Magmatic modification of African crust: Implications for strain localization and basin subsidence

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Background

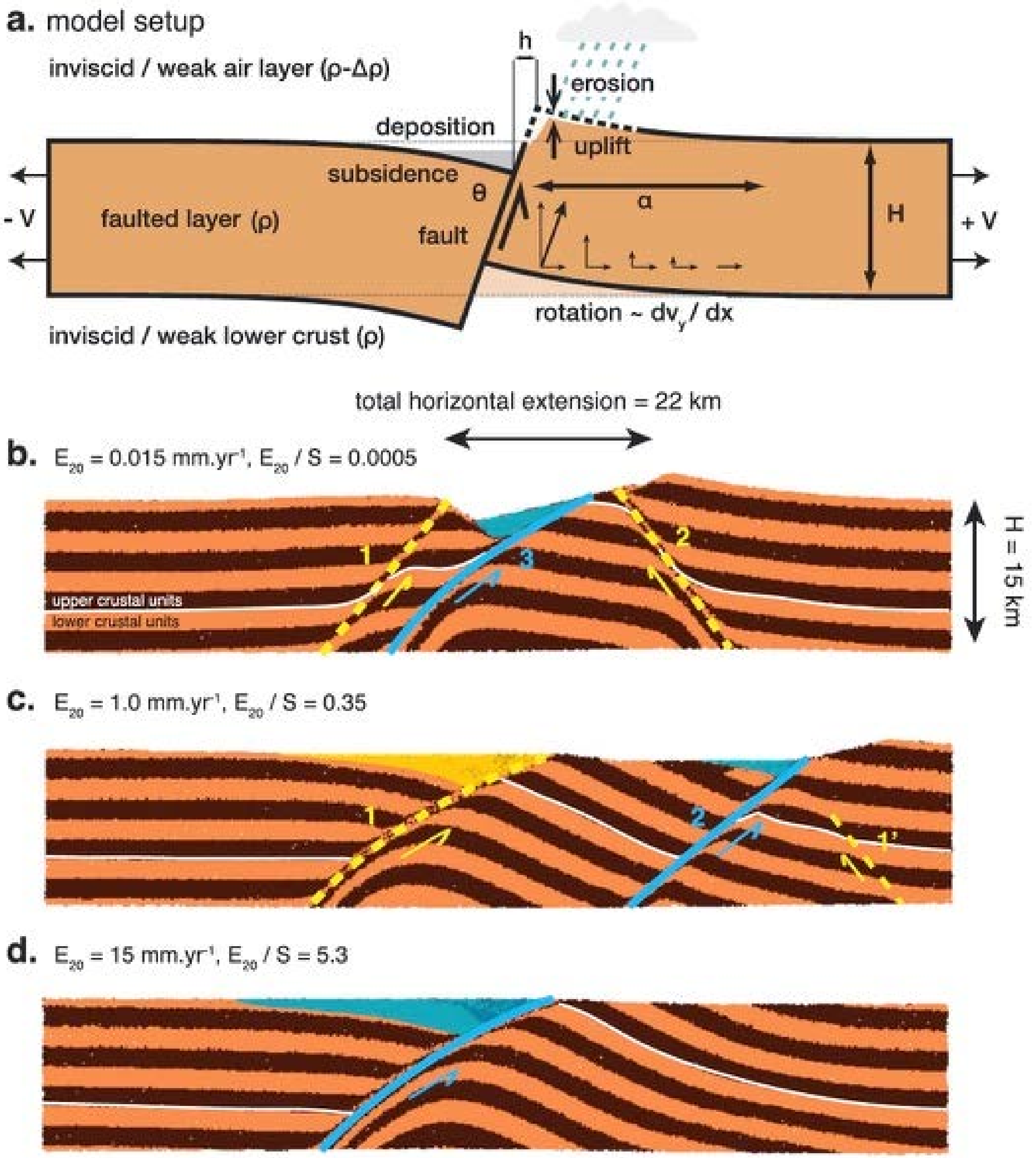
Scales and architecture of extensional systems spatially variable. Endmembers, plus all between

1) ‘cratonic’ rifts – develop in cold, thick lithosphere; often associated with magmatism or flood magmatism
2) ‘orogenic’ rifts – develop in collapsing orogens where crust is hot, mantle may be hydrated

Differences confirm critical importance of crust and mantle rheology- Fault length, depth extent of seismicity scale with crustal strength

Focus of this talk: cratonic rift development

Olive et al., GRL, 2014



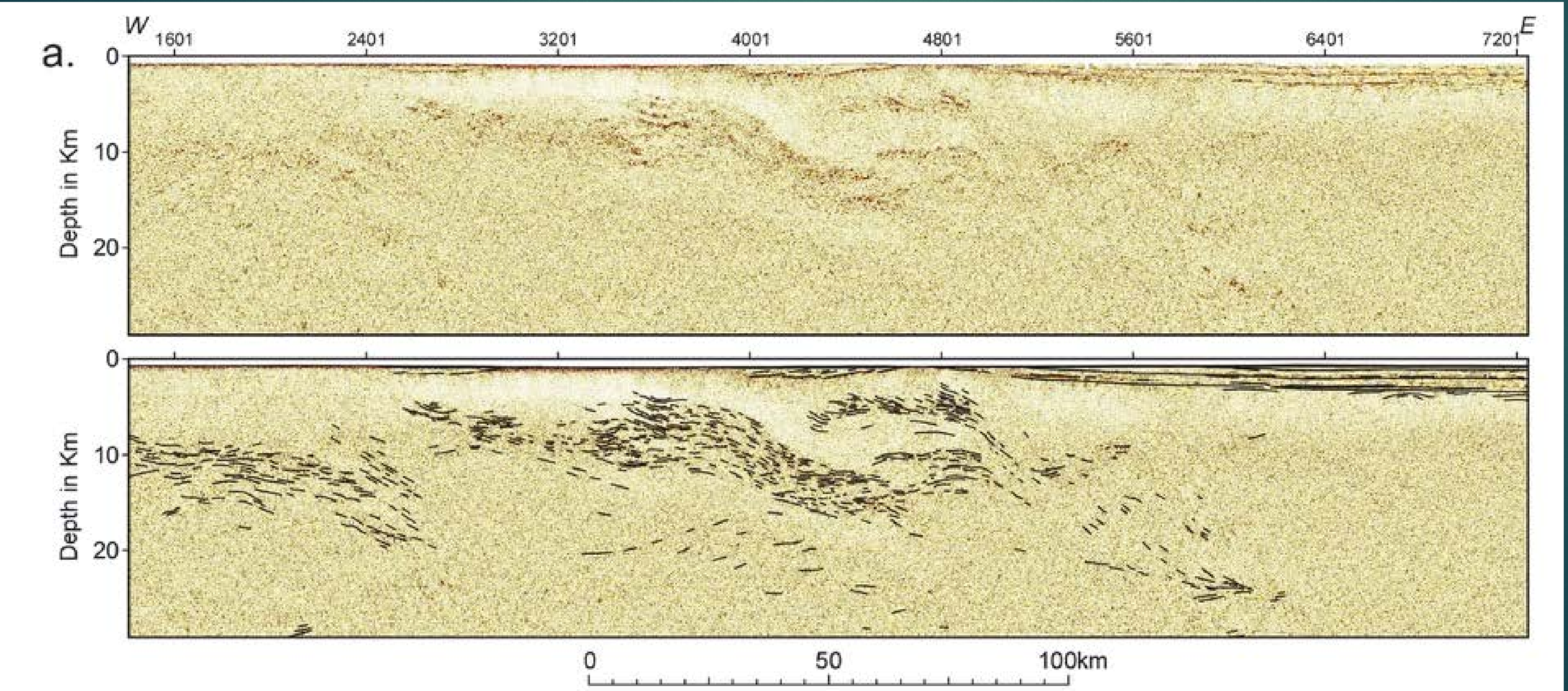
Many thermo-mechanical models. None of them capable of maintaining half-graben for large strains.

What do we know about the lower crust and upper mantle deformation?

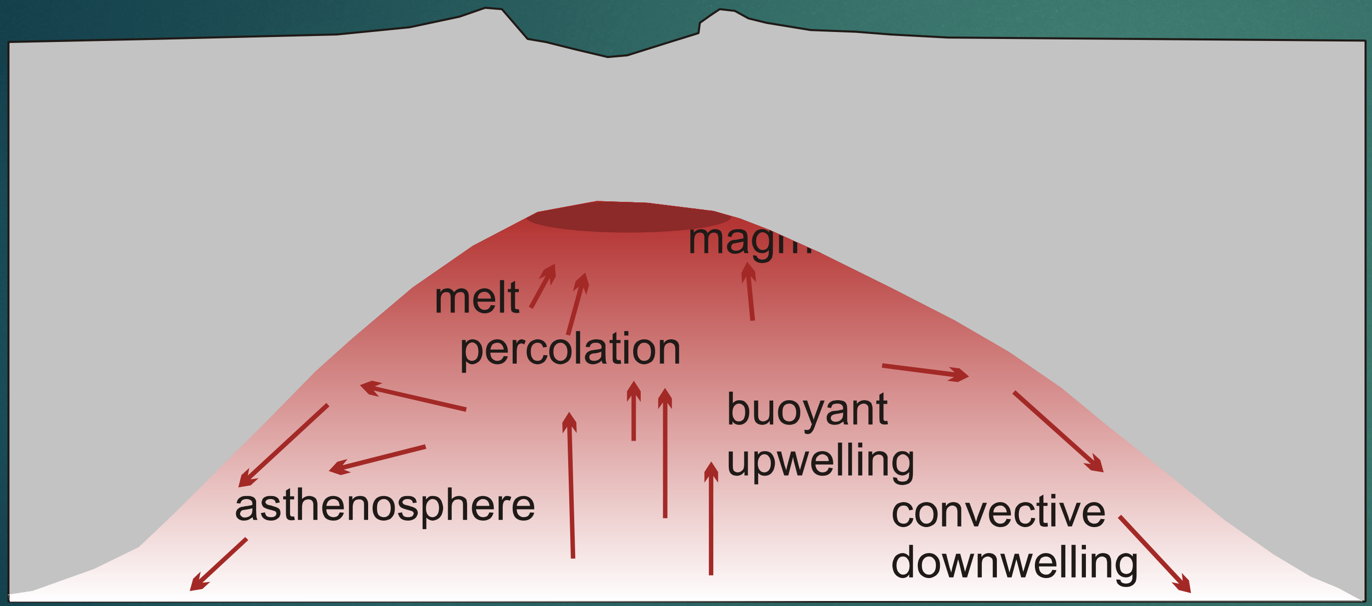
Lab models of diffusion and dislocation creep are limited to just a few mineralogies, and role of fluids are poorly understood.

Lower crustal and upper mantle earthquakes in rifts provide key clues as to fault geometries, yield strength, rift kinematics, and possible role of fluids

‘Standard’ approach to crustal imaging of continental basins – reflection seismic – no kinematic information, steep structures poorly imaged or not imaged



Daly et al., Tectonics, 2014



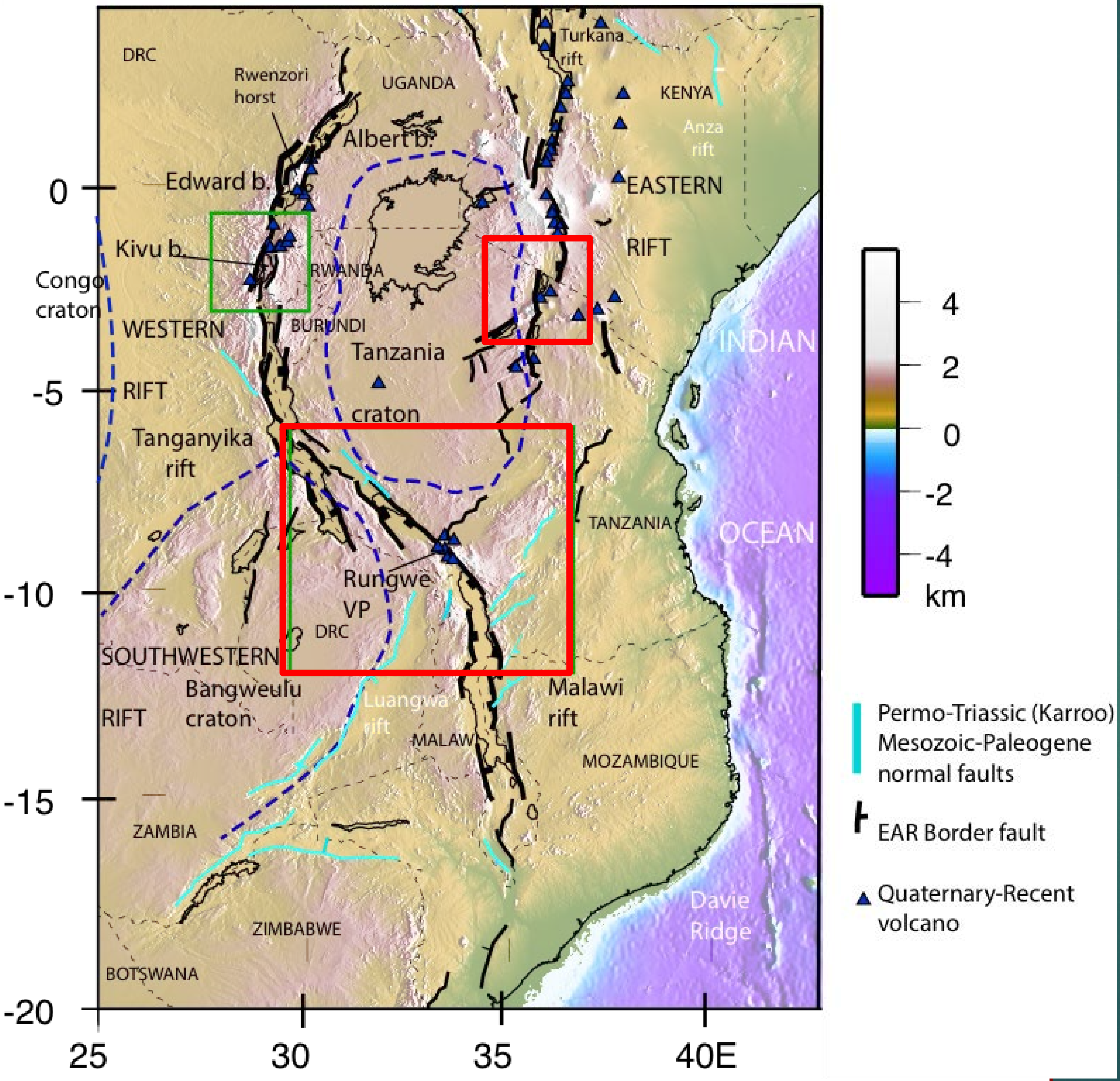
Ebinger et al., 2013

Syn-rift magmatism:

starts deep, and hidden - hard to detect intrusions in mantle, lower crust

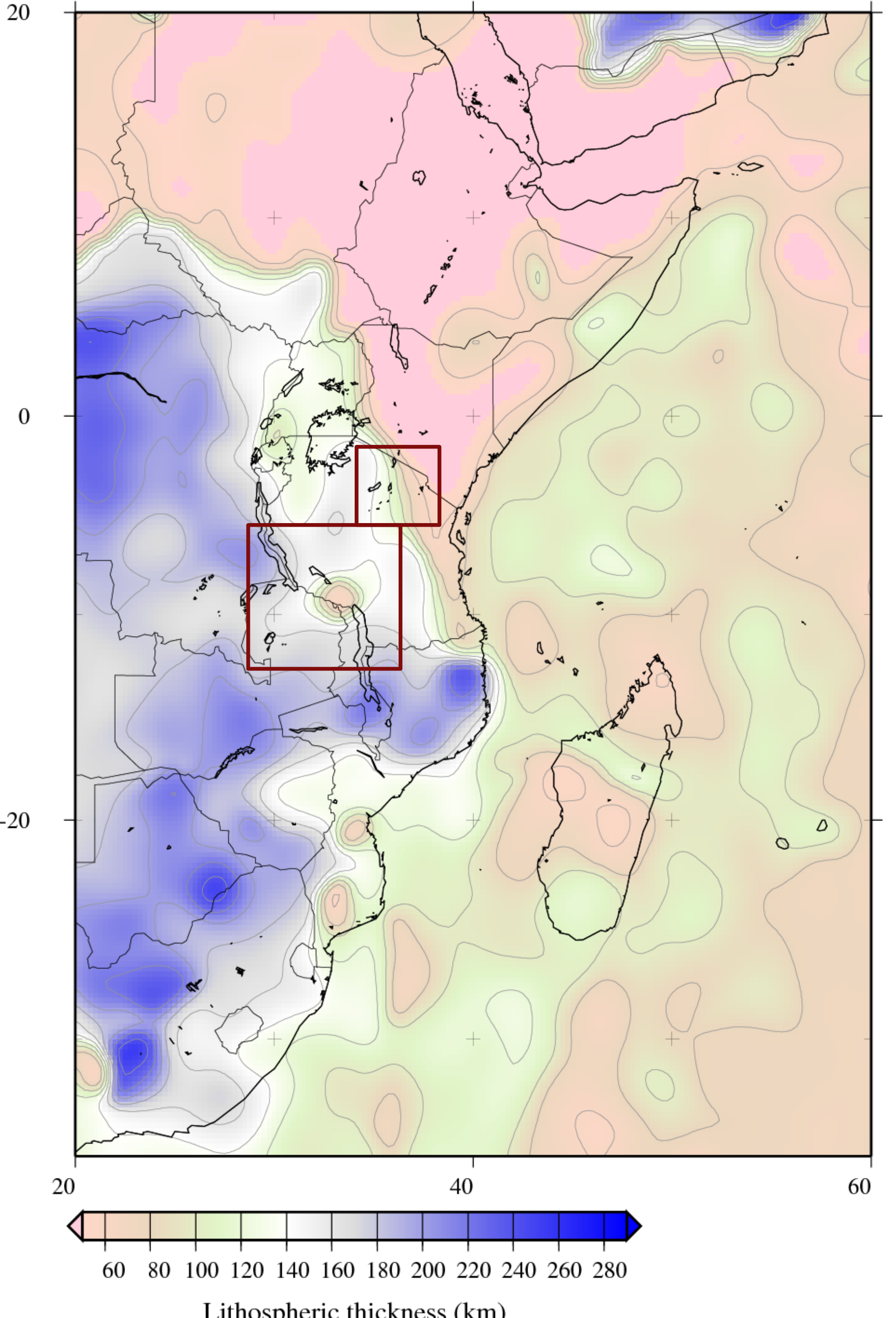
magma transfers heat increases bulk density
more post-rift subsidence

introduces volatiles
reduces fault strength,hydrocarbon mobility
has short and long-term implications for strength



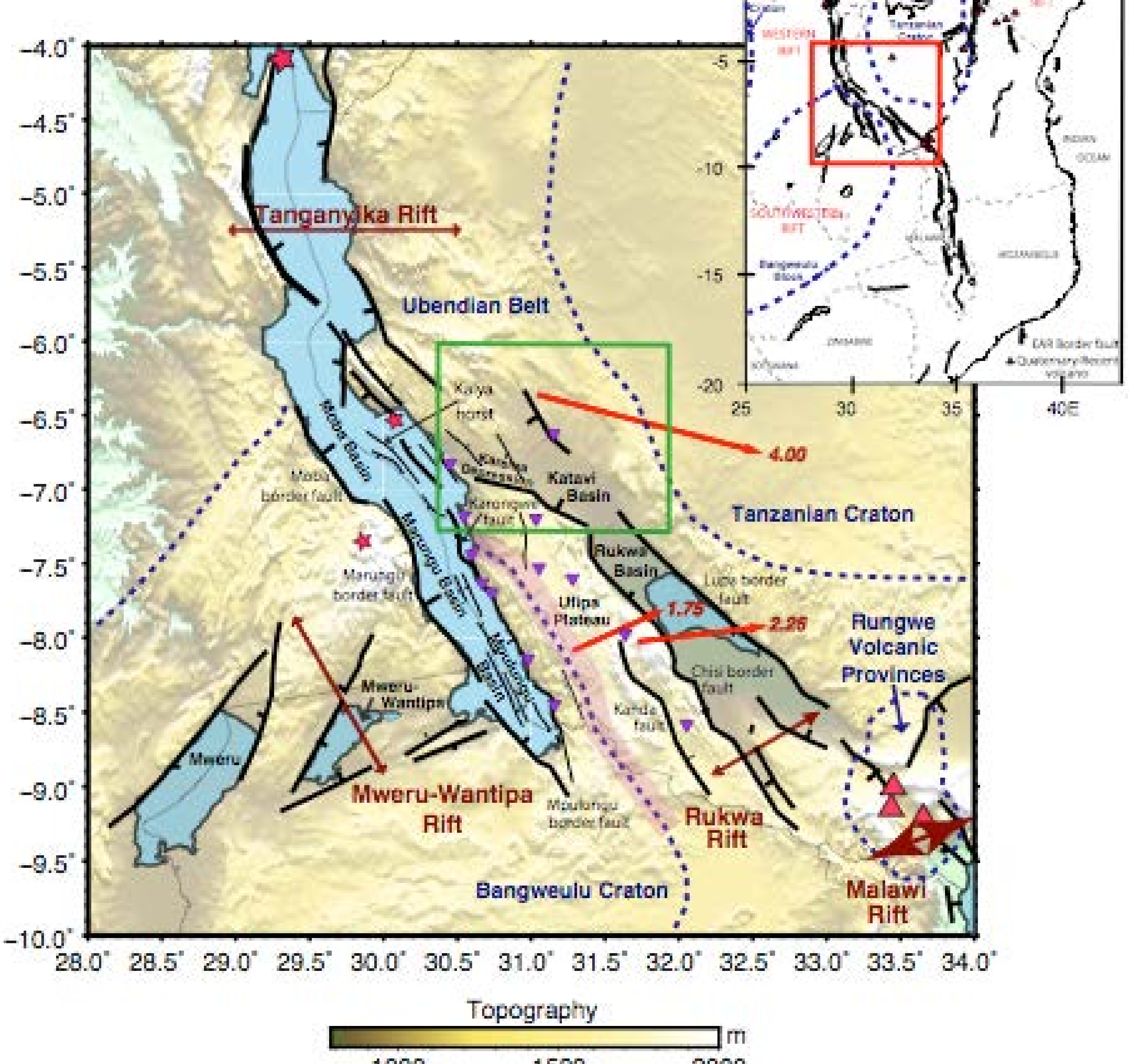
Objectives:

- Compare and contrast crust and lithospheric-scale half-graben fault kinematics in magmatic, weakly magmatic, and amagmatic cratonic rifts, using new imaging studies and earthquake analyses
- Where is strain localized? Magma intrusion localized?
- Are border and intrabasinal faults shallow or deep?
- Thermal/subsidence implications.

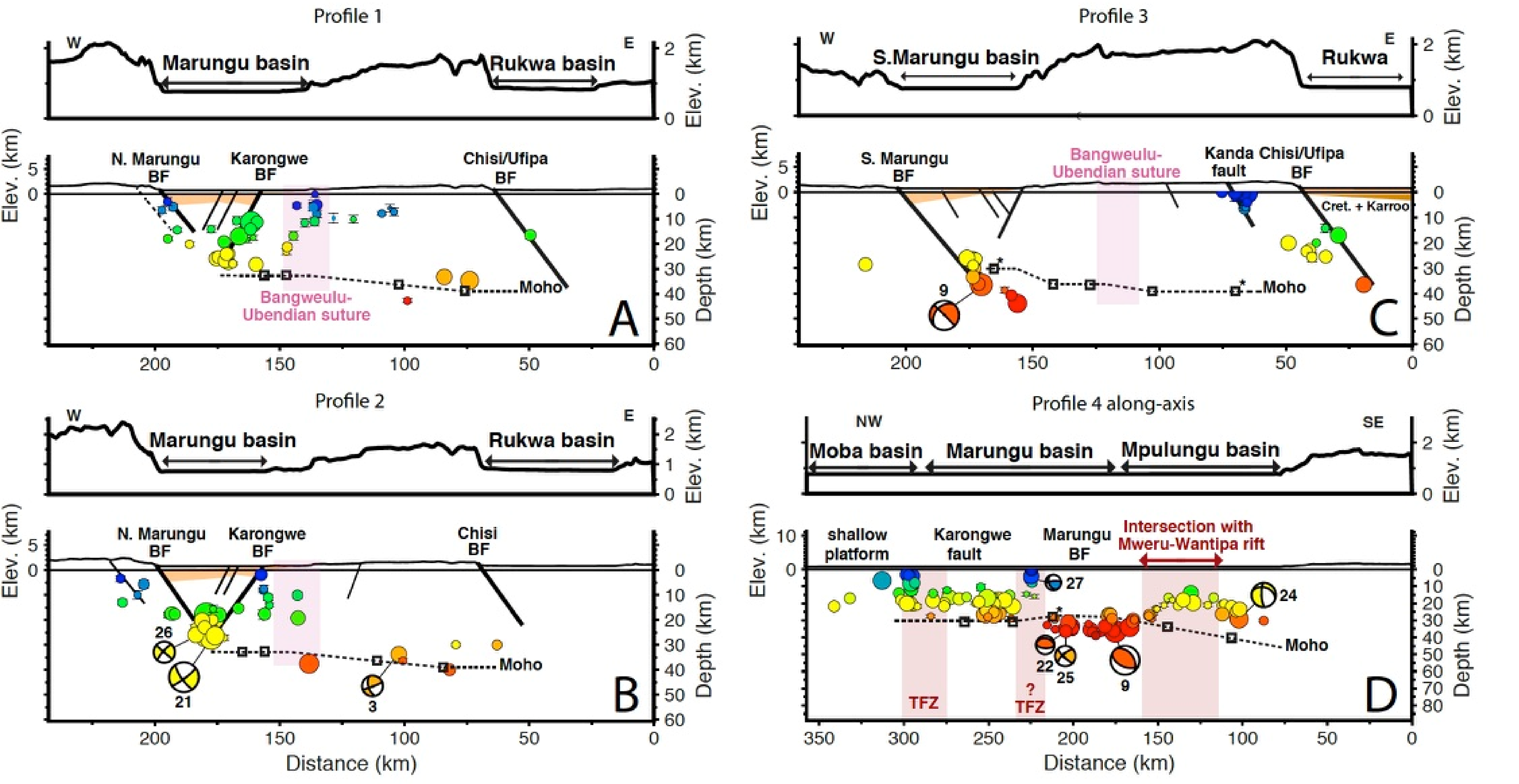


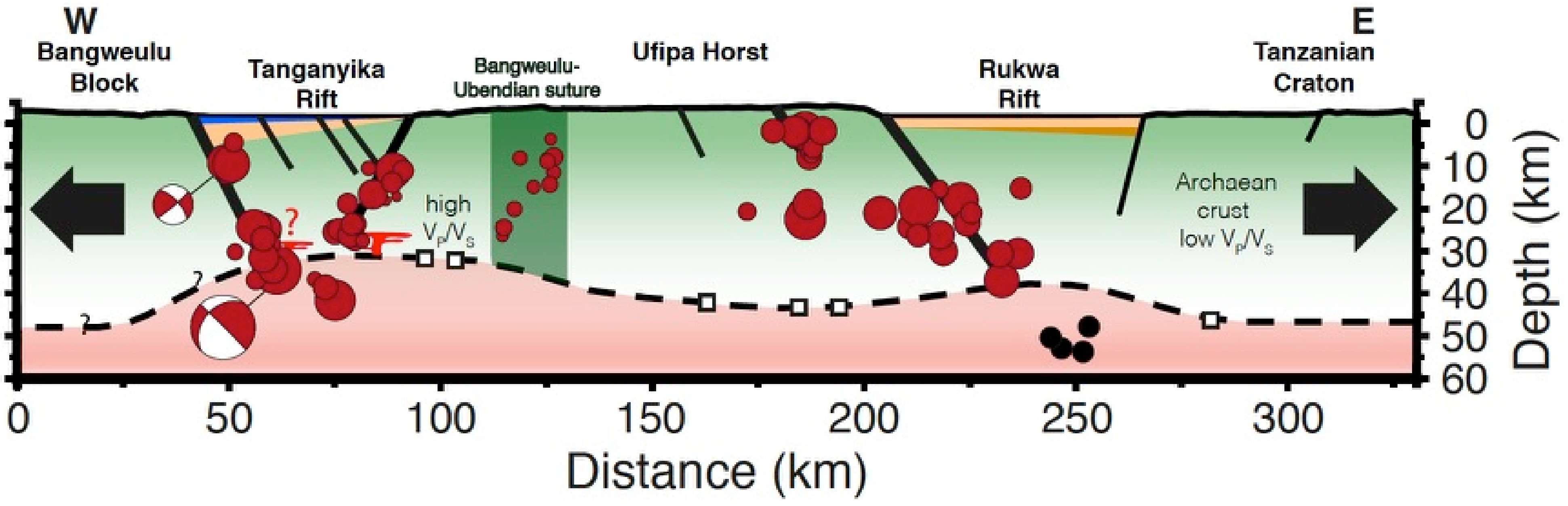
- Thick lithosphere is being rifted beneath EAR
- Strength of plate > plate pulling forces. Implies bottom-up heating and metasomatic processes pre-condition plate to extension.
- Figure from Fishwick et al., 2018, in press.

TANGA14 – Crustal-scale normal faults in cratonic lithosphere



Lavayssiere, Drooff, in review, GJI, 2018

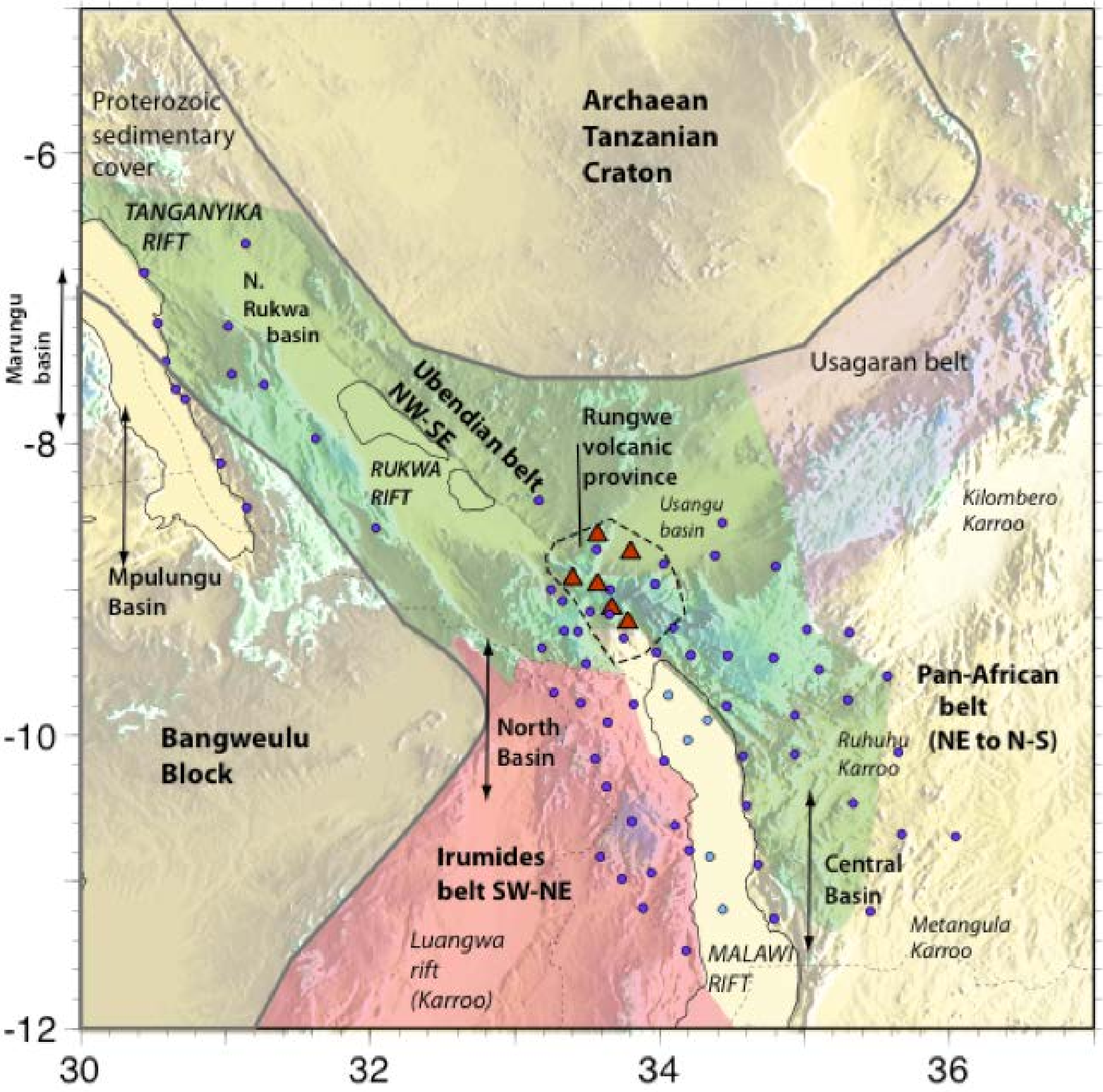




Crustal structure from Hodgson et al., 2017; Figure from Lavayssiere, in review

12 My (or more) after rift initiation, extension is achieved by slip along large offset, steep (>45º) border faults that penetrate to lower crust.

Time-space patterns of upper mantle EQs and high Vp/Vs in lower crust suggest deep magma intrusion



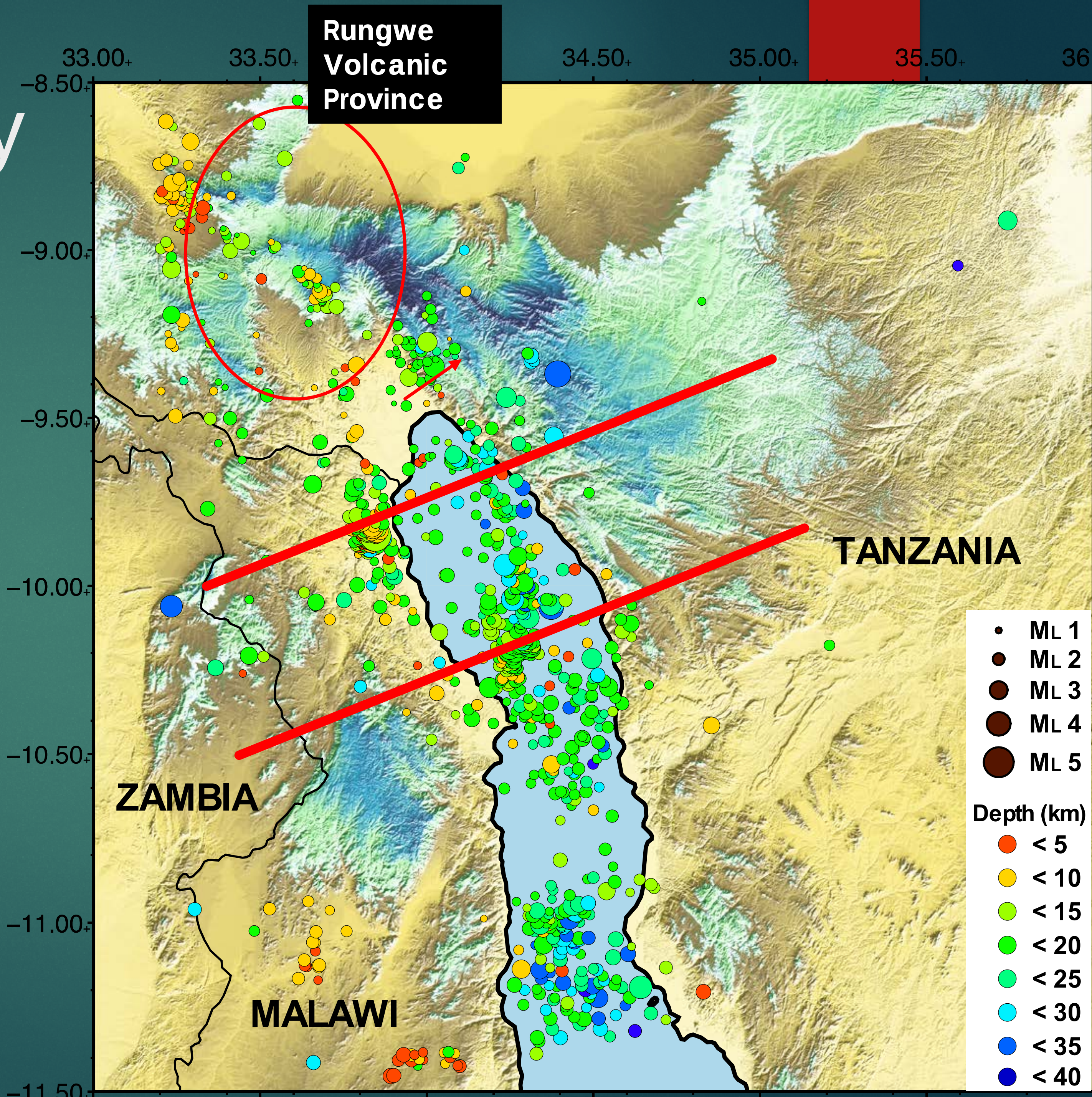
- SEGMeNT Project

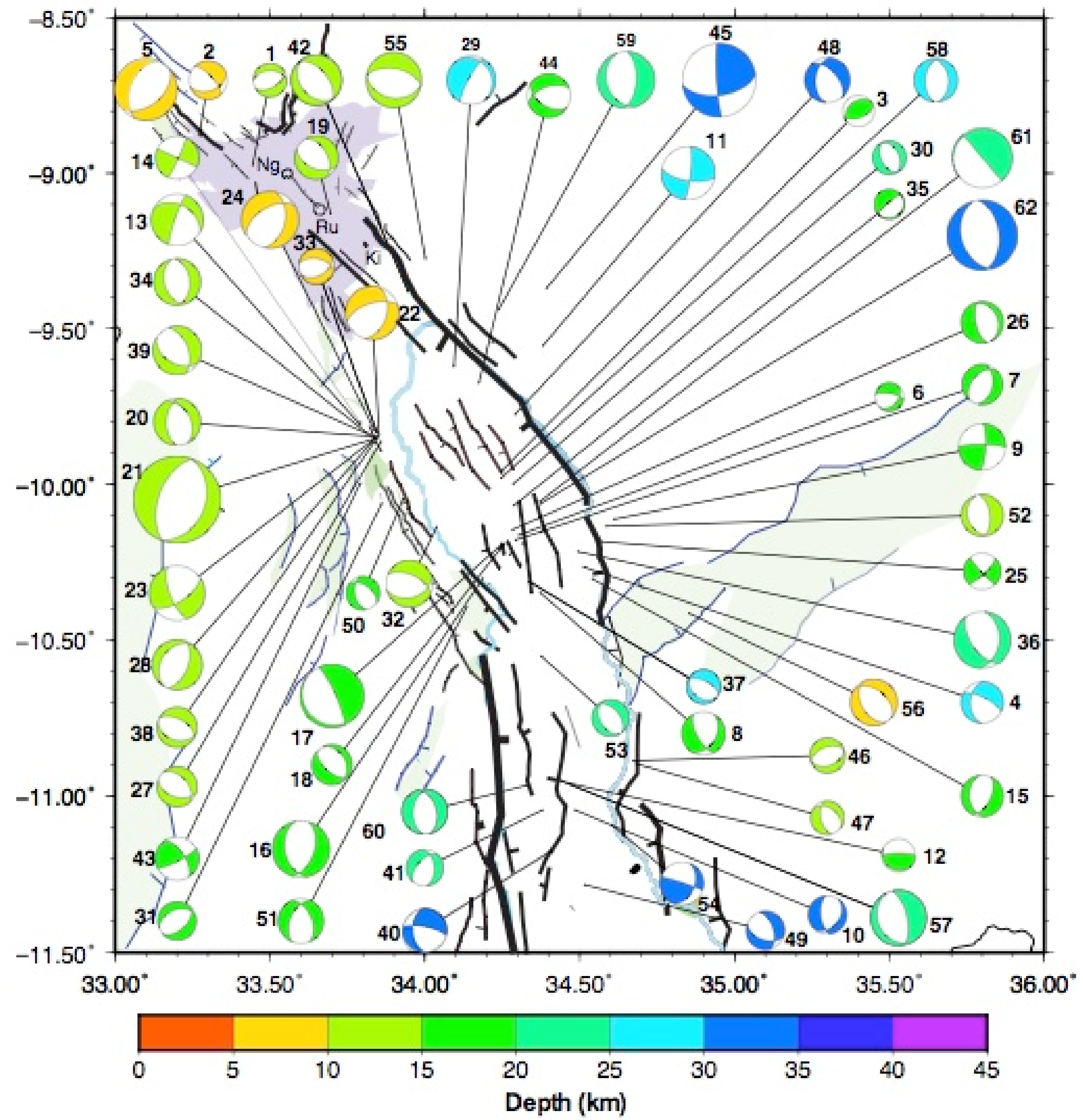
D Shillington, lead PI

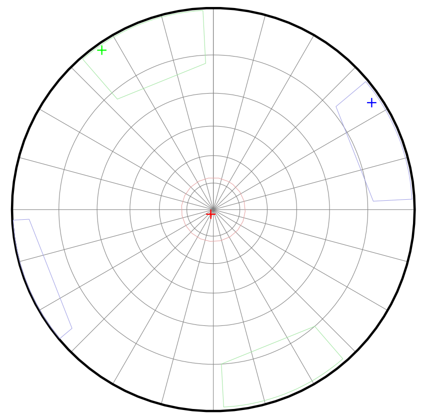
- Crust and upper mantle framework
- 18 Ma Magmatic province at northern end
- 63 onshore + 17 OBS seismometers; reflection with Syracuse streamer
- Crustal thinning << than mantle lithospheric thinning – heating from below consistent with magmatism at rift onset and proximity to superplume (Accardo et al., 2017; Grijalva et al., in press; Hopper et al., in prep).

SEGMeNT Seismicity

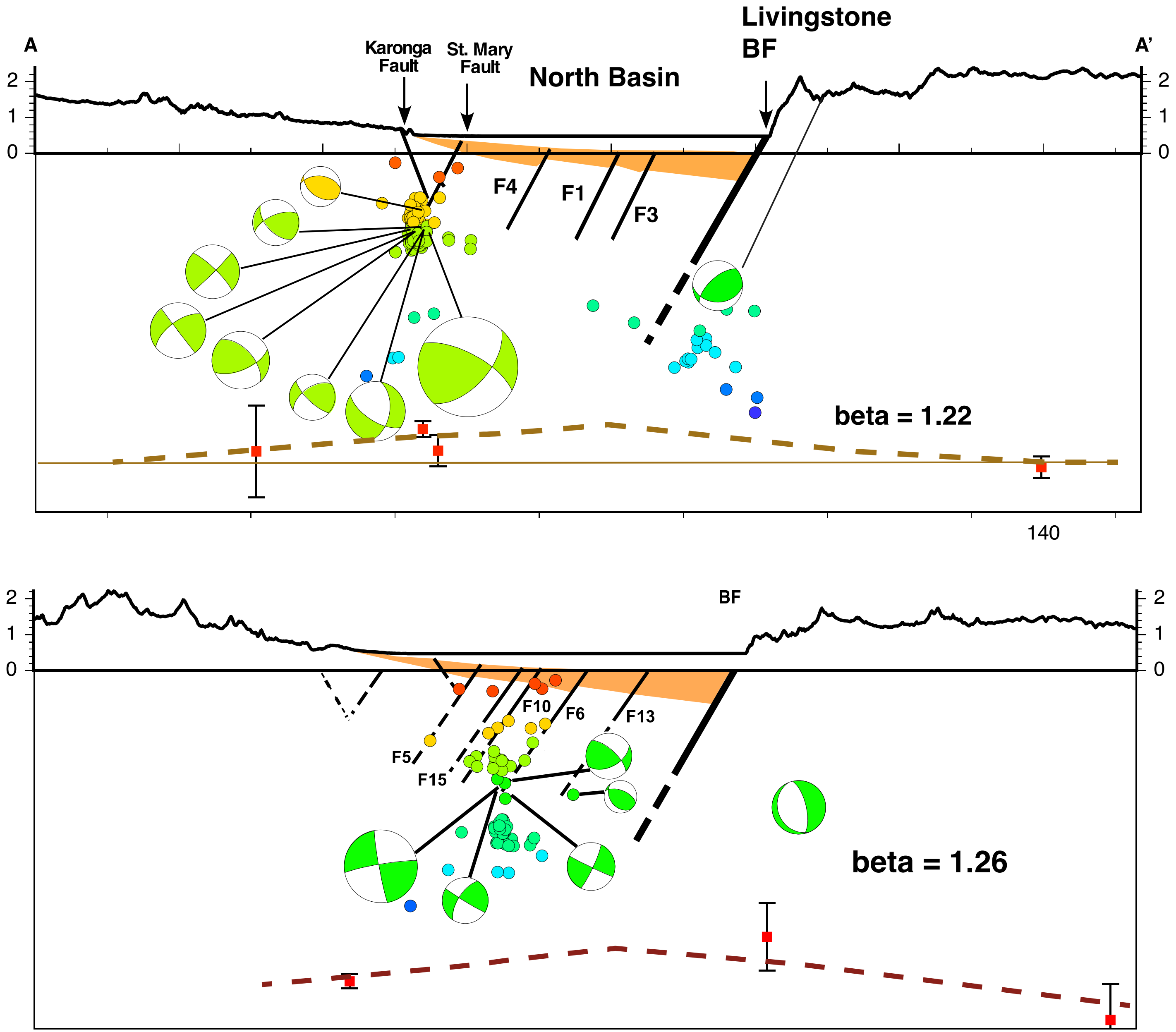
- Recorded from 2013-2015 by SEGMeNT network on 63 land and 17 OBS
- N=1160 (much lower rate than Tanganyika)
- 0.7 < ML < 5.2
- Depths 0.2 to 38.6 km
- Some activity beneath Rungwe volcano, the Rungwe volcanic province
- Double-difference locations (<1 km errors in location) in subsequent figs



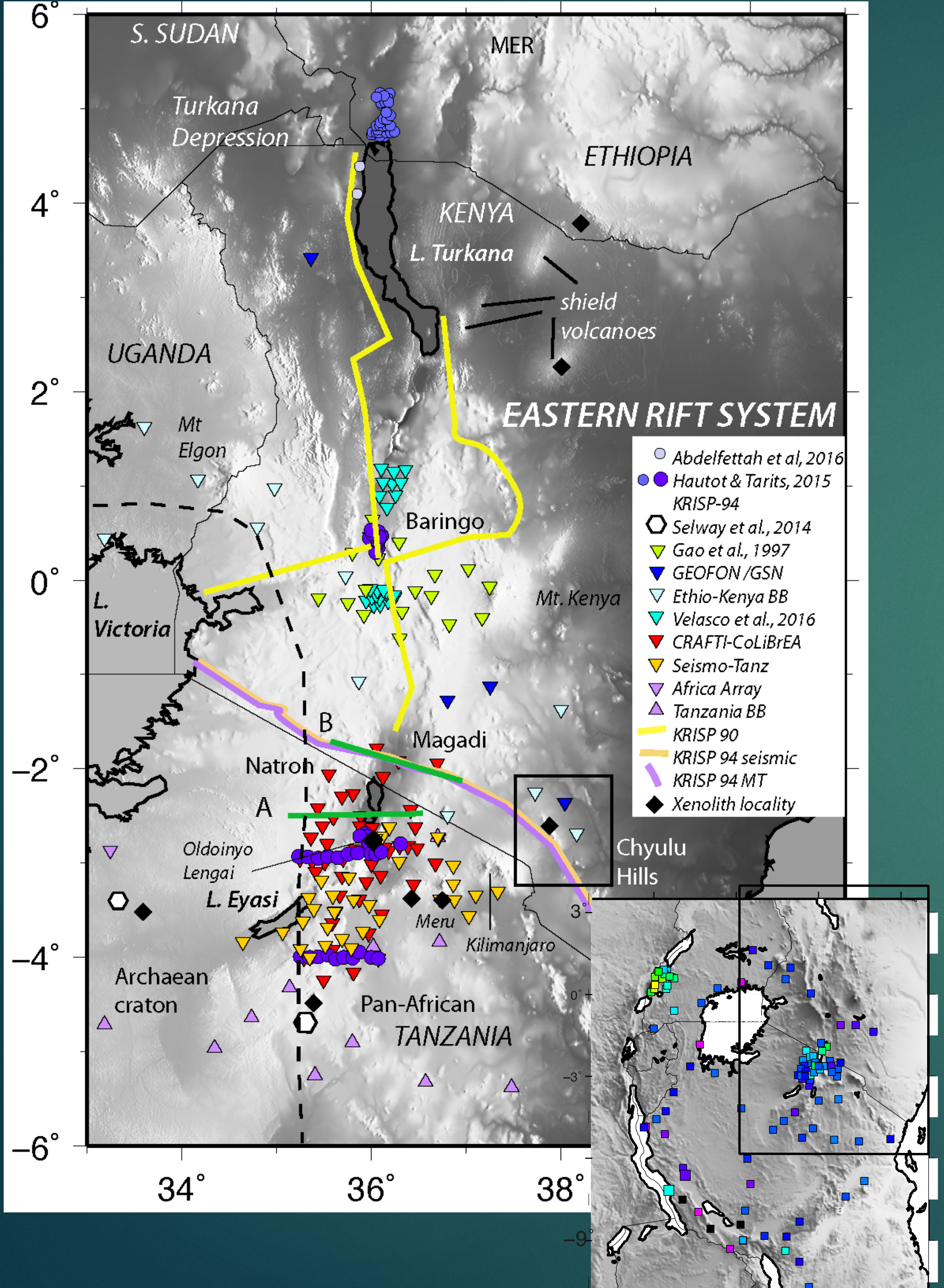




- 62 events with <10 solutions and <20° variation of strike, dip and rake; $1.7 \leq ML \leq 5.1$
- Extension direction N76°E
- Border and intrabasinal faults rupture in lower crust

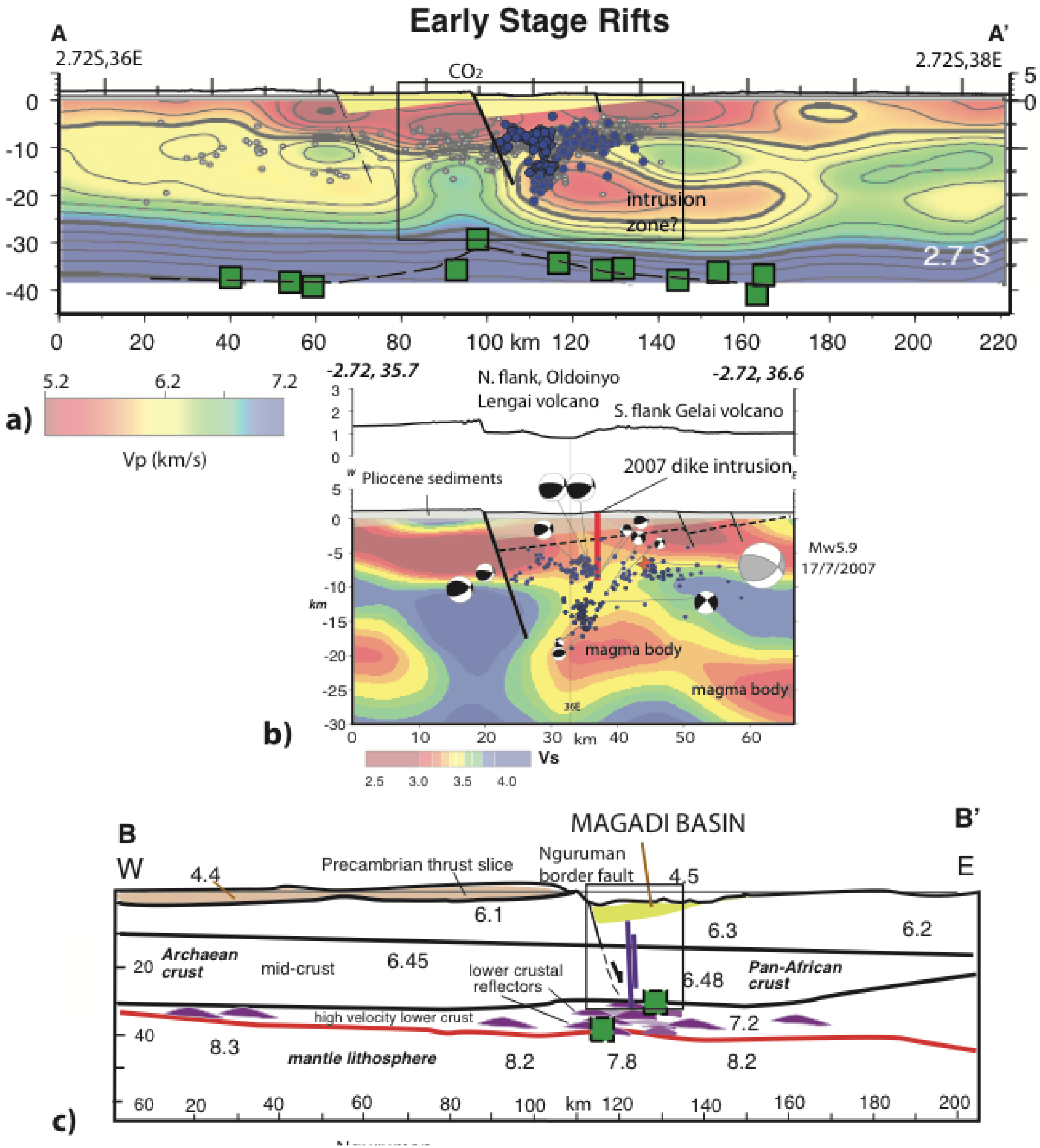


- Steep border faults to 25-30 km
- Intrabasinal faults continue to 15-20 km depth
- Preferred nodal plane dips decrease at depths > 15 km to approx. 40º
- Beta factors < 1.25, whereas mantle tomography and Sp receiver functions suggest mantle lithospheric thinning is almost 2 or more (Accardo et al.,GJI, 2017; Grijalva et al., 2018; Hopper et al., submitted).
- Crustal thickness from Borrego et al. GJI, 2018



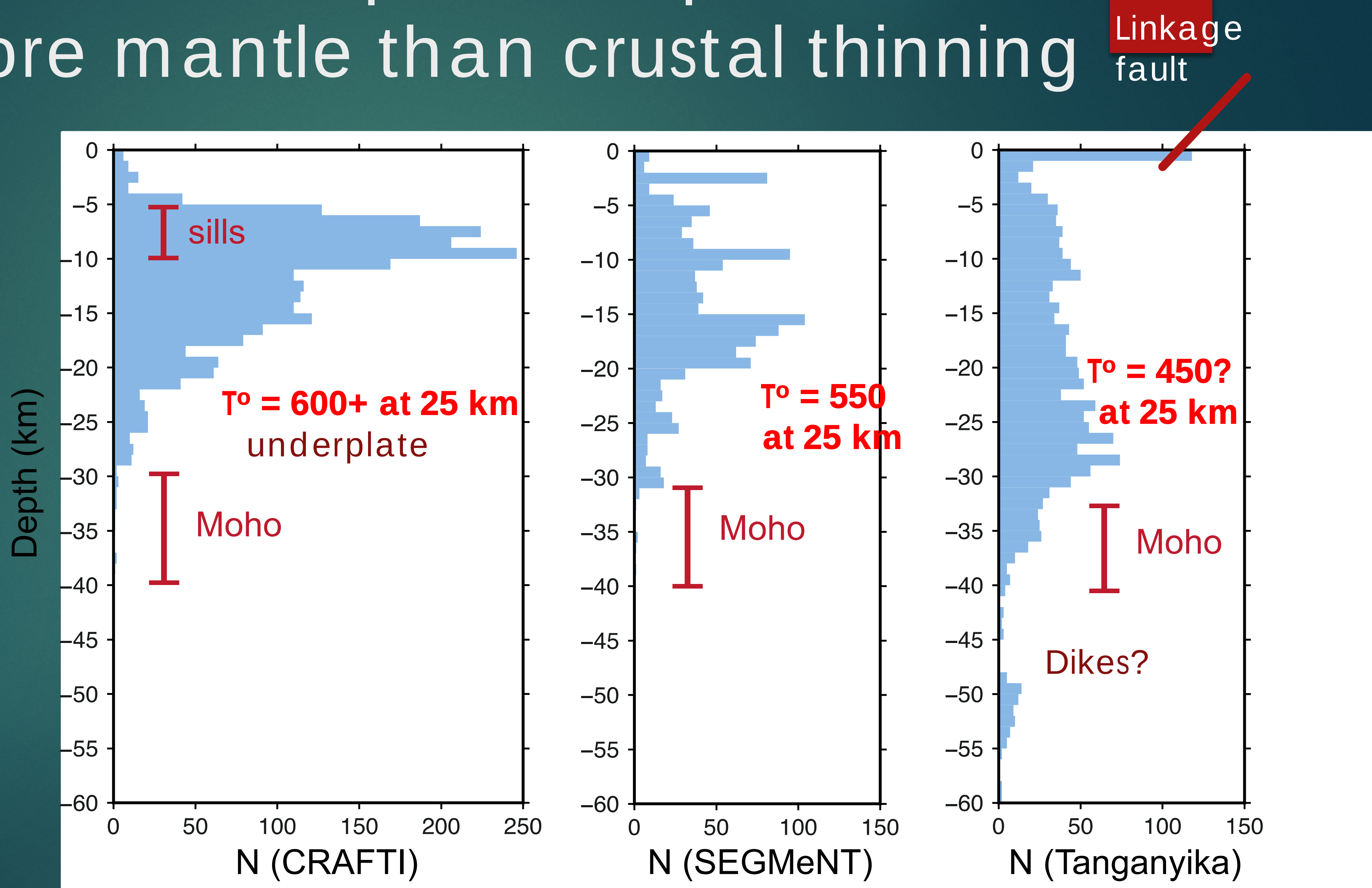
Magadi-Natron rift : < 7 *My-old structures, yet ~20% new igneous crust; site of dike intrusion- eruption in 2007-8; underlain by Archaean mantle lithosphere.*

- 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 some arcs



Comparison of earthquake depths – all rifts with more mantle than crustal thinning

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

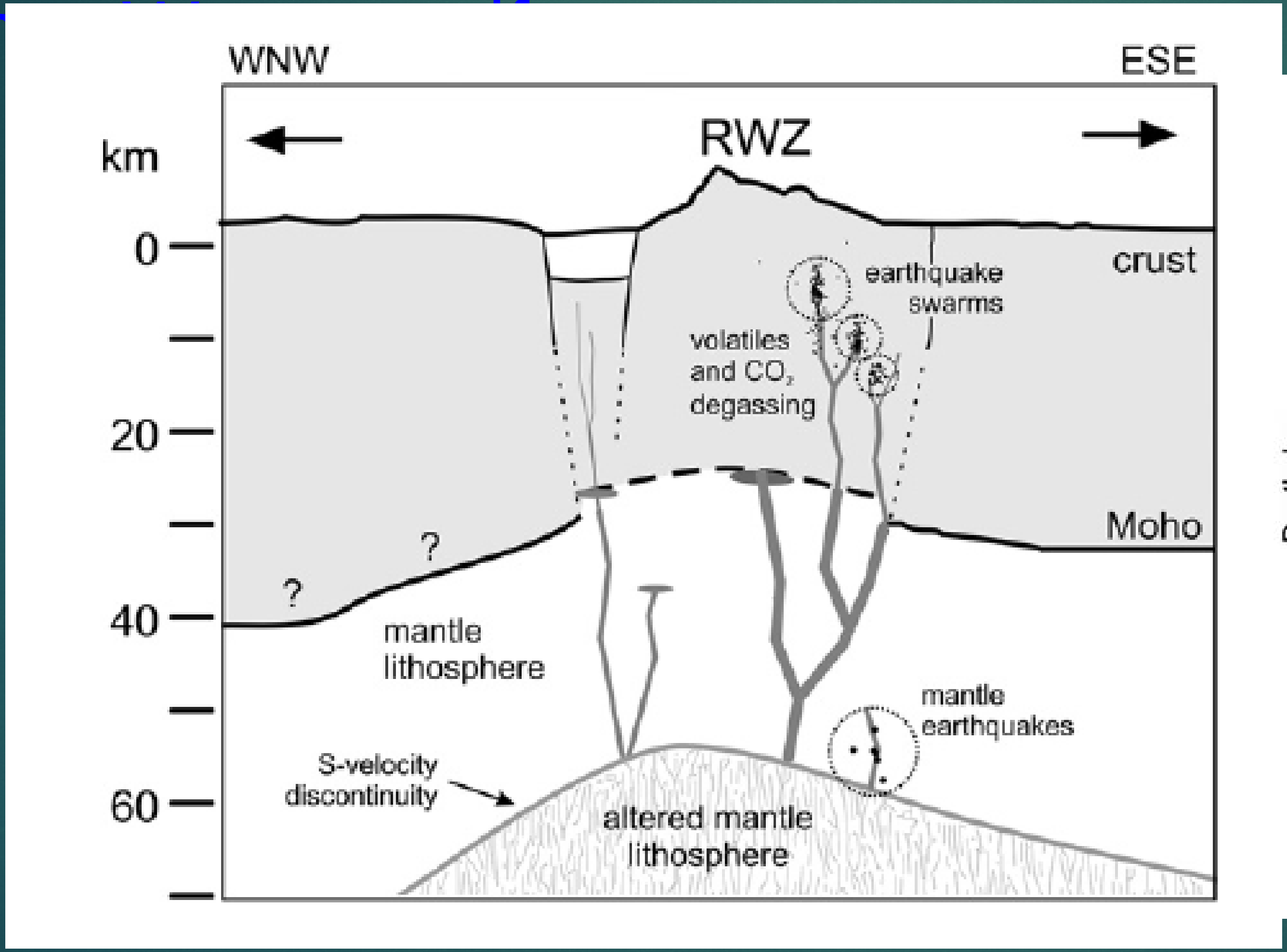


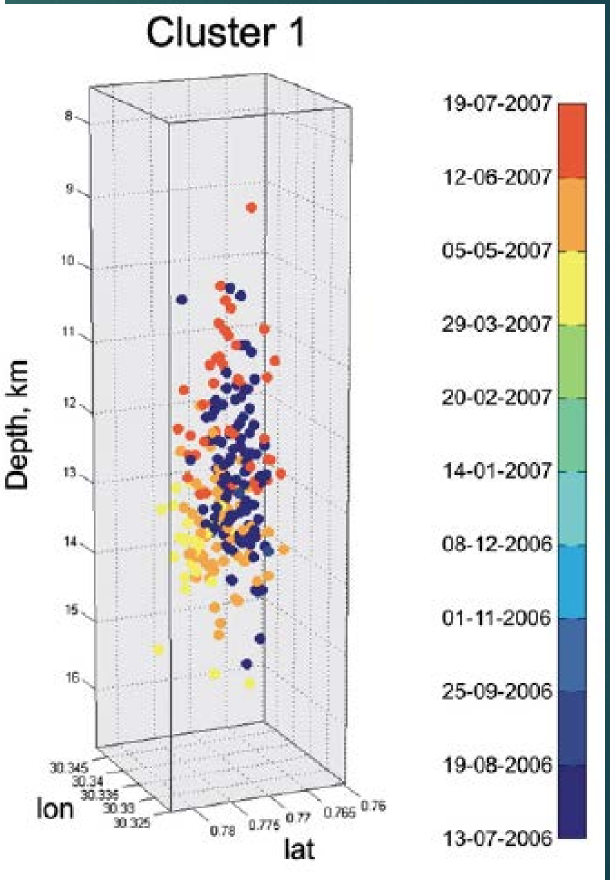
Conclusions

- **Steep, deep border faults continue to the base of the crust in early stage cratonic rifts in basins ranging from < 5 Ma to > 12 Ma.**
- **Border faults decrease in activity as shallow magma chambers develop and intrusion accommodates opening.**
- **Syn-rift cratonic basins exploration models should include enhanced early heating.**
- **No evidence for shallow detachment faulting in half-graben cratonic basins**
- **Modern extension direction in all areas is sub E-W**

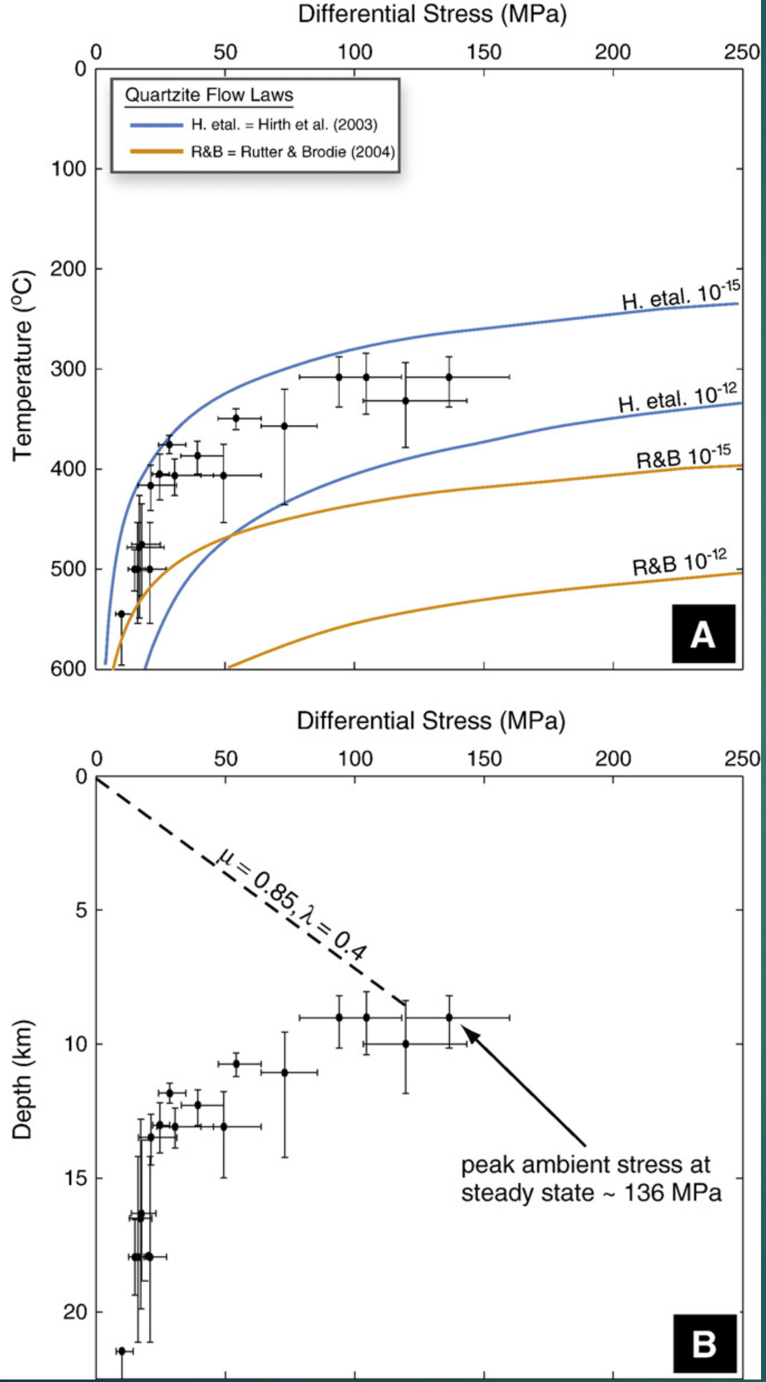
Lower crustal and upper mantle earthquakes - presence of fluids even in ‘amagmatic’ rifts. Rapid stressing by magma intrusion, high pore pressure, super-critical CO2 induce lower crustal fault zones that localize strain

Upward-migrating earthquake swarms in upper mantle and crust – Albert-Edward rift zon





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



One of the few in situ measurements of rheology - Behr and Platt 2016

Current estimates of lower crustal composition and rheology come from:

Density variations
Vp, Vs, Vp/Vs
Xenoliths
Volatiles

Behr & Platt, EPSL, 2016