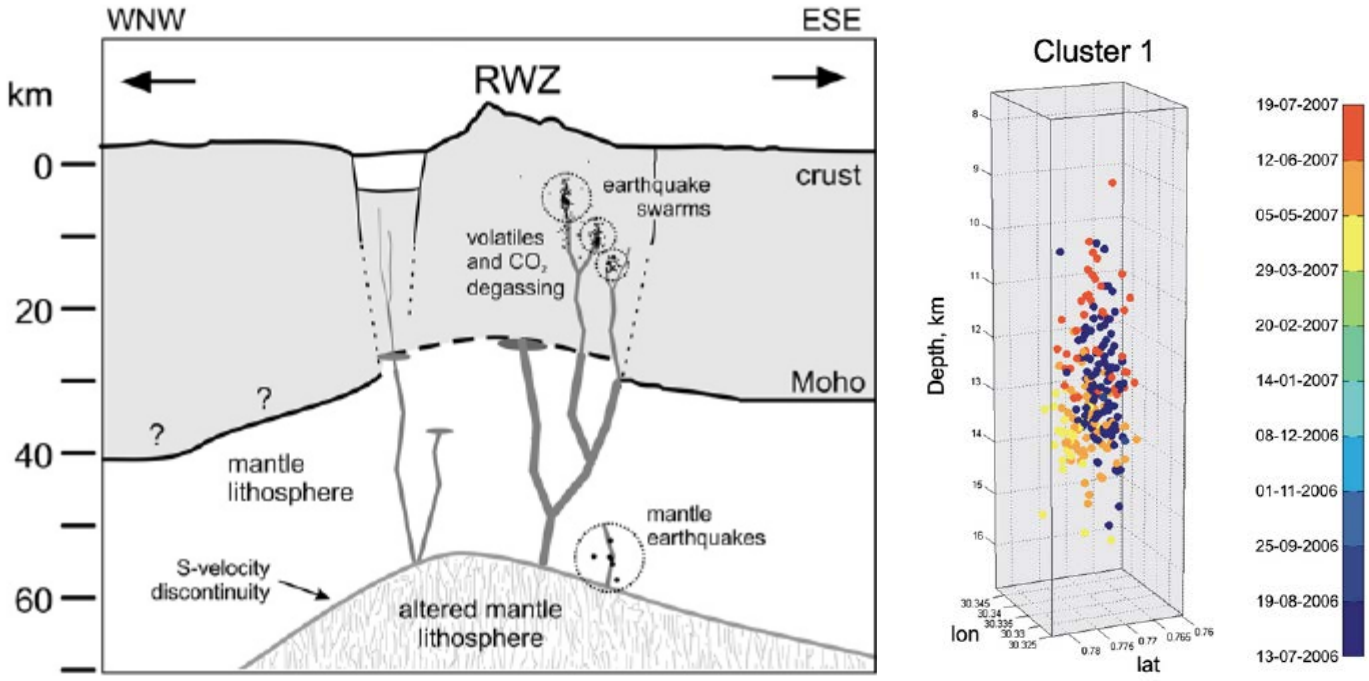
Dike intrusion occurs in between the large events detectable with satellite geodesy: Earthquakes in 2013 show large dilatational component and correlate with dike intrusion EQs from 2007. 30 similar events between 1995-2017 found using cross correlation of waceforms from permanent station KMBO - Sarah Jaye Oliva



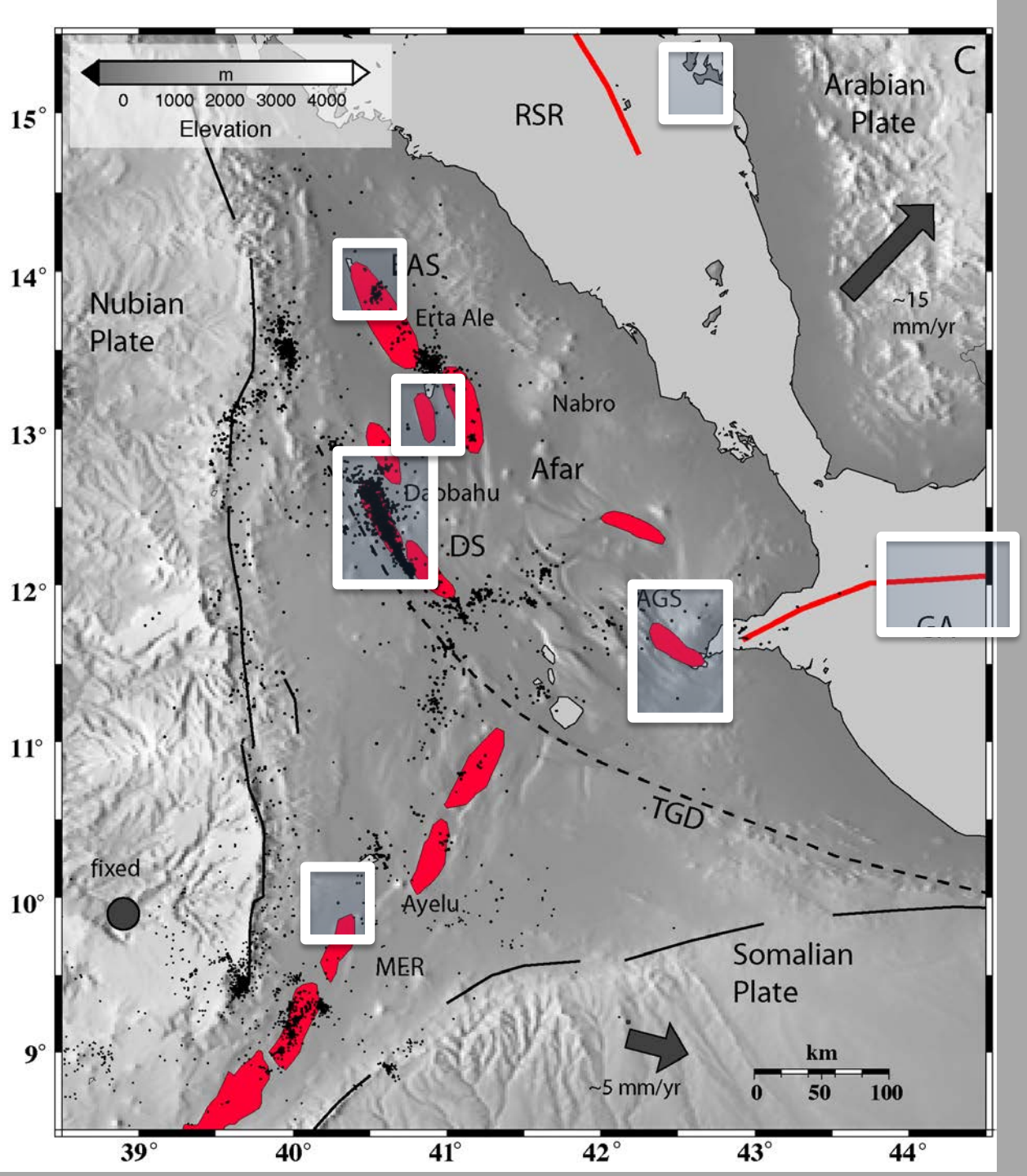


Oliva et al., GRL, 2019
and poster

Upward-migrating earthquake swarms in upper mantle and crust – Albert-Edward rift zone, Western rift ; Petrology, melt inclusions indicate pervasive CO_2-rich fluids



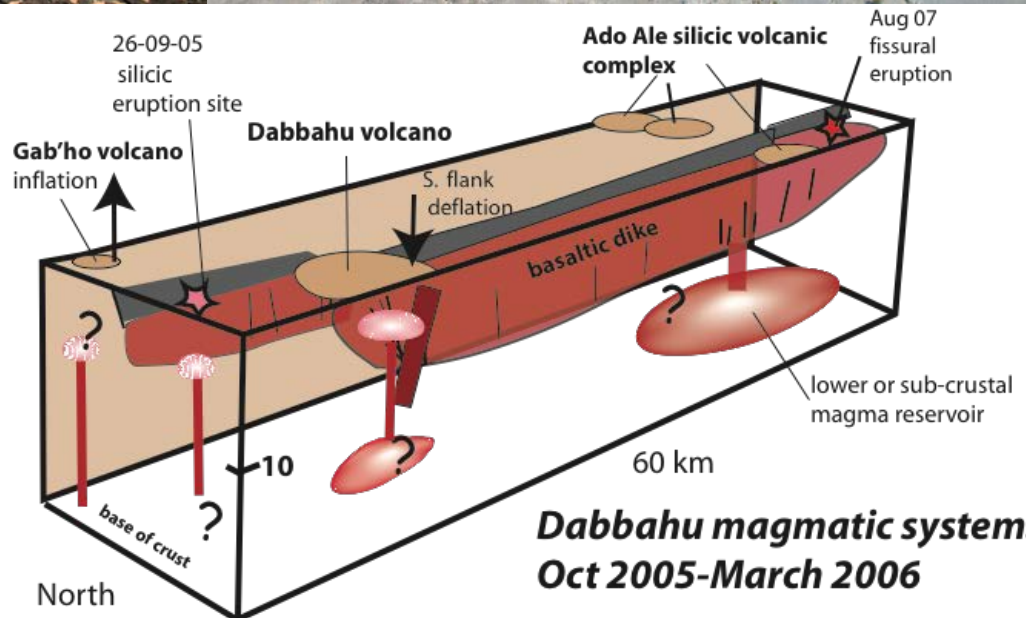
Ps, Sp RF constrain crust, mantle depths – Lindenfeld et al. Tectono, 2012; Homuth et al., 2015; Wallner and Schmeling, 2010.



Afar Depression

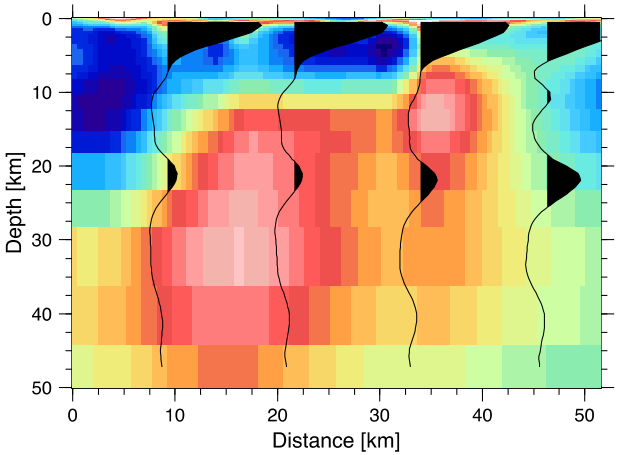
- Zones of Holocene-Recent magma intrusion = volcanoes + dike intrusion zones
- Boxes outline historic fissural eruptions and dike intrusion zones

Ca. 35 km-long, 8 m-wide dike induced unrest at Dabbahu volcano, and peralkaline eruption at small cone near Gab'ho volcano



Ebinger et al., 2008

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



cano

Post-intrusion deformation – 'aftershocks'

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

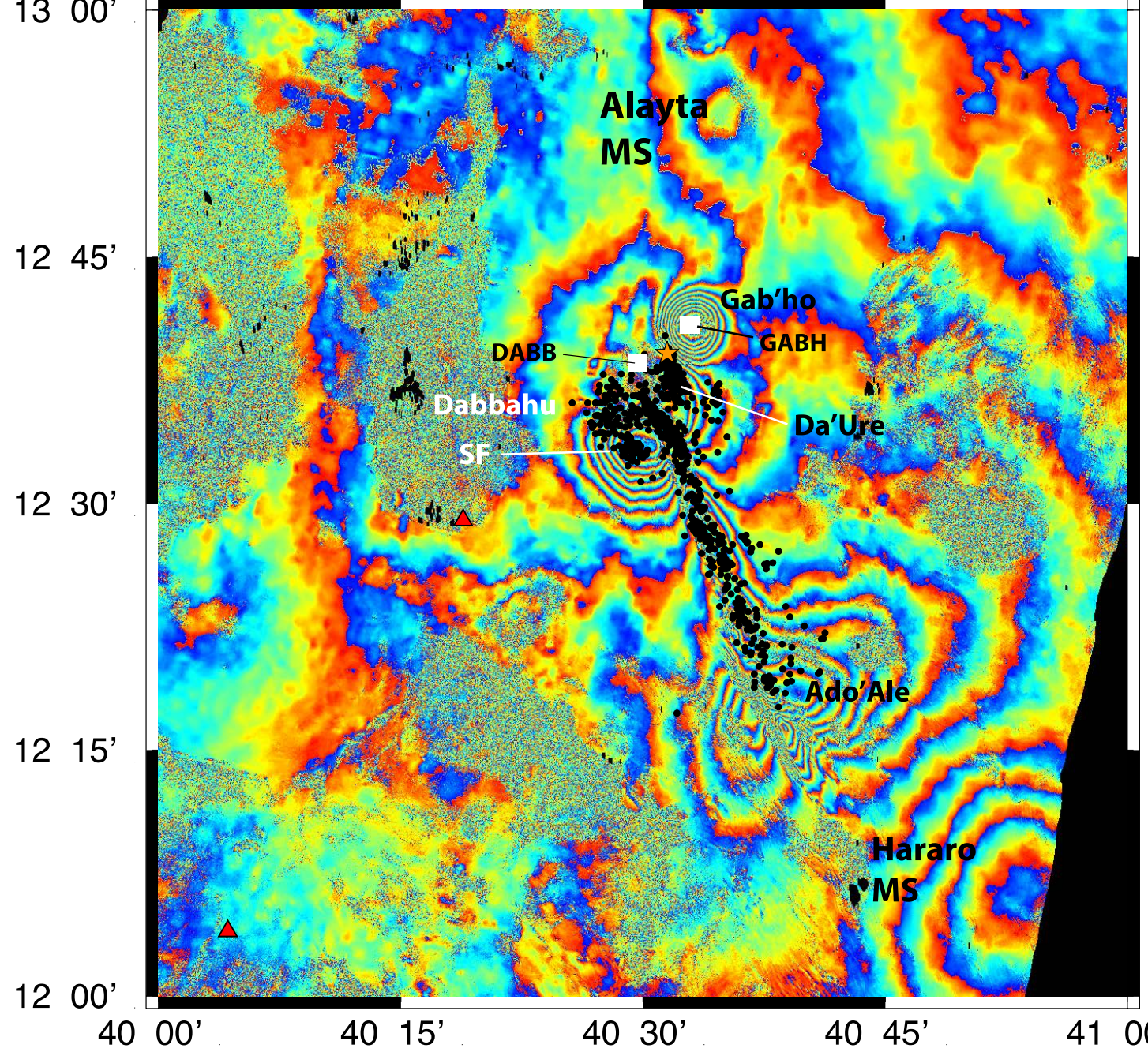
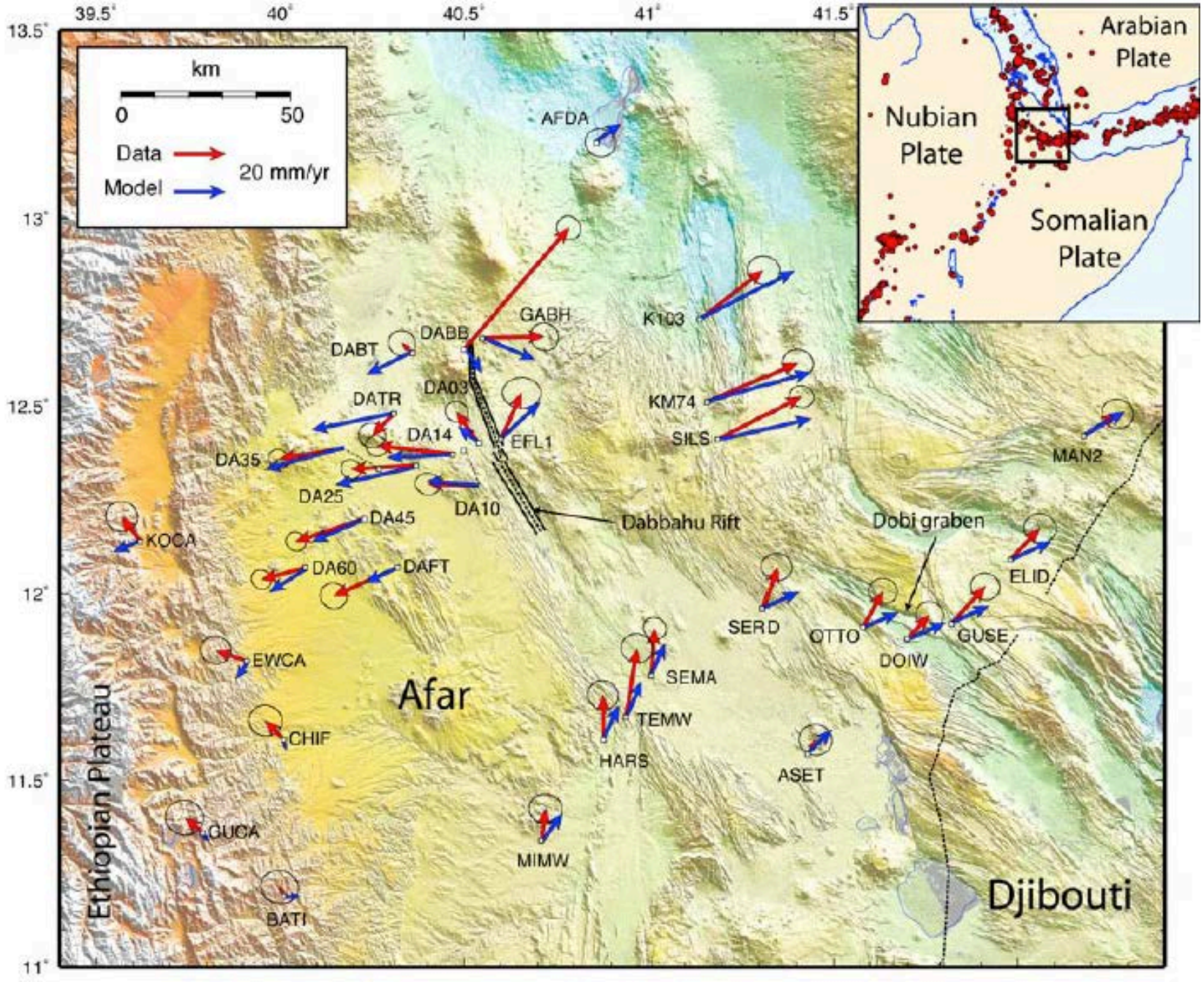
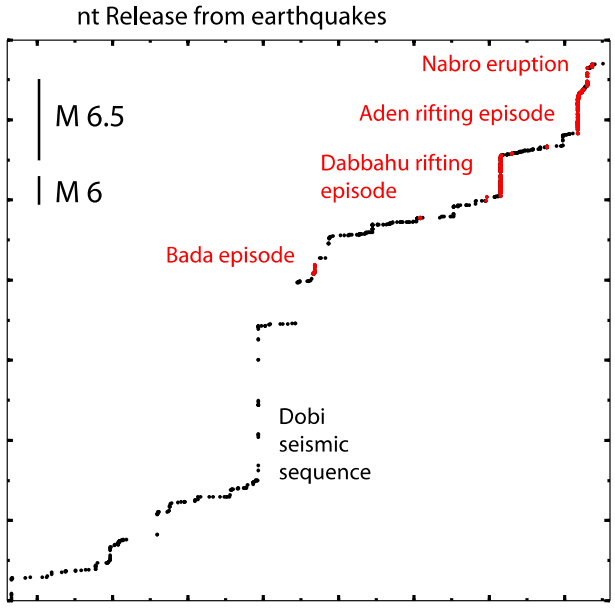


Figure 9, Ebinger et al.


39.5°
40°
40.5°
41°
41.5°
13.5°
13°
12.5°
12°
11.5°
11°
km
0
50
Data
Model
20 mm/yr
AFDA
GABH
DABB
DABT
DA03
DATR
DA14
EFL1
DA35
DA25
DA10
DA45
DA60
DAFT
KOCA
EWCA
CHIF
GUCA
BATI
MIMW
HARS
TEMW
SEMA
ASET
SERD
OTTO
DOIW
GUSE
ELID
MAN2
K103
KM74
SILS
Dabbahu Rift
Dobi graben
Afar
Ethiopian Plateau
Djibouti
Arabian Plate
Nubian Plate
Somalian Plate



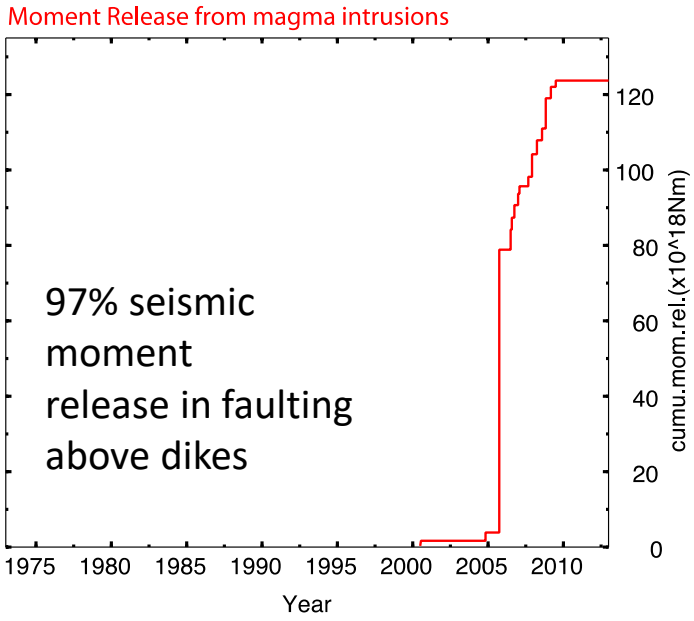


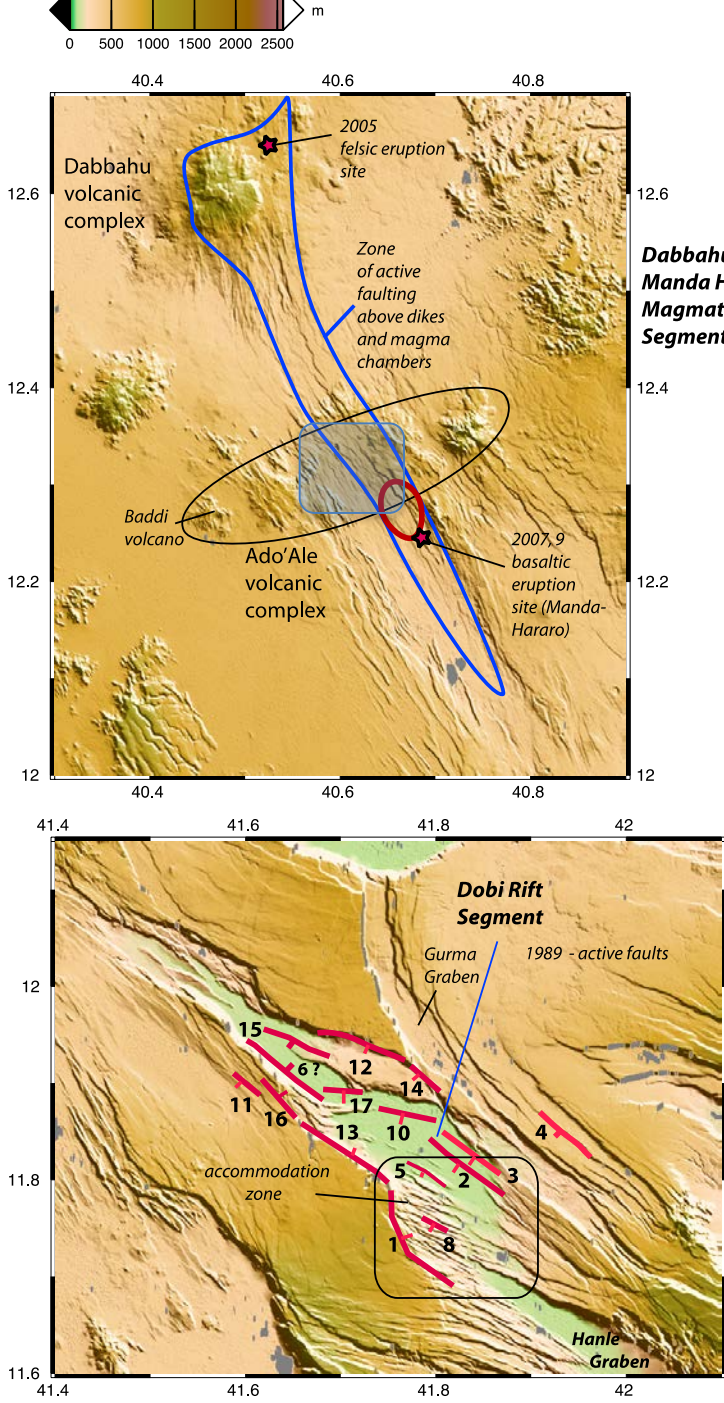
Figure 4, Ebinger, van Wijk, Keir

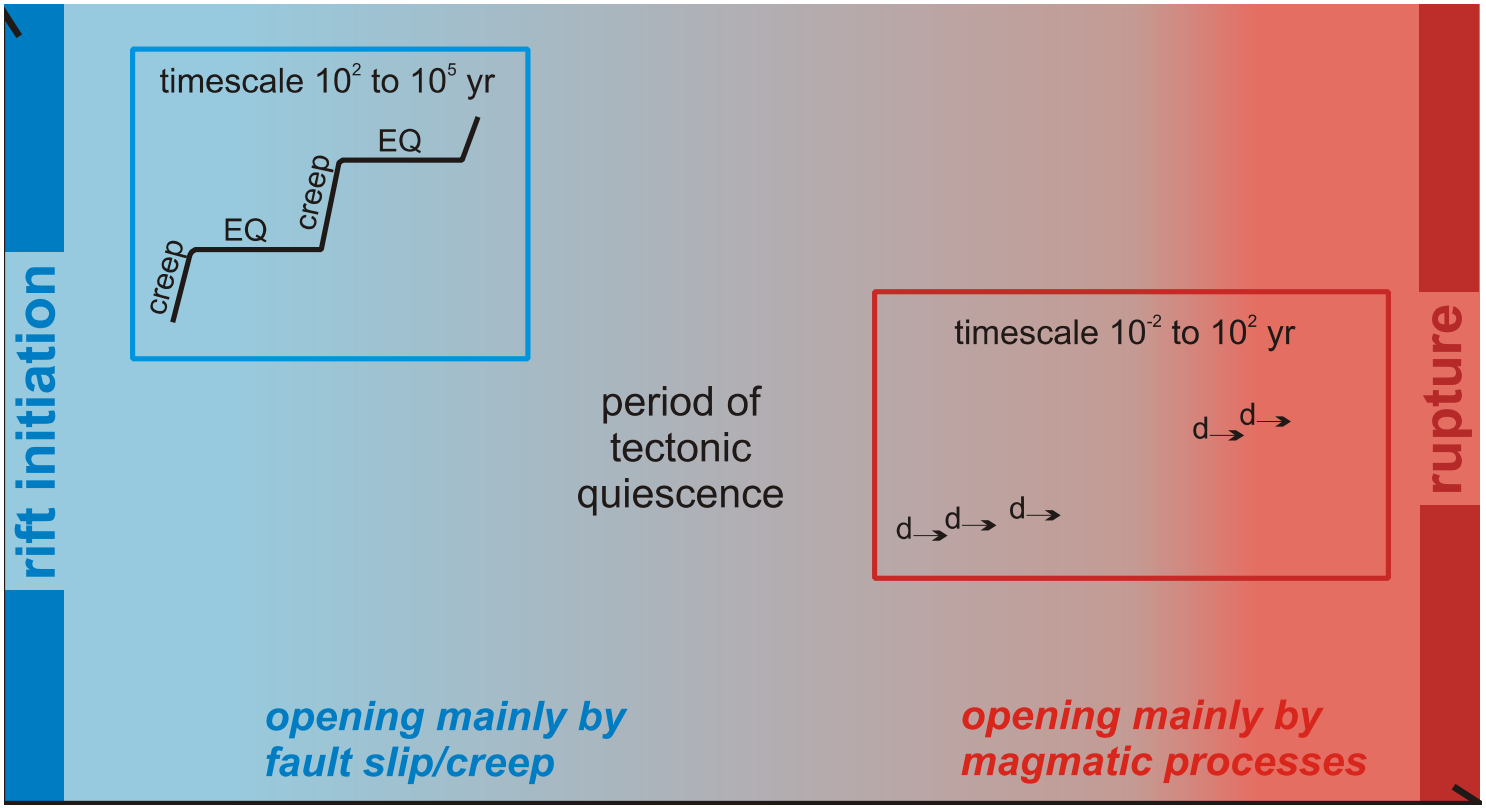
Rifting at plate rupture:

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





Ebinger, van Wijk, Keir, 2013

3 Rift Fault-Dike Triggered Eruptions

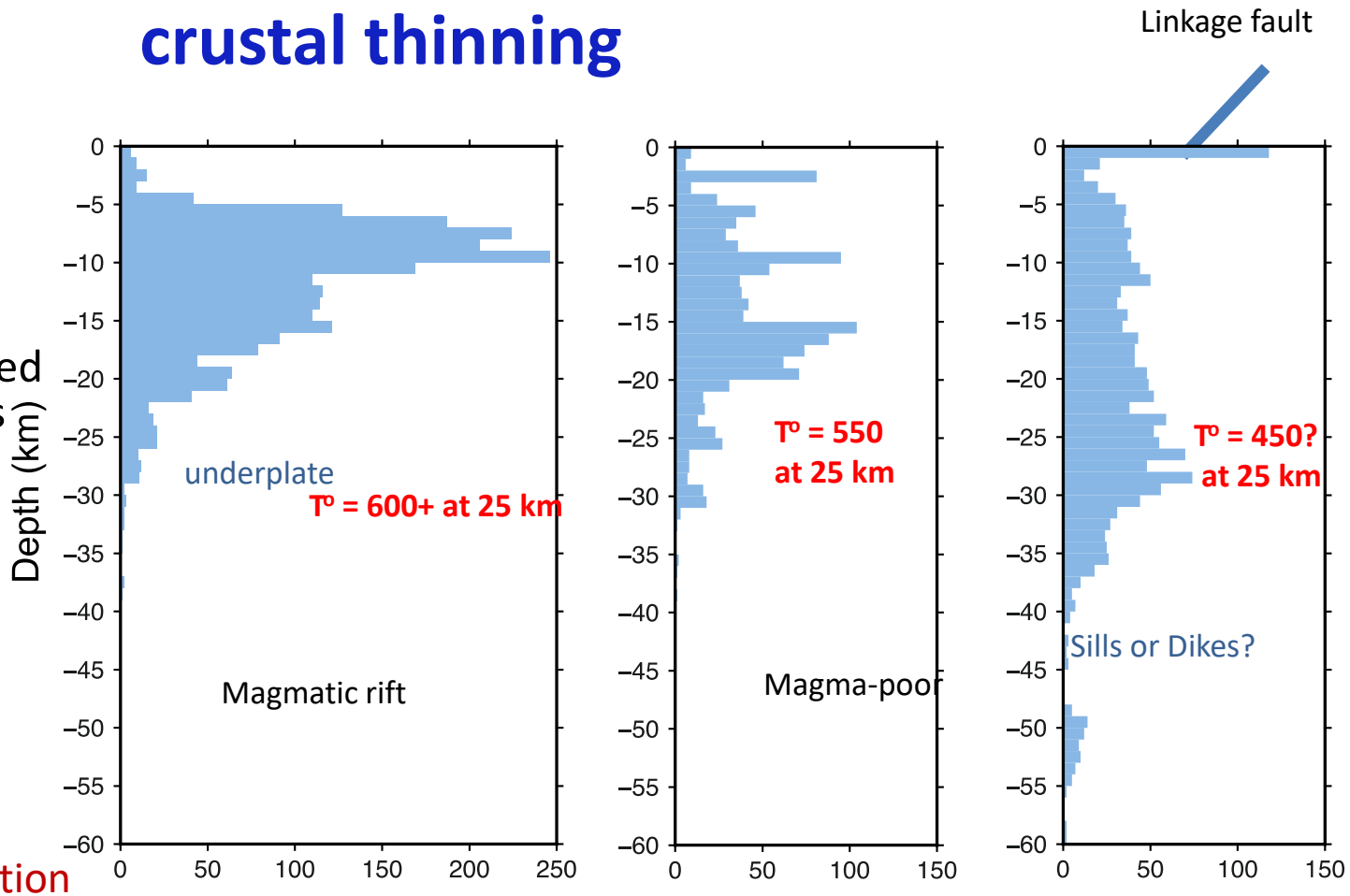
- 2005 Afar – dike triggered pantellerite eruption and activity at Dabbahu volcano 2005 -
- 2007 Natron –Manyara – fault-dike-eruption at Oldoinyo Lengai
- Oranui, Taupo – 27 ka ??

Allan, A.S., Wilson, C.J., Millet, M.A. and Wysoczanski, R.J., 2012. The invisible hand: Tectonic triggering and modulation of a rhyolitic supereruption. *Geology40*(6), pp.563-566.

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 a Tectonics 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-

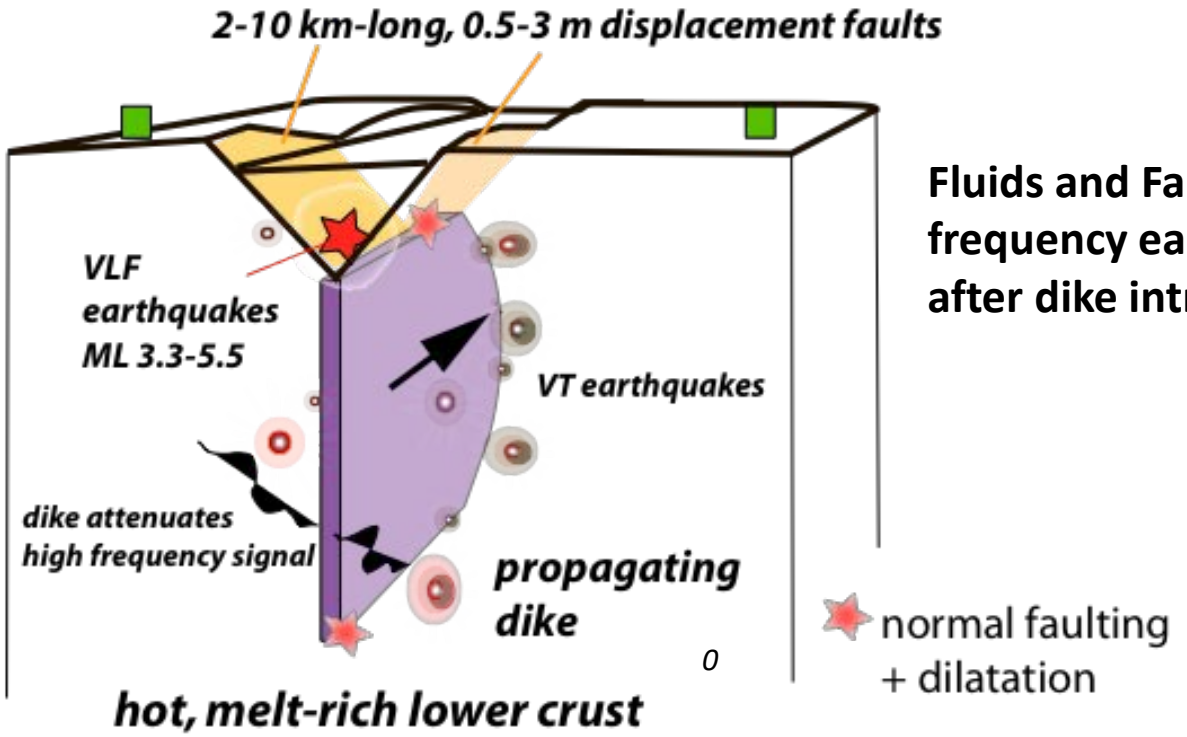
March expedition to mid-segment. JRowland

Characteristic morphology created by faulting above dikes – short, large displacement faults - < 1 m/s propagation rate. Dike earthquakes $M_L < 5.6$

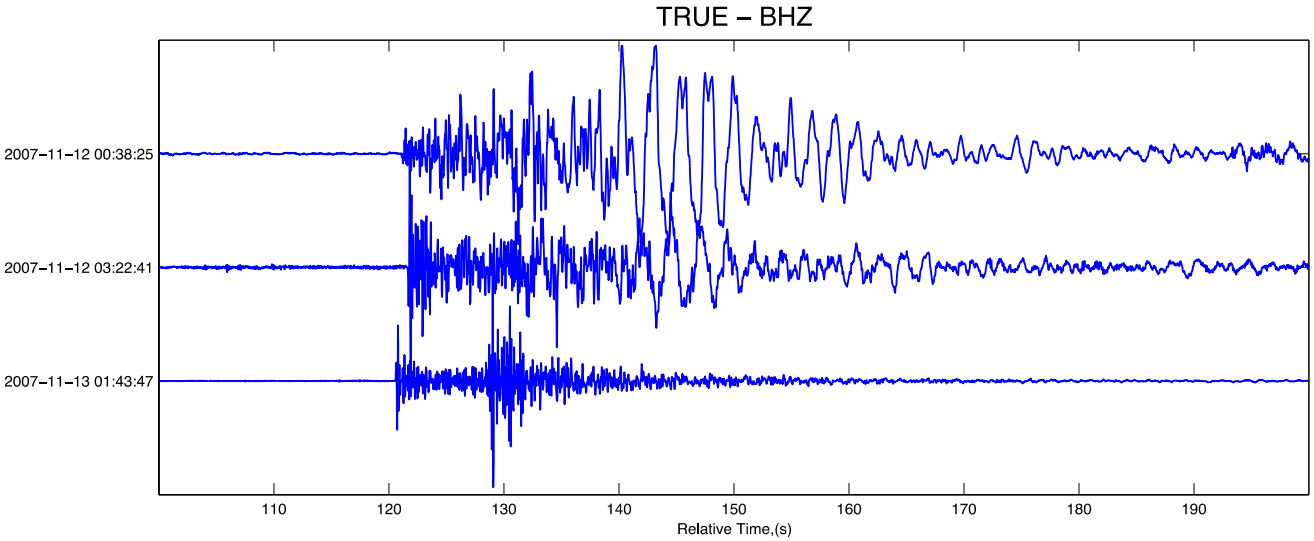
$M_0 = \mu L\ W\ s$ where is shear modulus of rock at EQ source, L is length of fault plane, W is fault width, and average fault s is slip; $M_0 = 4 \times 10^{16}$ Nm

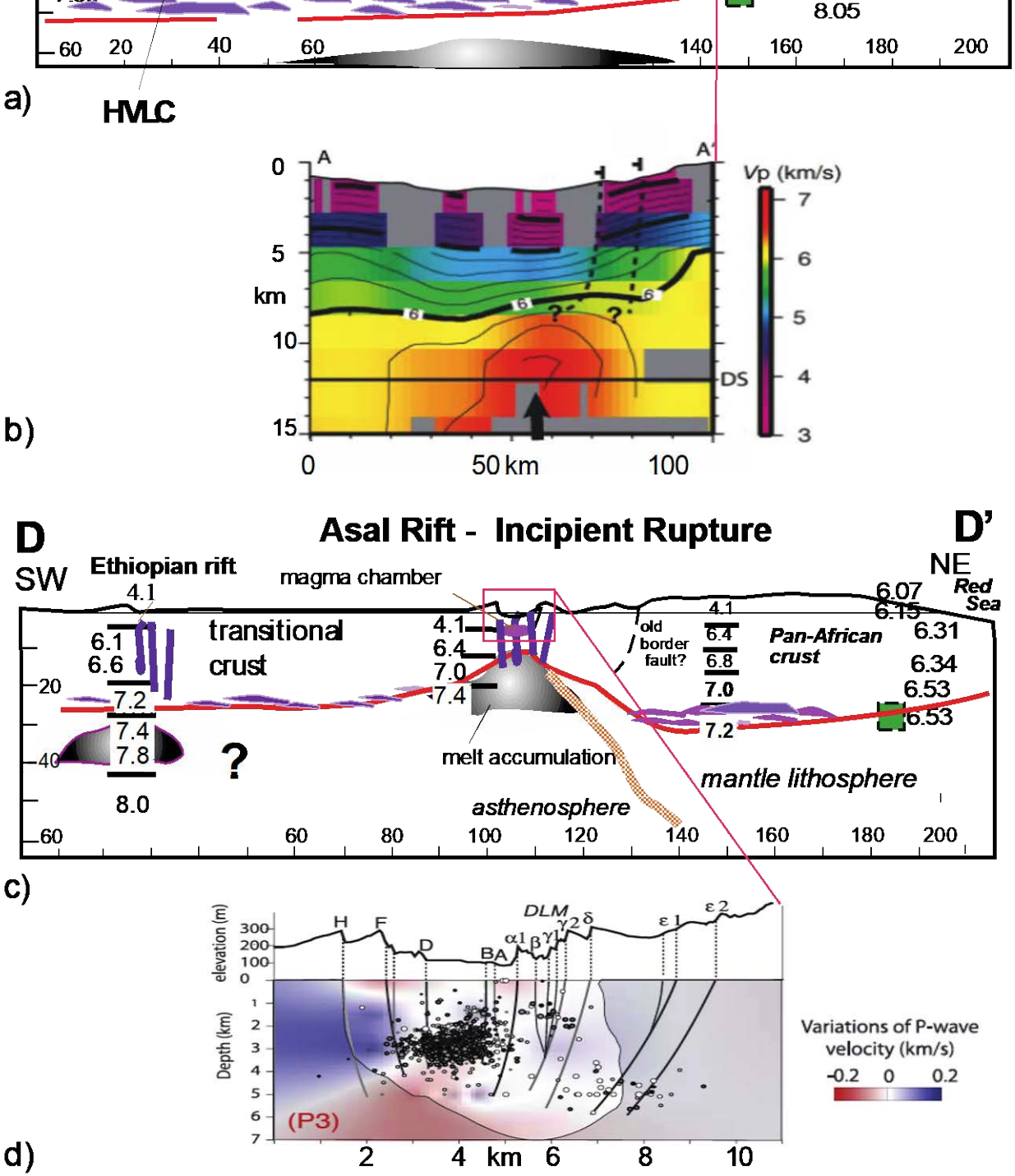
Dabbahu dikes: slip 1-3 m (0.5 expected from normal fault EQs worldwide)

- 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)

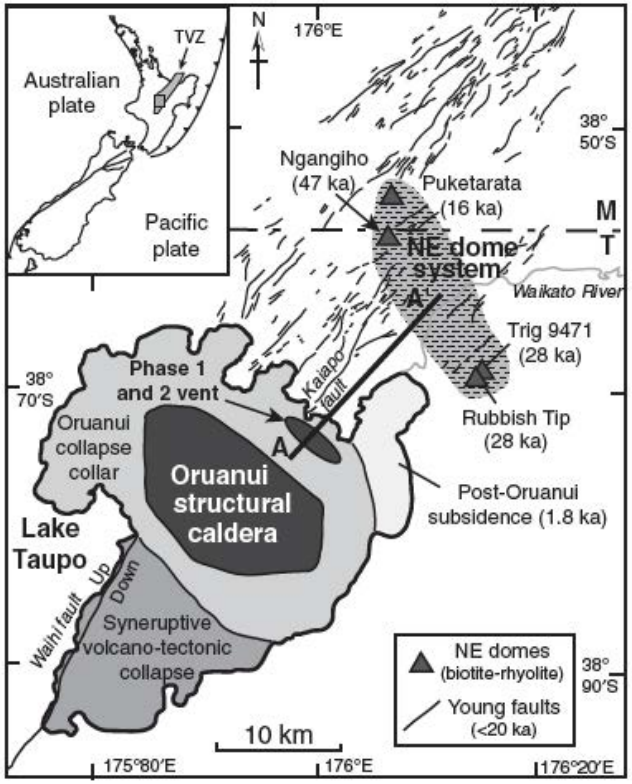


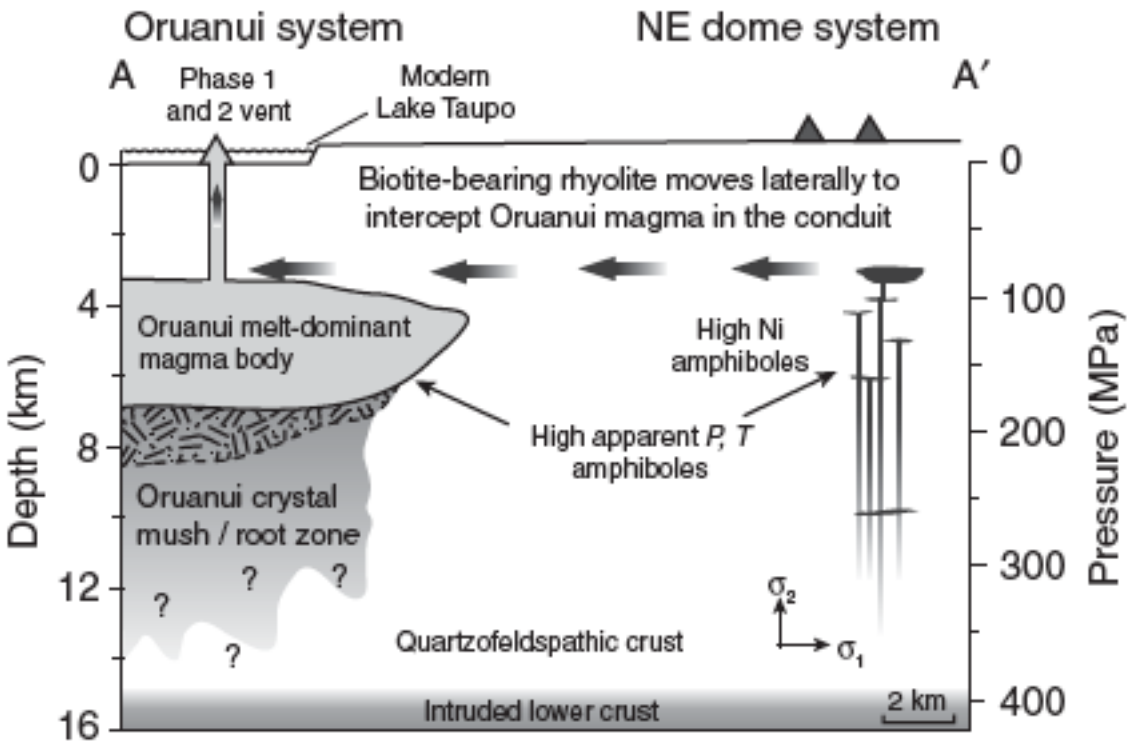
Fluids and Faulting III: Low-frequency earthquakes during and after dike intrusion.



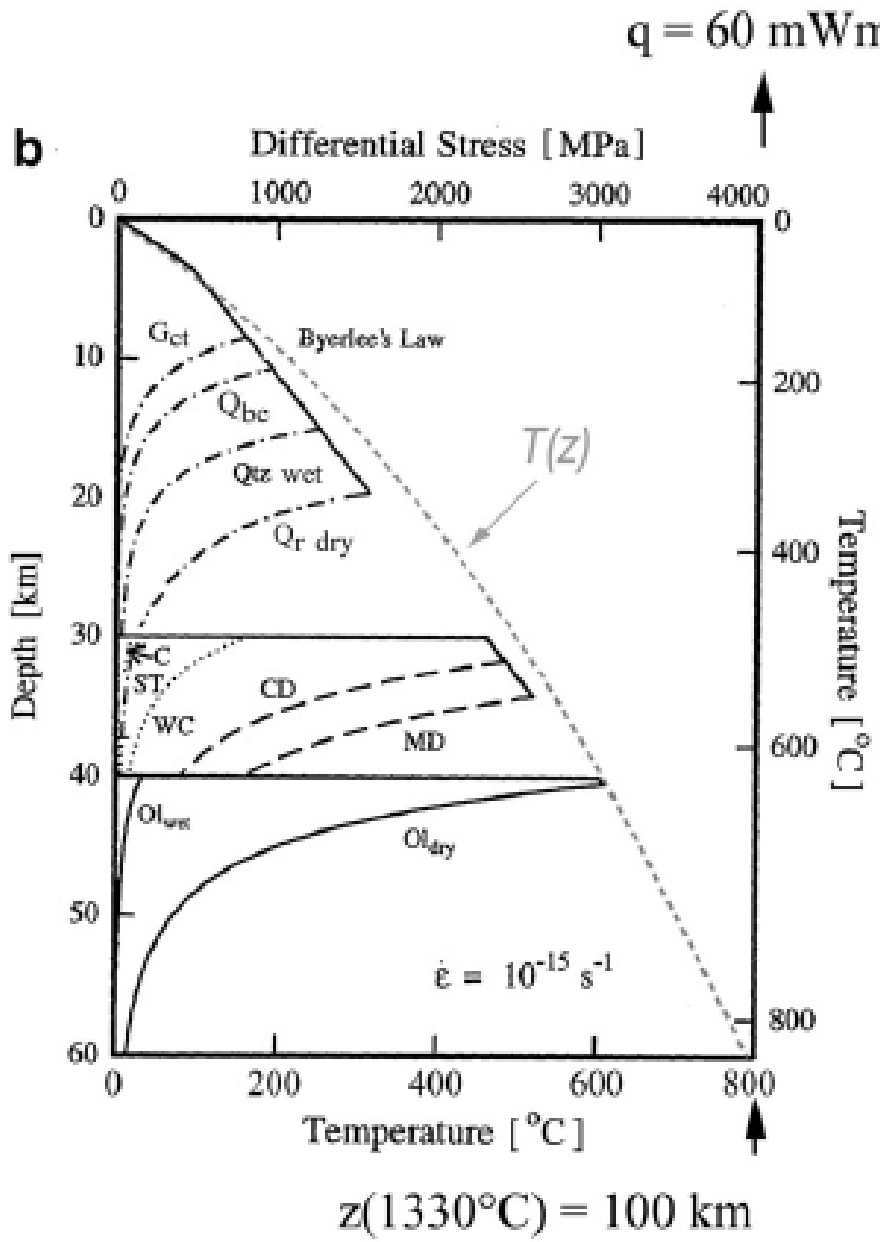

a)
HMLC
8.05
60
20
40
60
140
160
180
200
b)
A
A'
0
5
km
10
15
Vp (km/s)
7
6
5
4
3
DS
0
50 km
100
c)
D
SW
Asal Rift - Incipient Rupture
D'
NE
Ethiopian rift
magma chamber
Red Sea
transitional crust
old border fault?
Pan-African crust
melt accumulation
mantle lithosphere
asthenosphere
4.1
6.1
6.6
7.2
7.4
7.8
8.0
6.4
6.8
7.0
6.07
6.15
6.31
6.34
6.53
20
40
60
80
100
120
140
160
180
200
d)
elevation (m)
300
200
100
0
H
F
D
BA
DLM
α1
β
γ1
γ2
δ
ε1
ε2
Depth (km)
(P3)
2
4
km
6
8
10
Variations of P-wave velocity (km/s)
-0.2
0
0.2

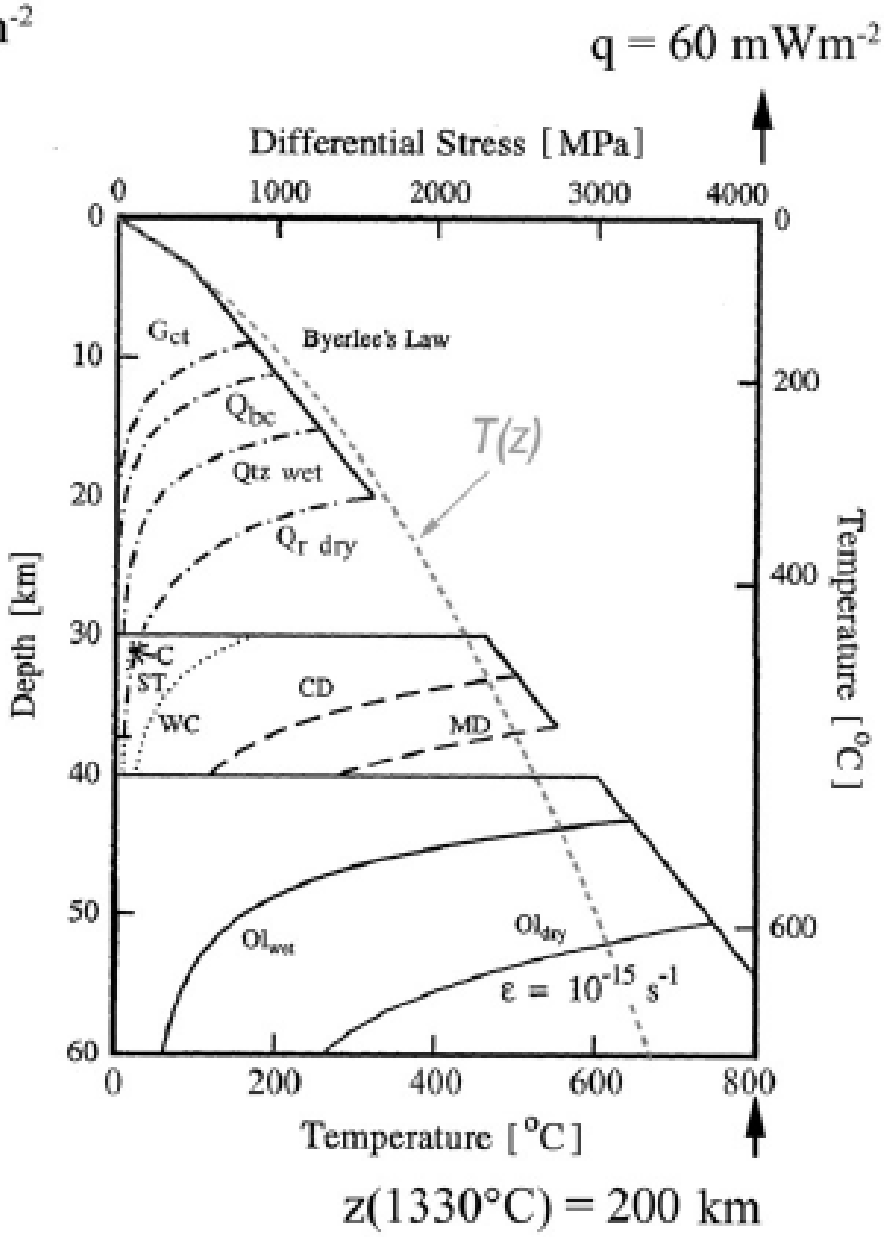
Ancient example? 27 ka super-eruption; 530 km^3 lava; chemical mixing Allan et al., 2012; dike-triggering may explain Stop-start nature of eruptions





Allan, A. S., Wilson, C. J., Millet, M. A., & Wysoczanski, R. J. (2012). The invisible hand: Tectonic triggering and modulation of a rhyolitic supereruption. Geology, 40(6), 563-566.

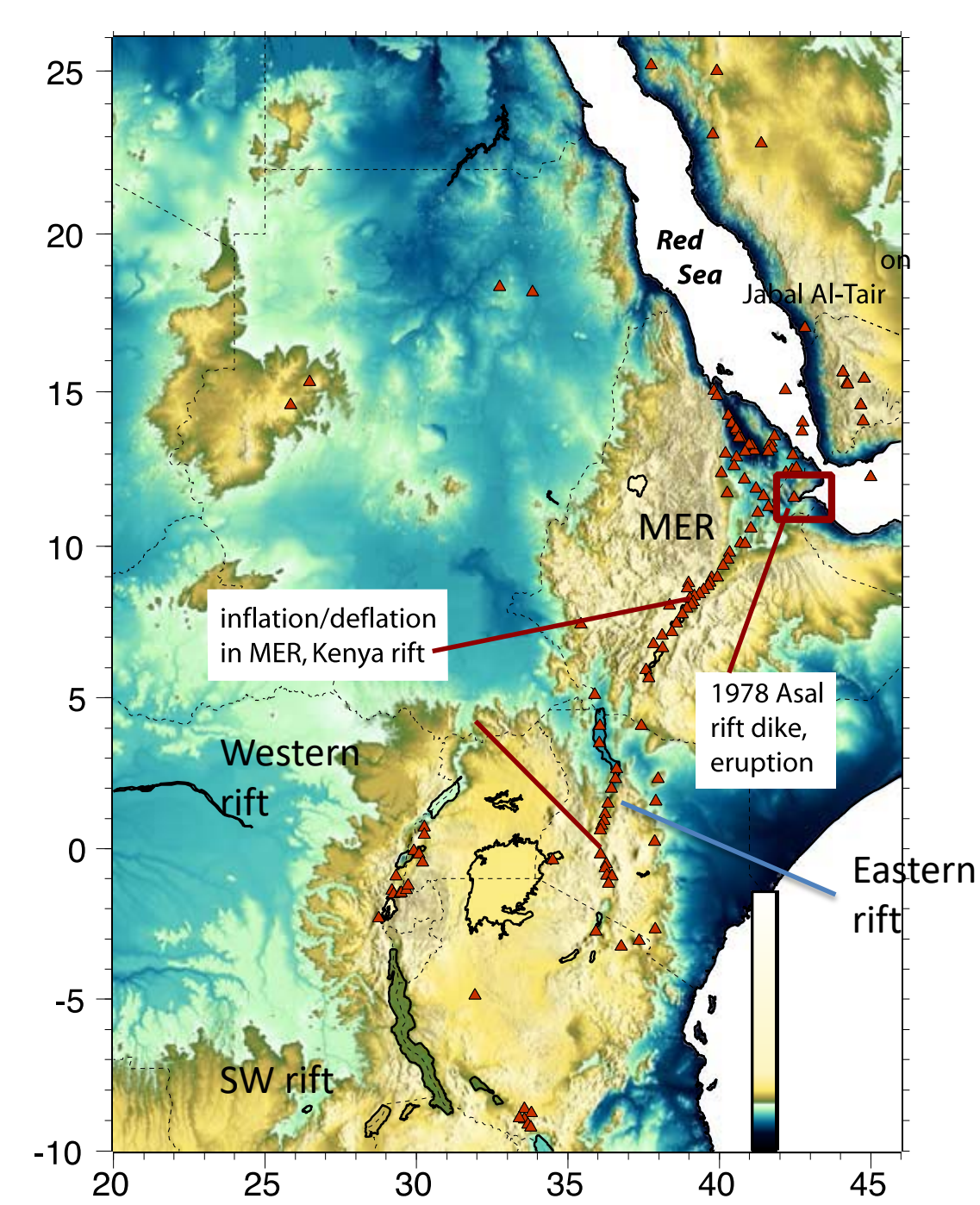




Burov, 2011

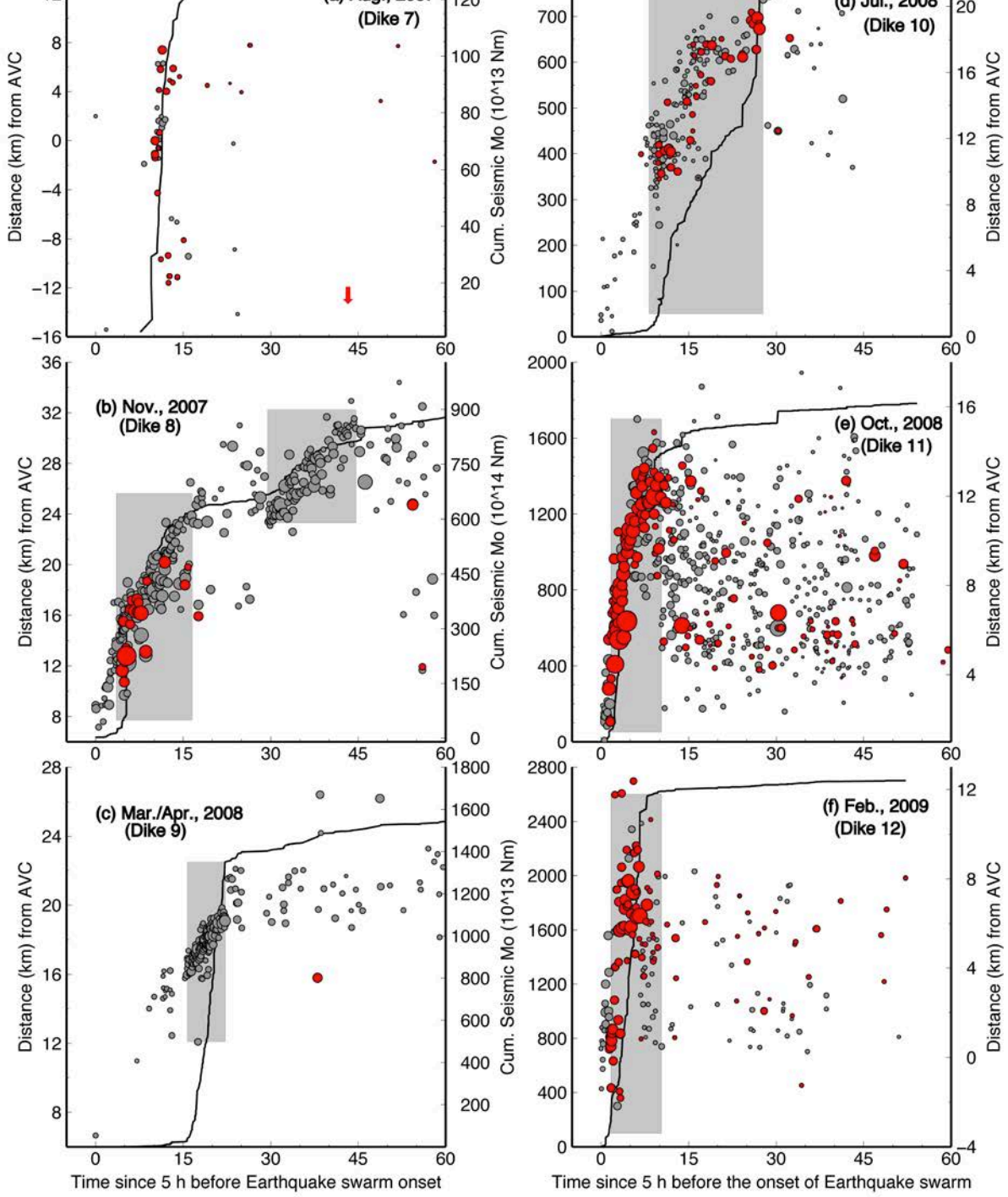
zlith = 100 km

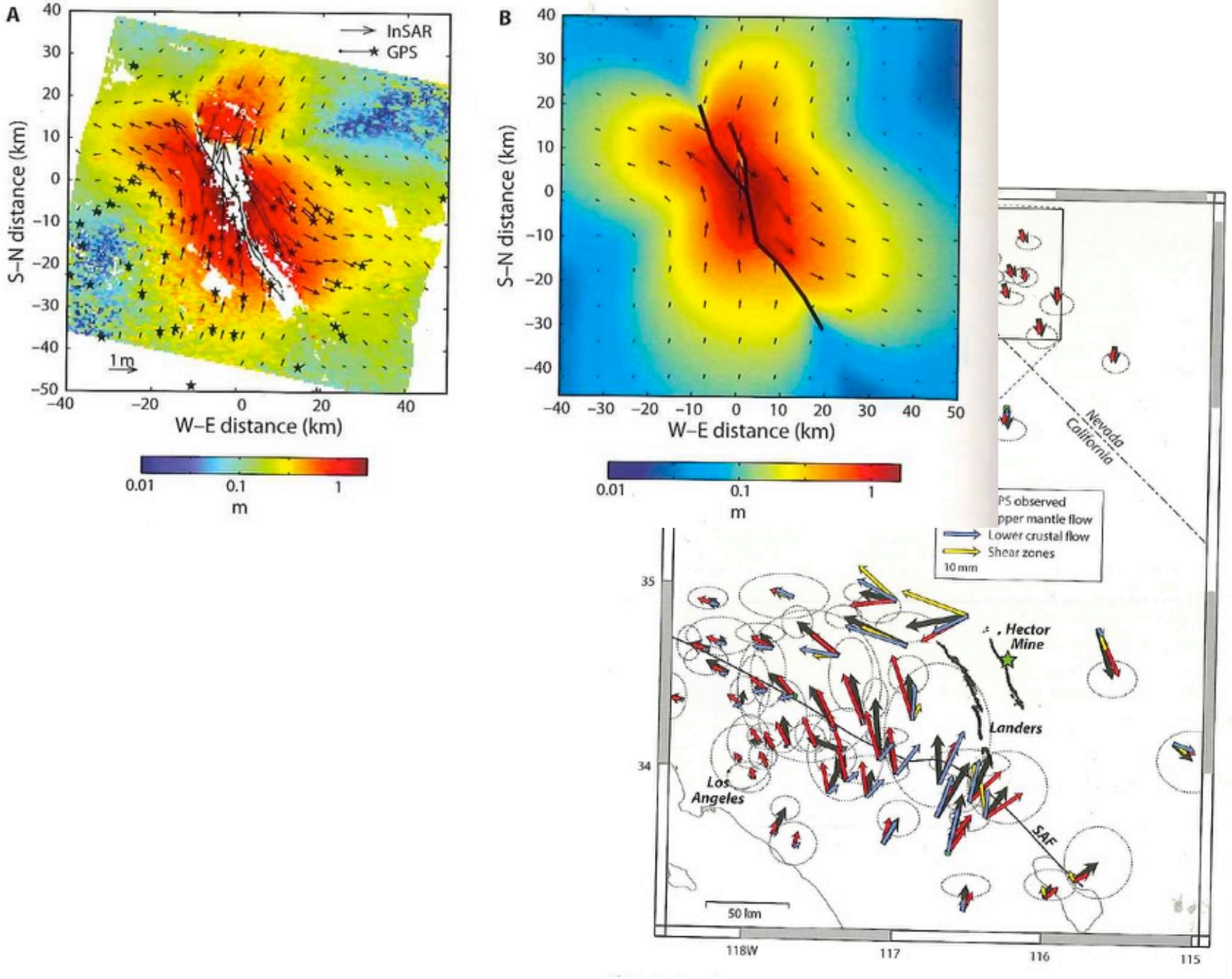
zlith = 200 km



Confirmed magma intrusion and volcanic eruption events within the East African rift system: triangles, Holocene volcanoes (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.


(Dike 7)
(d) Jul., 2008
(Dike 10)
(b) Nov., 2007
(Dike 8)
(e) Oct., 2008
(Dike 11)
(c) Mar./Apr., 2008
(Dike 9)
(f) Feb., 2009
(Dike 12)
Distance (km) from AVC
Cum. Seismic Mo (10^13 Nm)
Cum. Seismic Mo (10^14 Nm)
Time since 5 h before Earthquake swarm onset
Time since 5 h before the onset of Earthquake swarm


A
InSAR
GPS
1 m
S–N distance (km)
W–E distance (km)
0.01
0.1
1
m
B
S–N distance (km)
W–E distance (km)
0.01
0.1
1
m
Nevada
California
PS observed
pper mantle flow
Lower crustal flow
Shear zones
10 mm
Hector Mine
Landers
Los Angeles
SAF
50 km
118W
117
116
115
35
34