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Present-day strain rates and large-scale dynamics of the East African Rift

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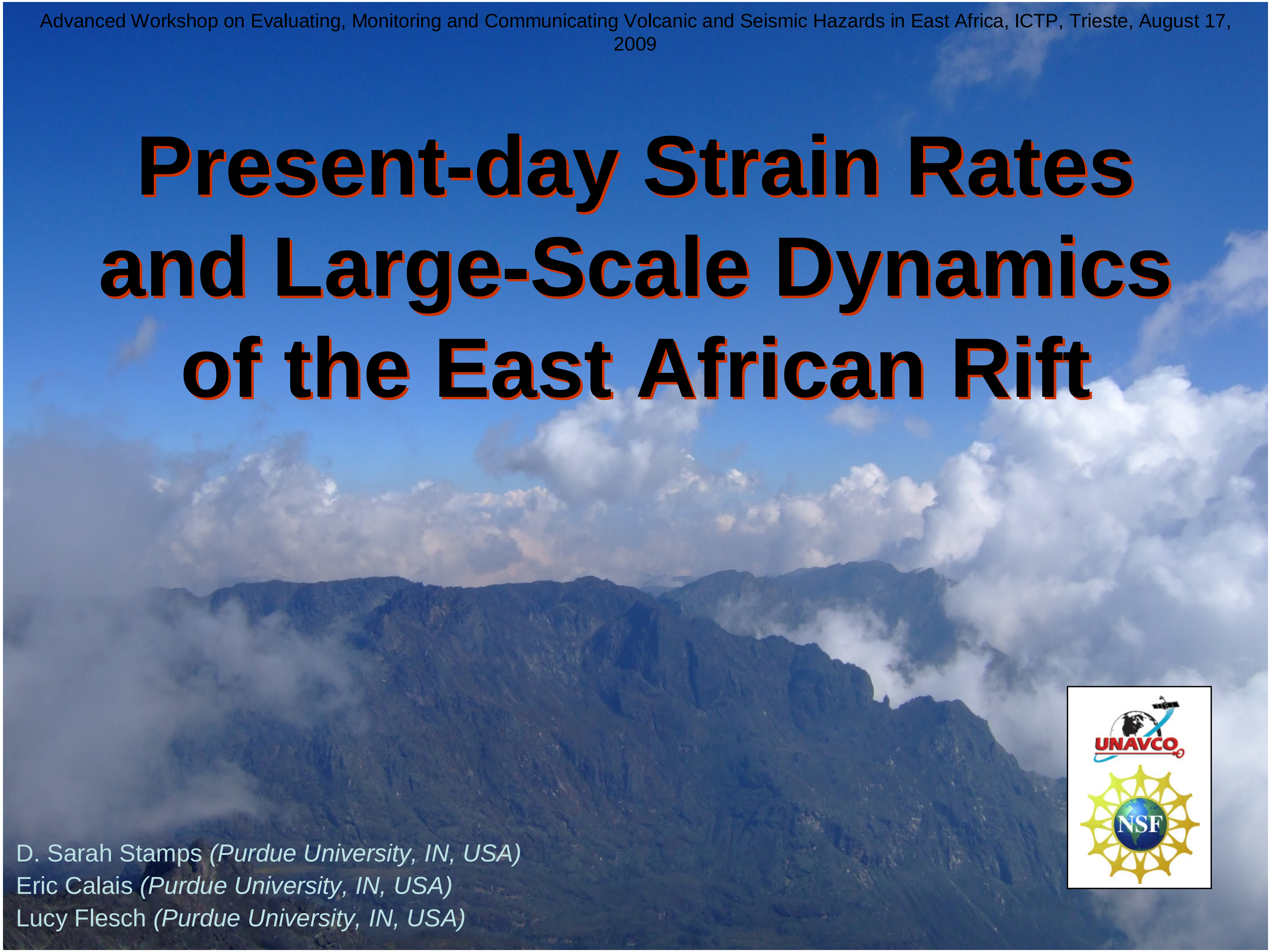
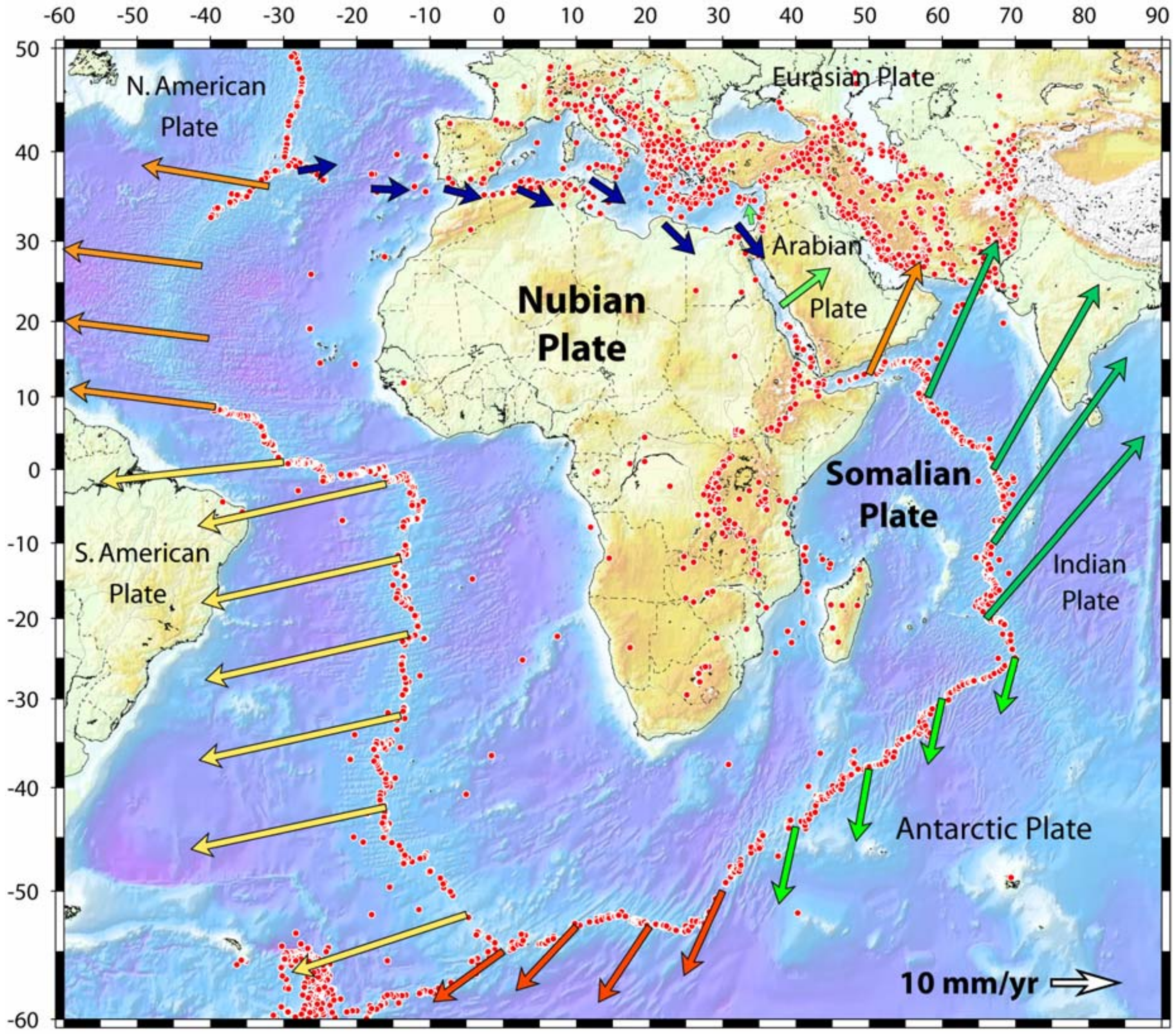


Present-day Strain Rates and Large-Scale Dynamics of the East African Rift

D. Sarah Stamps *(Purdue University, IN, USA)*
Eric Calais *(Purdue University, IN, USA)*
Lucy Flesch *(Purdue University, IN, USA)*

Africa and the East African Rift

- Africa
  - continental mass breaking up
  - mostly surrounded by ridges
- East African Rift
  - 5000 km long
  - Moderate seismicity
  - High topography
- Intraplate stress field
  - buoyancy forces
  - mantle tractions
- Open questions:
  - Kinematics?
  - Forces?
  - Role of melt?



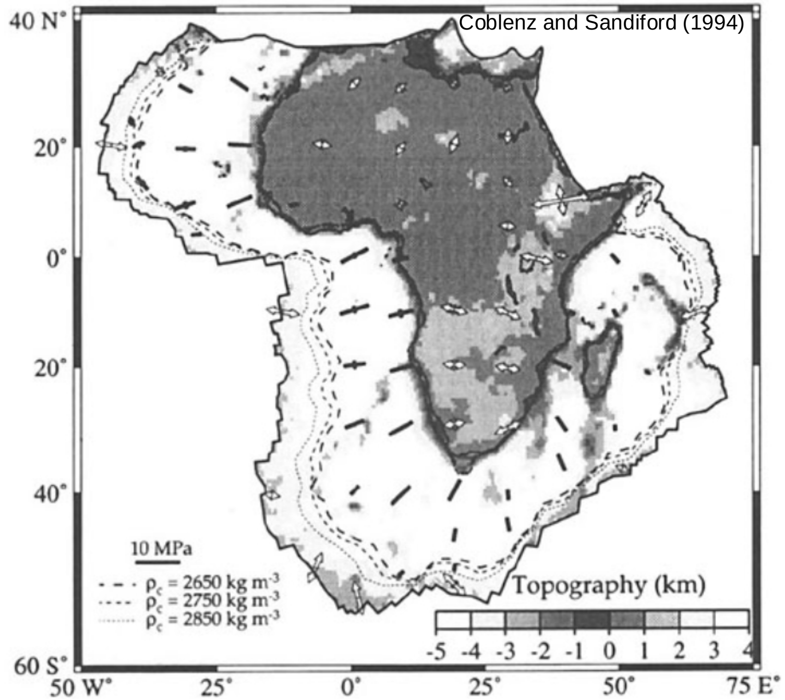
Present-day plate velocities with respect to Nubia

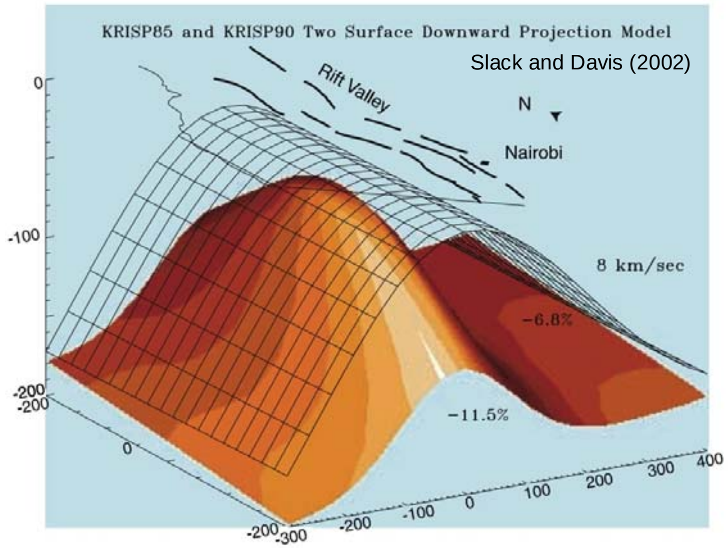
Role of lithospheric buoyancy forces?

- extensional state of stress
  Coblentz and Sandiford (1994)
  - geoid constrained lithospheric density structure
  - stress indicators from World Stress Map

- dynamic uplift + thermal erosion = rupture
  Davis and Slack (2002)
  - ex. Kenya dome
  - long-wavelength gravity and topography
  - tomography
  - small-scale convection

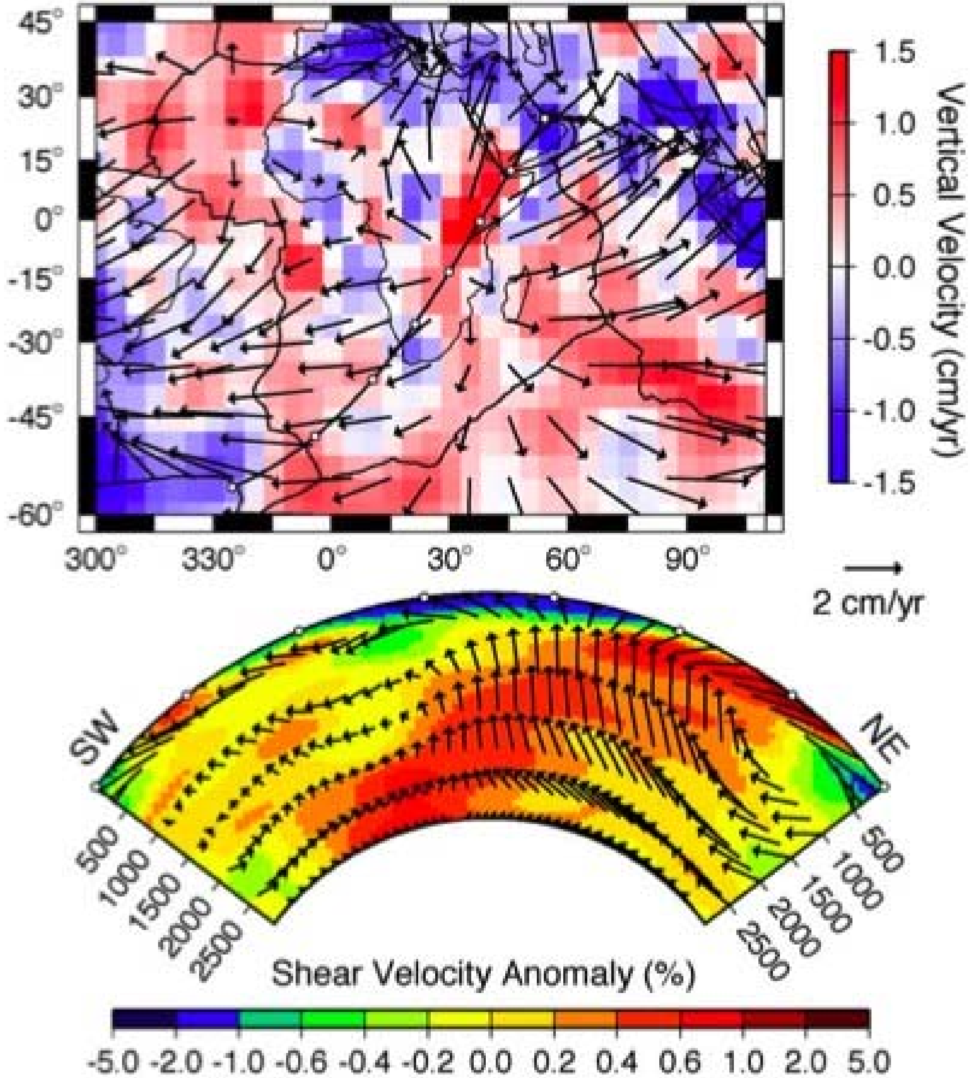
- Problems
  - cratonic rifts?





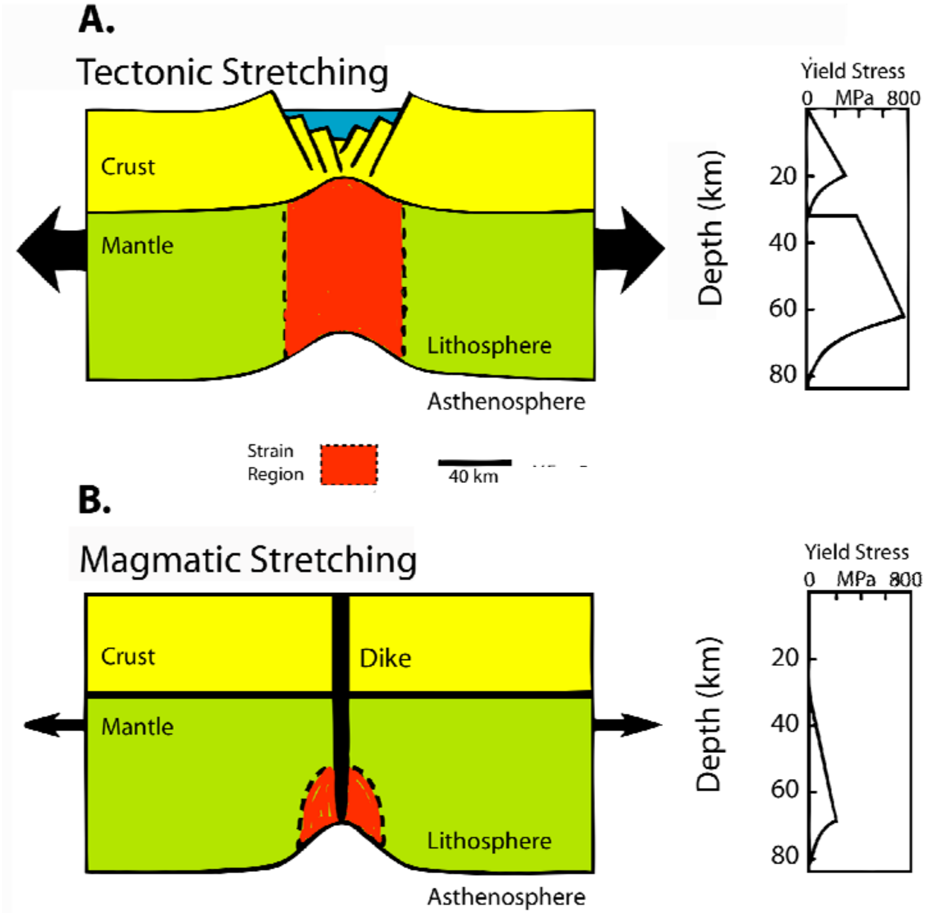
Role of mantle tractions?

- The African Superplume
  - positive shear velocity anomaly
  - divergent mantle flow
  - consistent with surface motions
- Problems:
  - Is the African Superplume buoyant?
  - Coupling?



Behn et al., 2004; Ritsema et al., 1999

Role of melt?

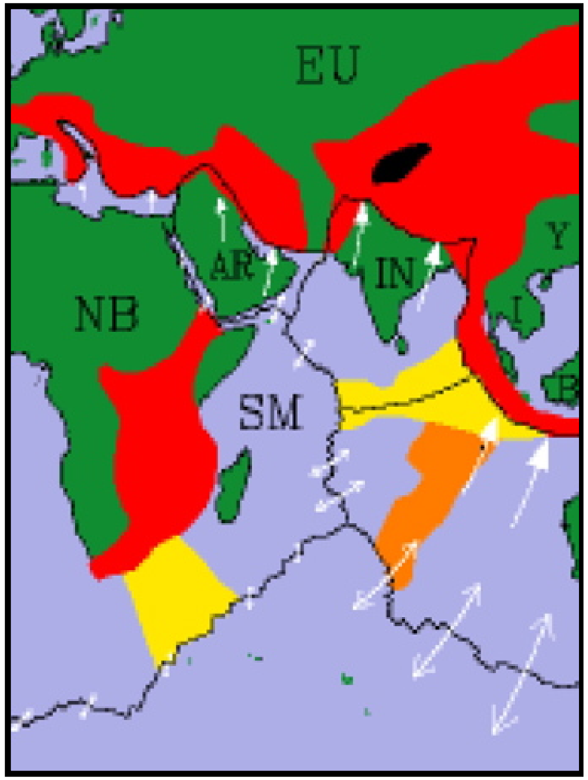


after Buck (2004)

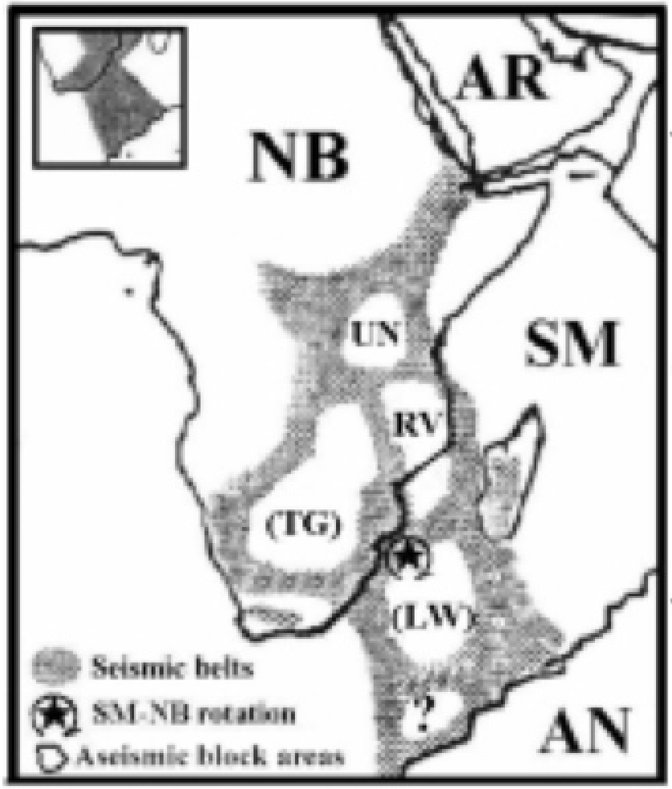
- Tectonic vs. Magmatic Stretching
- East African Rift:
  - Seismic tomography
    melt conditions are present
    (e.g. Keranen et al. 2006)
  - Seismic anisotropy
    consistent with melt lenses
    (e.g. Kendall et al., 2006)
  - Recent diking event (2007)
    youthful and barely extended Natron rift
    (Calais et al., 2008)
- Problems:
  - Not all rifts are very magmatic early on
    Western Branch

Kinematics

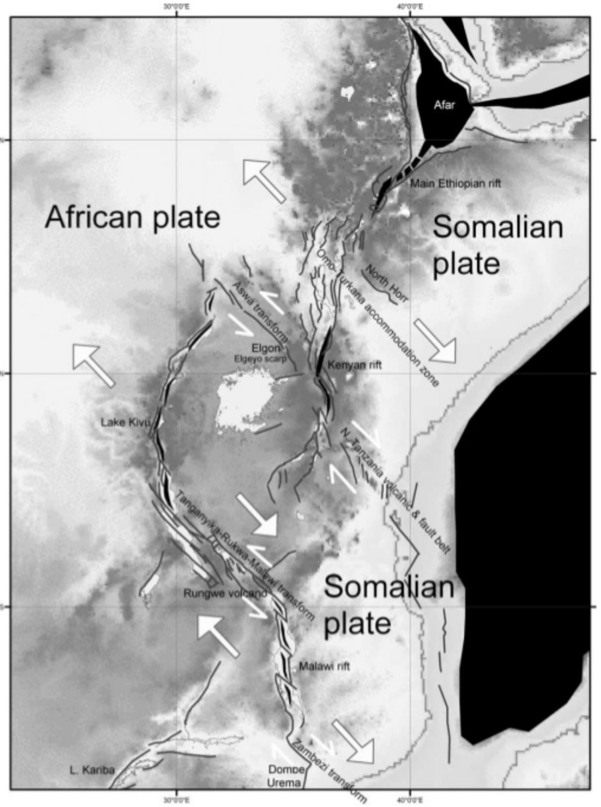
Previous kinematic models



Gordon and Stein, 1991: a diffuse plate boundary

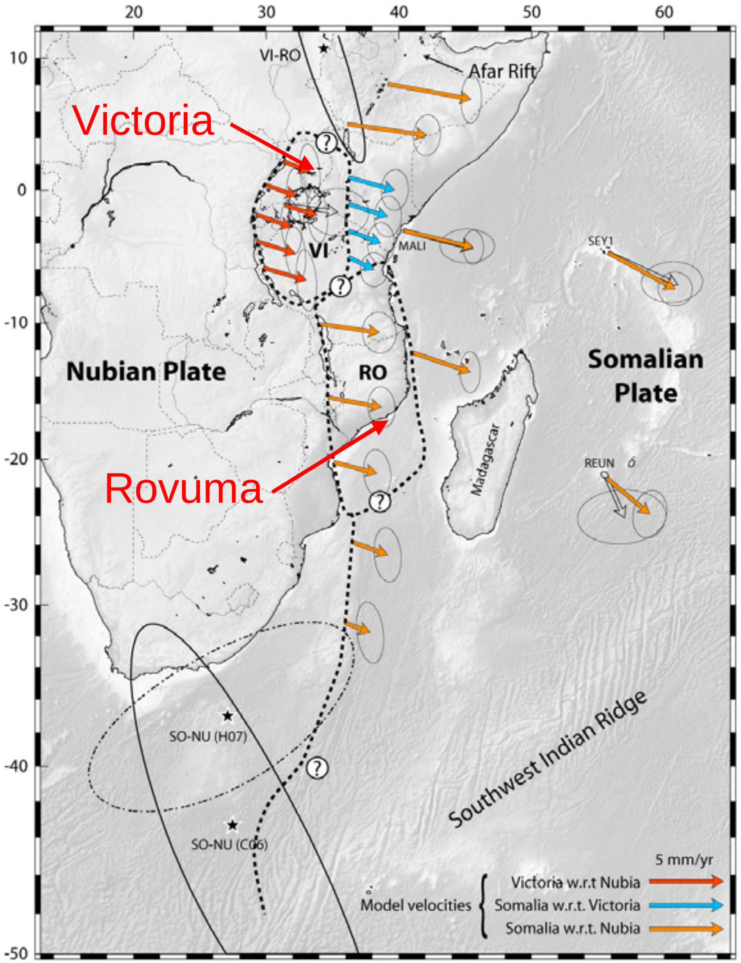


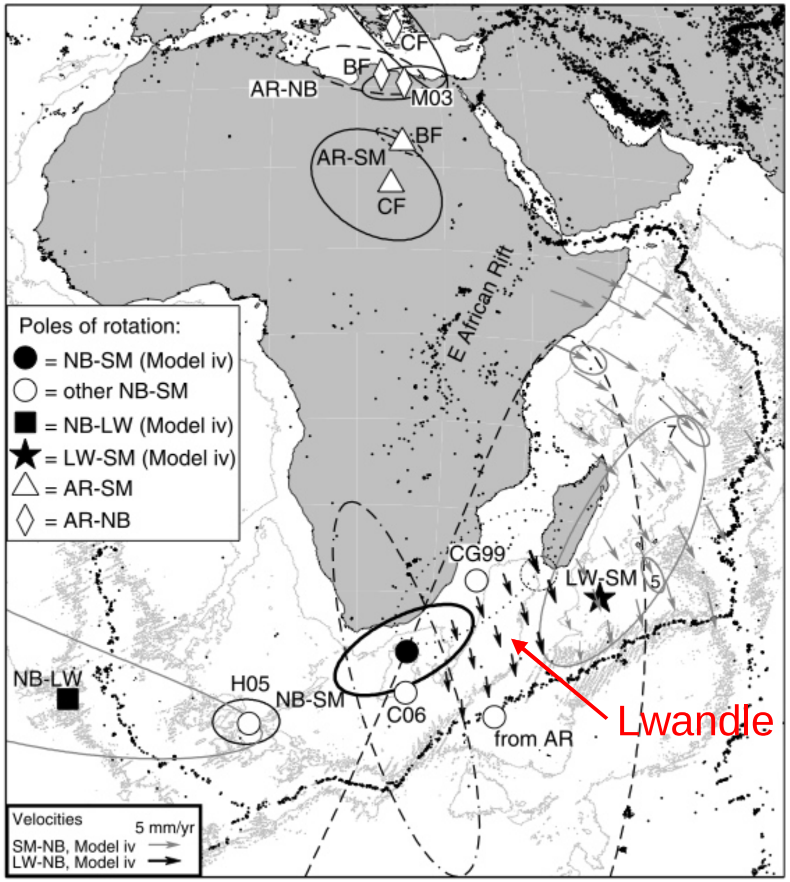
Hartnady, 2002: 4 rigid plates embedded within Nubia-Somalia plate boundary



Chorowicz, 2005: oblique NW-SE rifting

Two more recent models





Calais et al., 2006:

- GPS + slip vectors
- Somalia-Nubia plate motion
- 2 additional plates: Victoria (quantified) and Rovuma (not quantified)

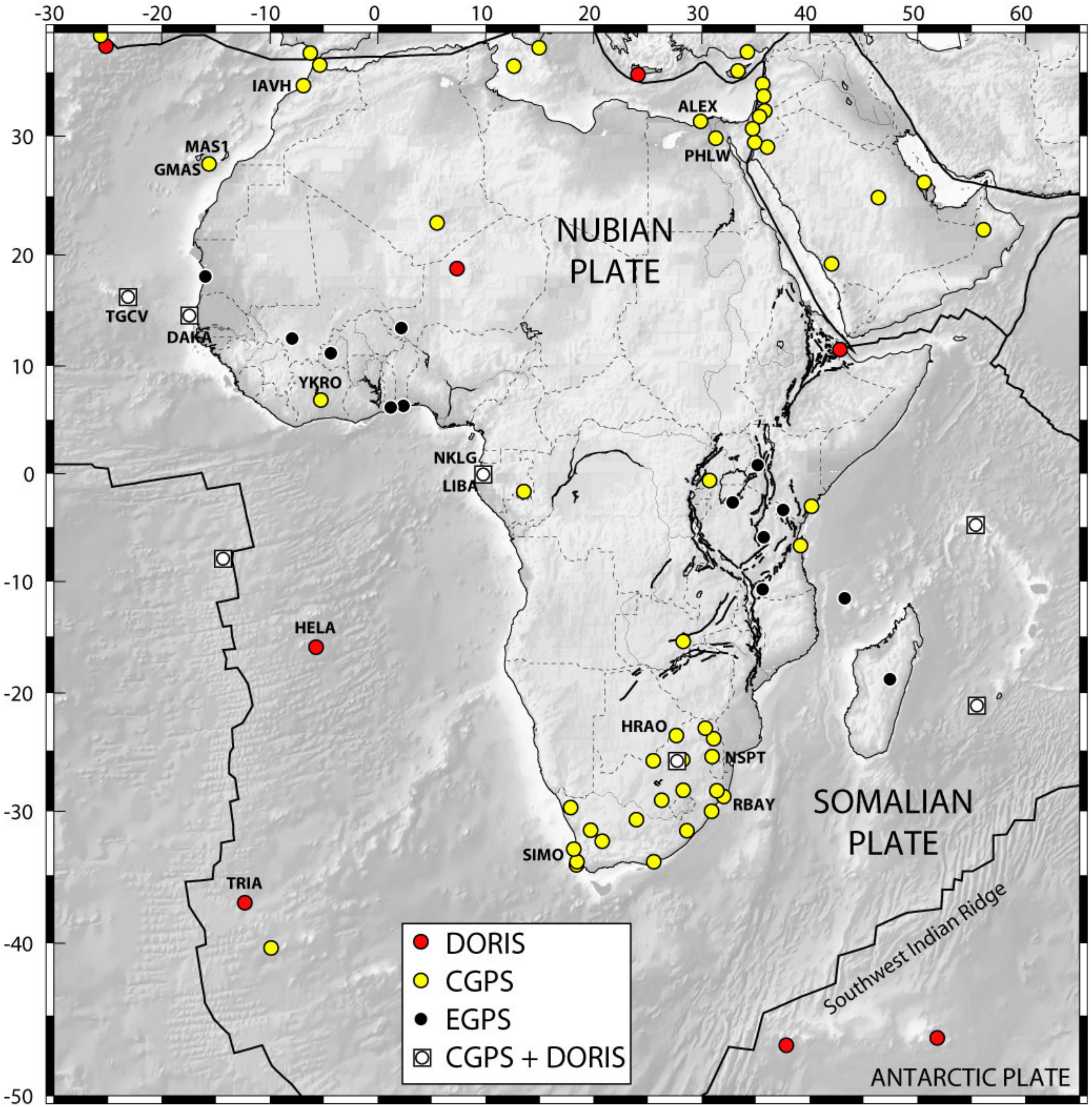
Horner-Johnson et al., 2007:

- 3.2 Ma average spreading rates and transform azimuths
- Somalia-Nubia plate motion
- 1 additional plate: Lwandle

1. Three data sets processed independently → position/velocity solution

2. Independent solutions combined (14-parameter transformation into ITRF2005) → position and velocities in ITRF2005

3. Velocities transformed into Nubia-fixed frame using “best-fit” 14 sites on Nubia:
   – Reduced chi2 = 1.5
   – RMS = 0.7 mm/yr



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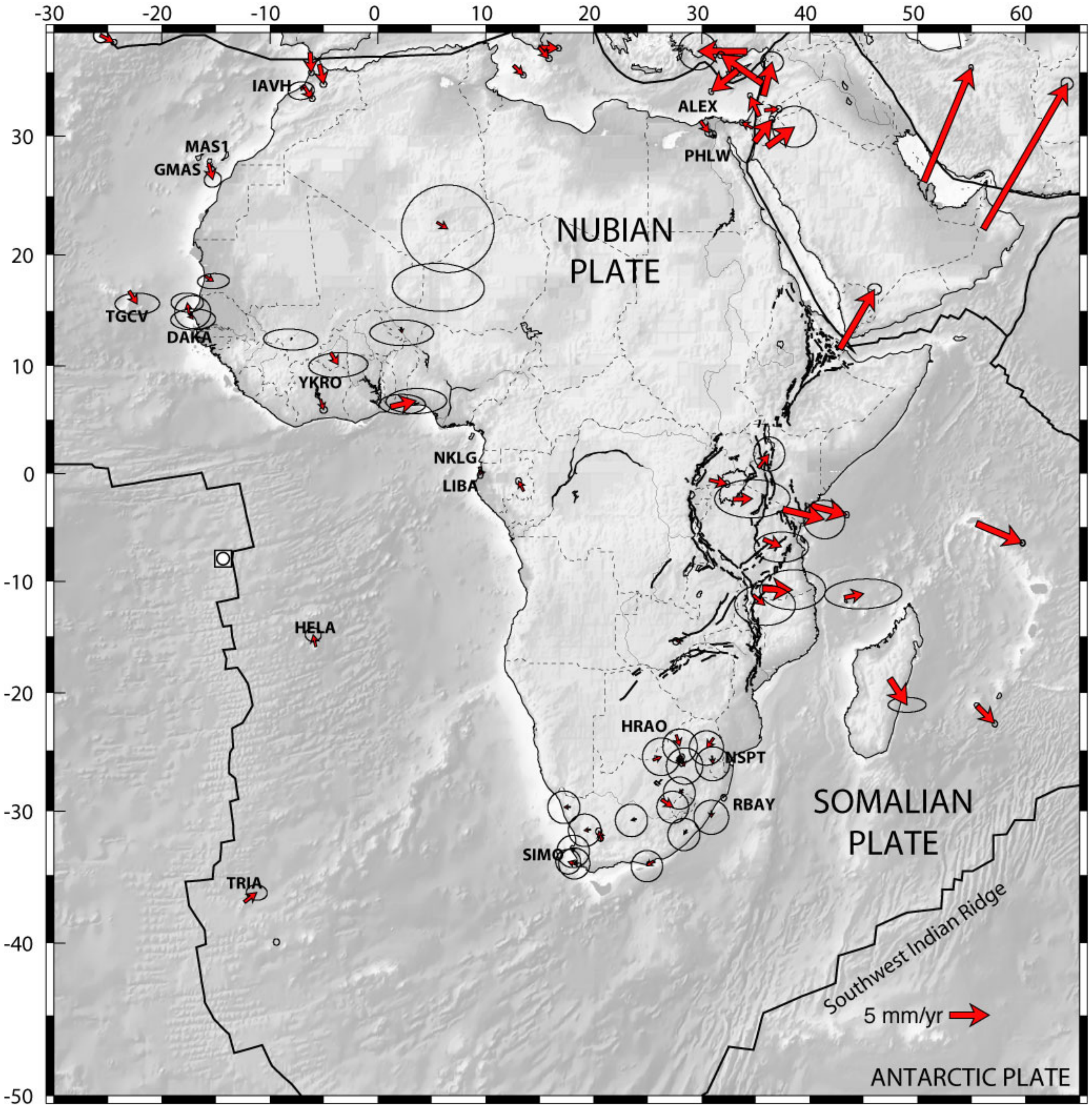
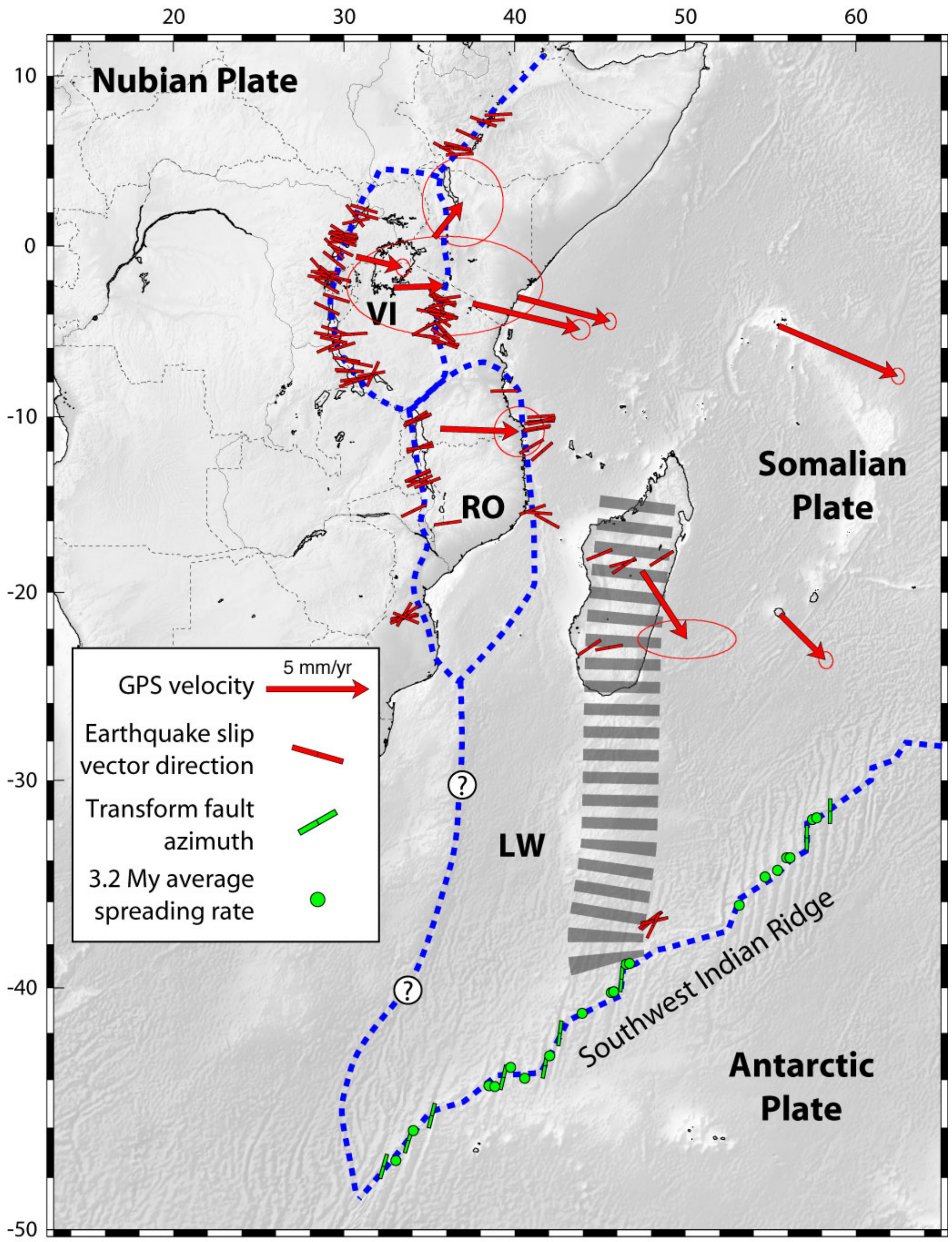


- Model:
  - rigid plate motions
  - Nubia, Somalia, Victoria, Rovuma, Lwandle
- Data:
  - GPS velocities, assigned to a plate (+ 12 GPS velocities on Antarctic plate)
  - Earthquake slip vector directions, assigned to a plate boundary
  - 3.2 My average data on the SWIR = transform fault azimuths + spreading rates.
- Solve for block angular velocities by joint inversion of GPS, ESV, and SR data.
- Use F-test statistics to quantify significance of chi2 difference between various scenarios

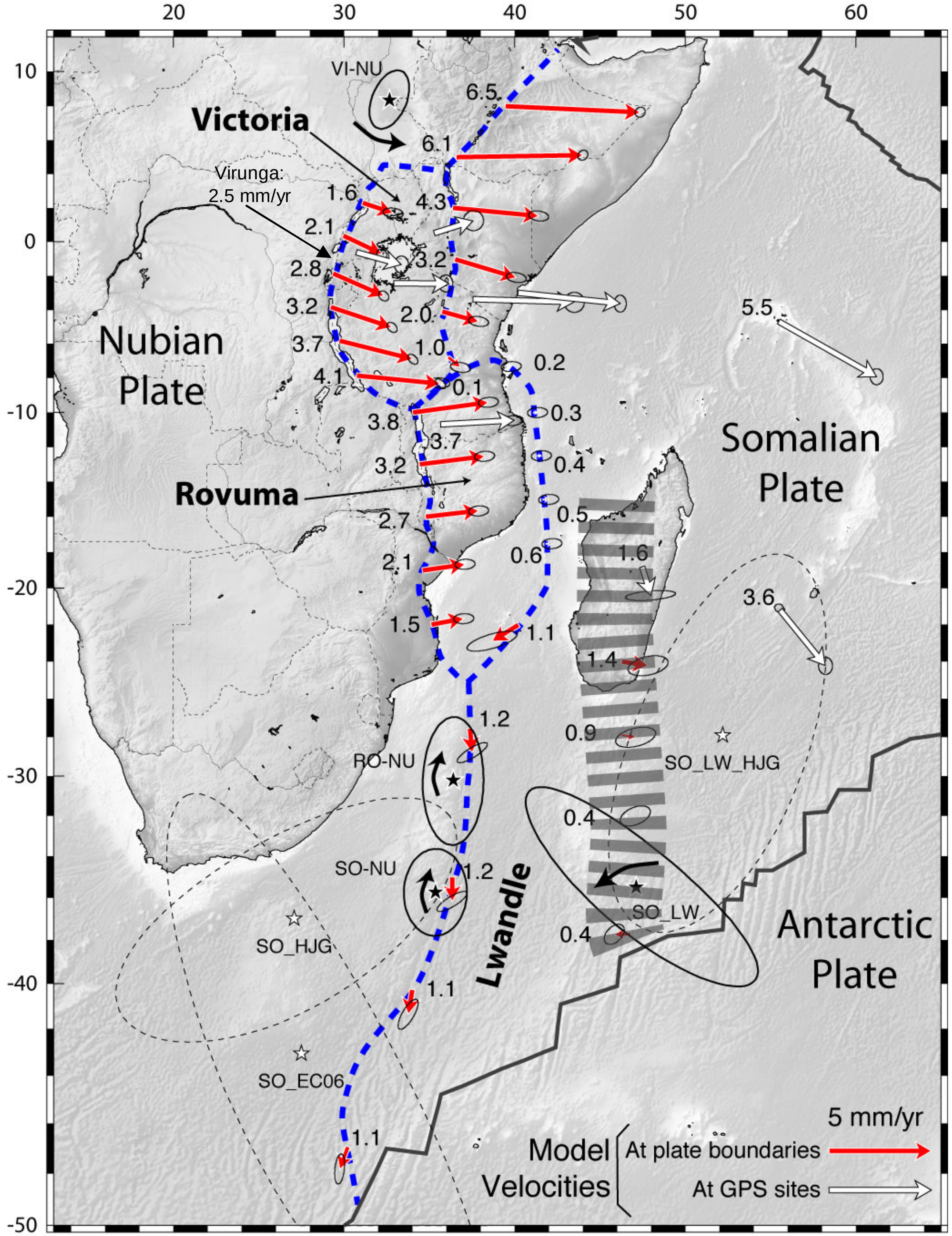


- Final model: 3 plates embedded in EAR
  - Reduced chi2 = 1.4
  - GPS RMS = 0.8 mm/yr
  - ESV RMS = 14 degrees
  - Spreading rates RMS = 0.6 mm/yr

- Predicted extension rates
  - increase from S to N
  - up to ~6.5 mm/yr in the northern MER
  - qualitatively consistent with expression of faulting (incl. Mad. Ridge)

- Extension directions ~E-W but vary slightly as a function of the plates involved.

- Spatial density of geodetic sites still very low.

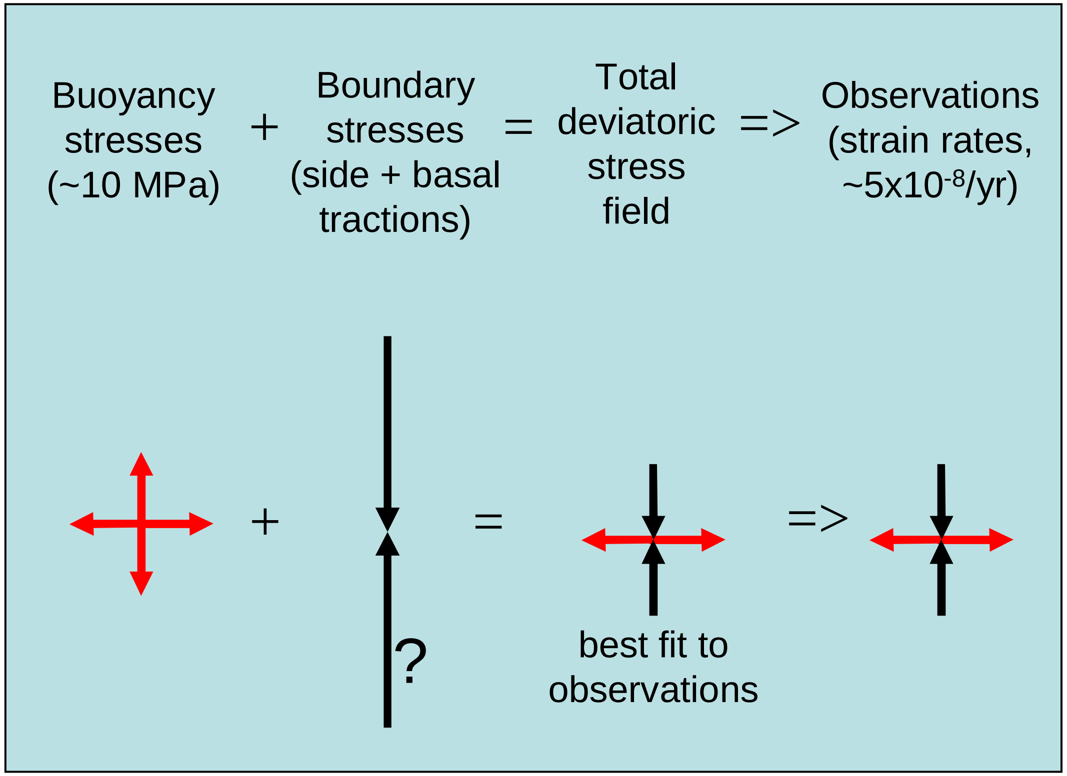


Stamps, D.S., et al. (2008), A kinematic model for the East African Rift, Geophys. Res. Lett., 35, L05304, doi:10.1029/ 2007GL032781.

Dynamics

Question: What forces drive the observed kinematics?

- Known/Observations
  - Buoyancy stresses: from lateral gradients in density
  - Strain rate: from GPS measurements + earthquakes
- We solve for the buoyancy stresses such that the total deviatoric stress field best matches the observed strain rates
- Africa surrounded by oceanic ridges:
  - Minimal role of traction along plate sides
  - Boundary stresses = should mostly reflect mantle tractions



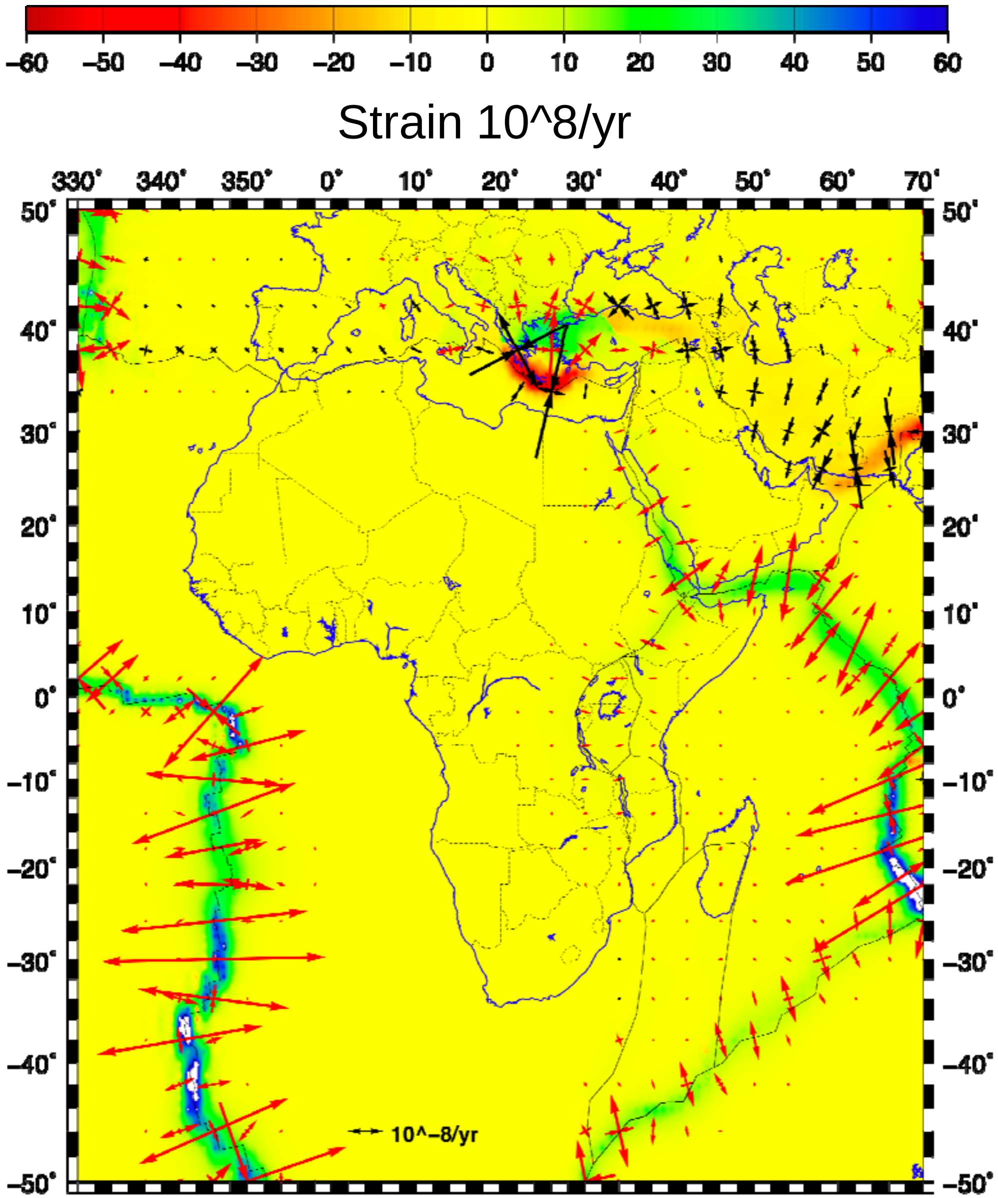
Strain Rate Field

STEP 1 :

convert velocities to strain rates

- Data:
  - GPS-derived model velocities (Stamps et al., 2008; Sella et al., 2002)
  - Earthquake moment tensors CMT catalog (M>3.5)

- Results:
  - localized deformation
  - low strain in EAR
  - high strain along ridges
  - high strain at subduction zone



GPE stresses

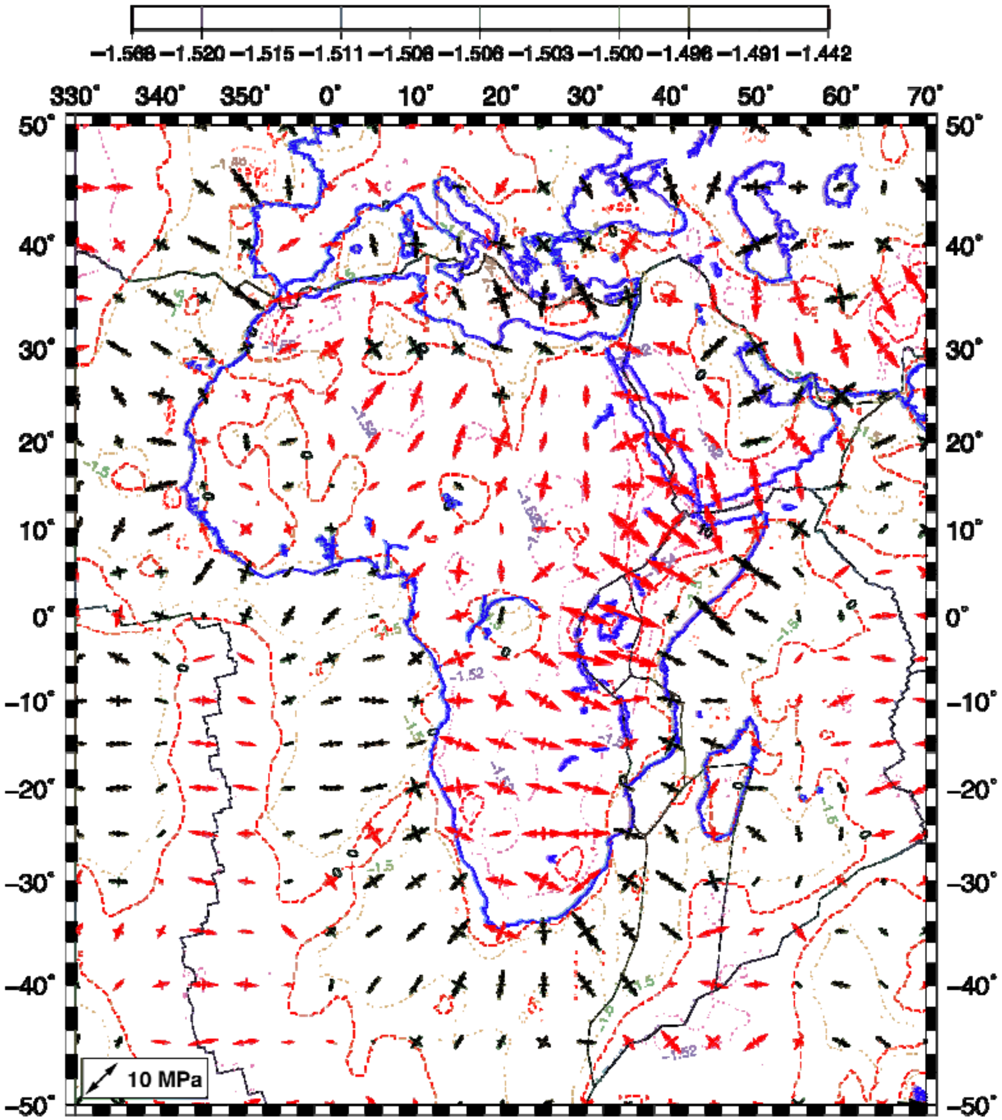
STEP 2:

compute deviatoric stresses associated with lateral gradients in GPE

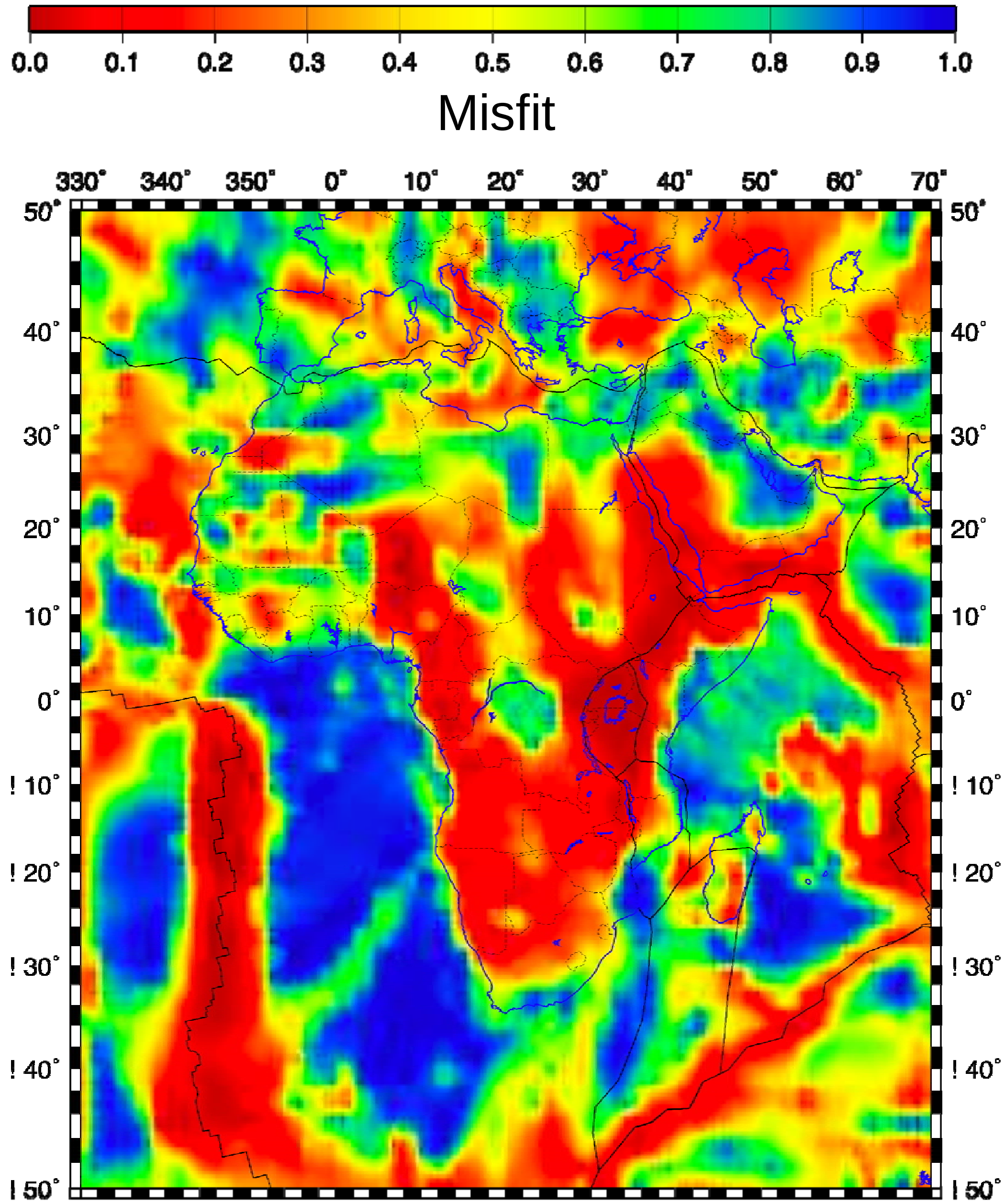
- Method:
  - Thin-viscous sheet approximation (Flesch et al, 2001)
  - Crust 2.0 (Bassin et al., 2000)
  - Estimate gravitational potential energy

$$\overline{\sigma}_{zz} = \frac{1}{L}\int_0^L \int_0^{z'} \rho(z')g\,dz'\,dz$$

  - Lateral gradients in GPE drive the lateral gradients in deviatoric stress



GPE Stresses vs. Strain Rates



STEP 3:

quantitative comparison between GPE stresses and strain rates

- Misfit function compares principal directions and "style" of strain and stress:

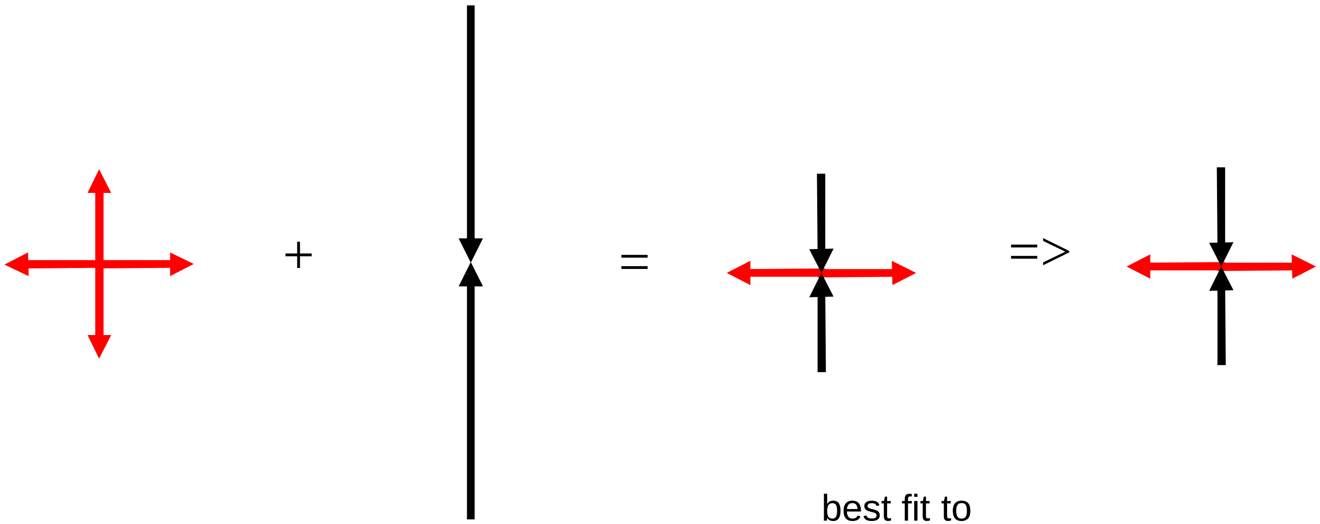
$$M = \frac{1}{2}\left(1 - \frac{\varepsilon.\tau}{ET}\right)$$

- Result:
  - Poor fit overall
  - Better in areas with strain data
  - Worse in areas w/o strain data

Stress Field Boundary Conditions

STEP 4

Buoyancy forces (~10 MPa) + Boundary forces (side + basal tractions) = Total deviatoric stress field => Observations (strain rates, ~5x10^{-8}/yr)



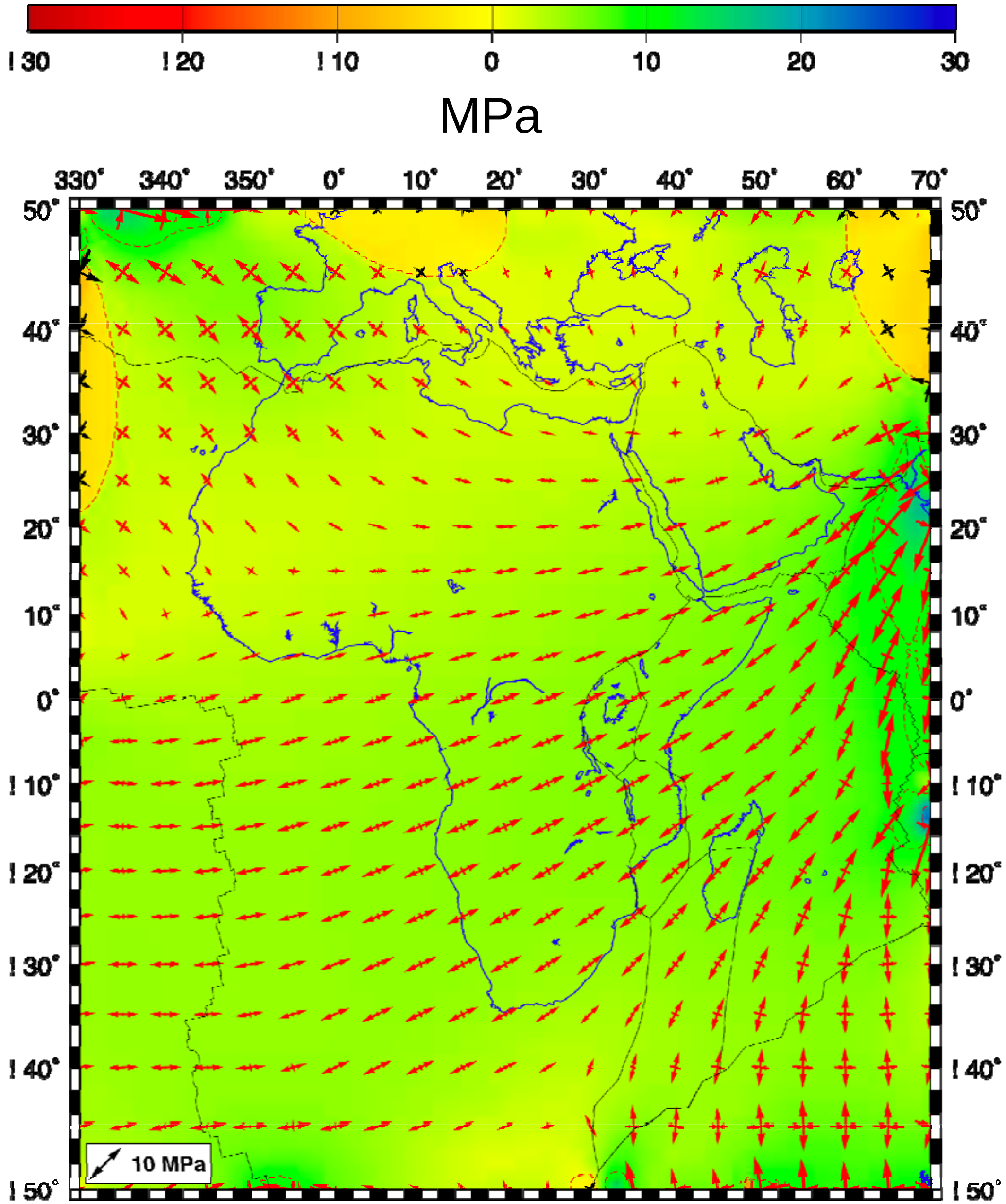
best fit to observations

?

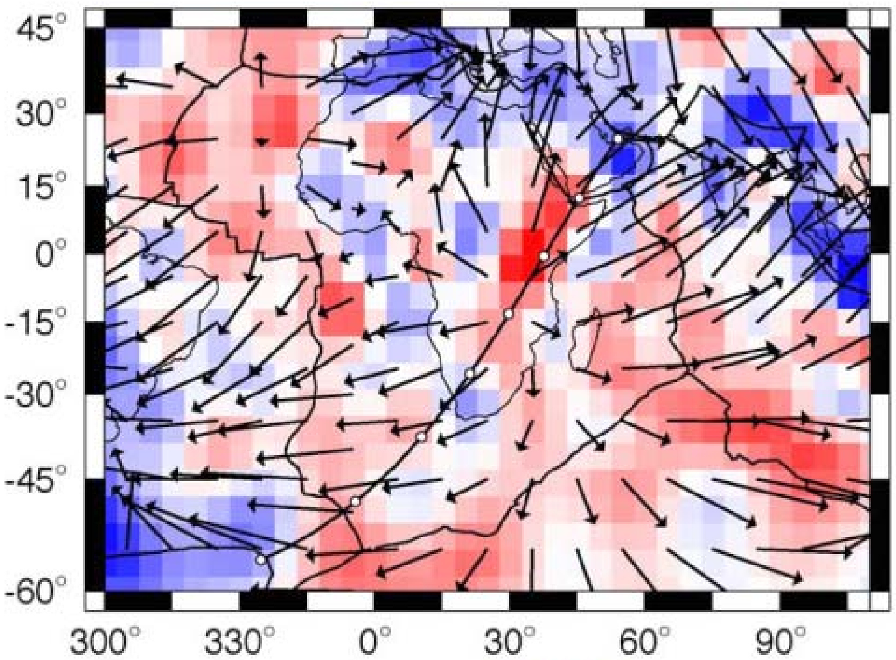
Stress Field Boundary Condition

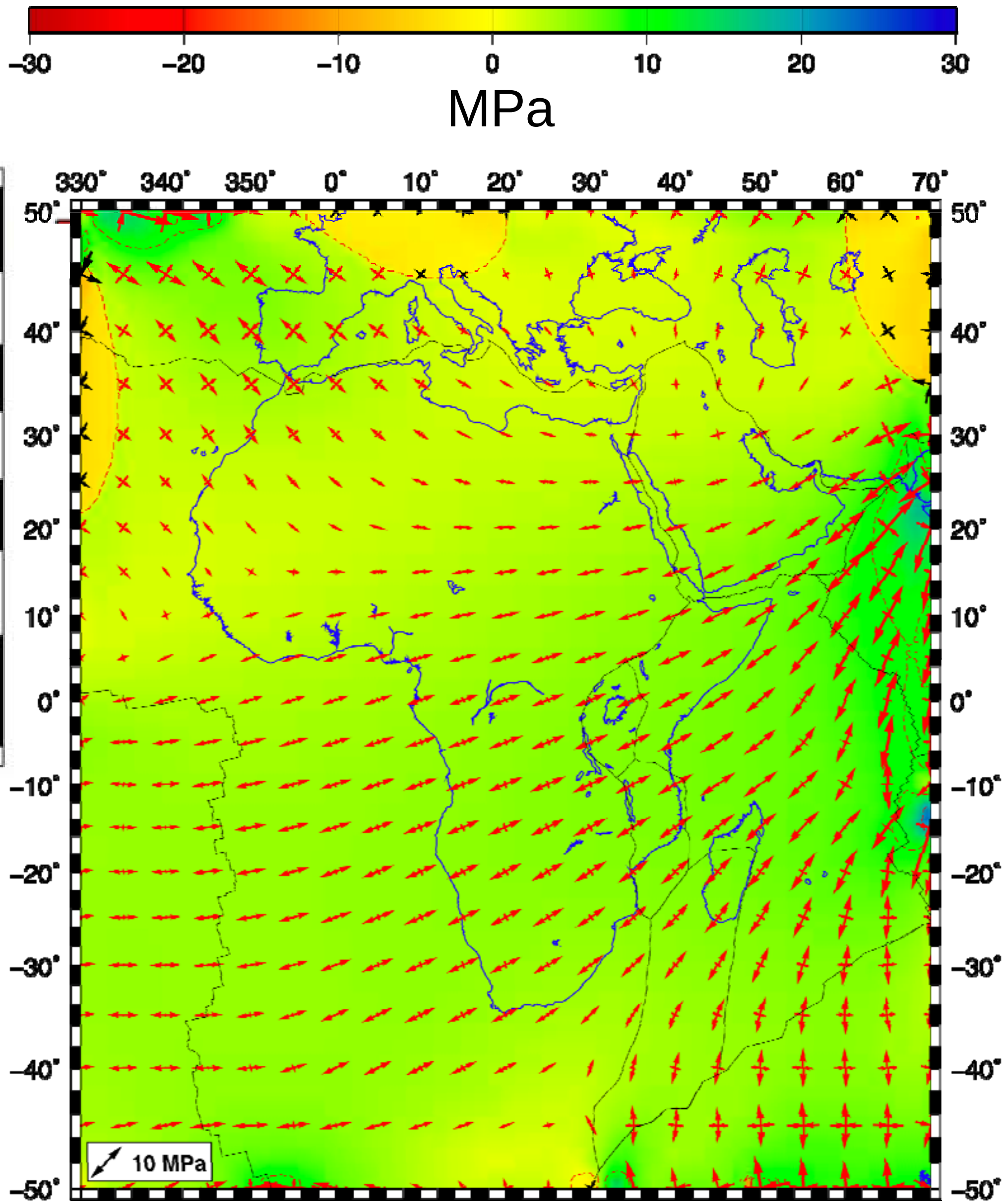
RESULTS

- Extensional boundary stresses
- Magnitude ~1-10 MPa: smaller, but comparable to GPE stresses
- Source of these stresses:
  - relative plate motions?
    - minimal due to ridges
  - response of mantle tractions



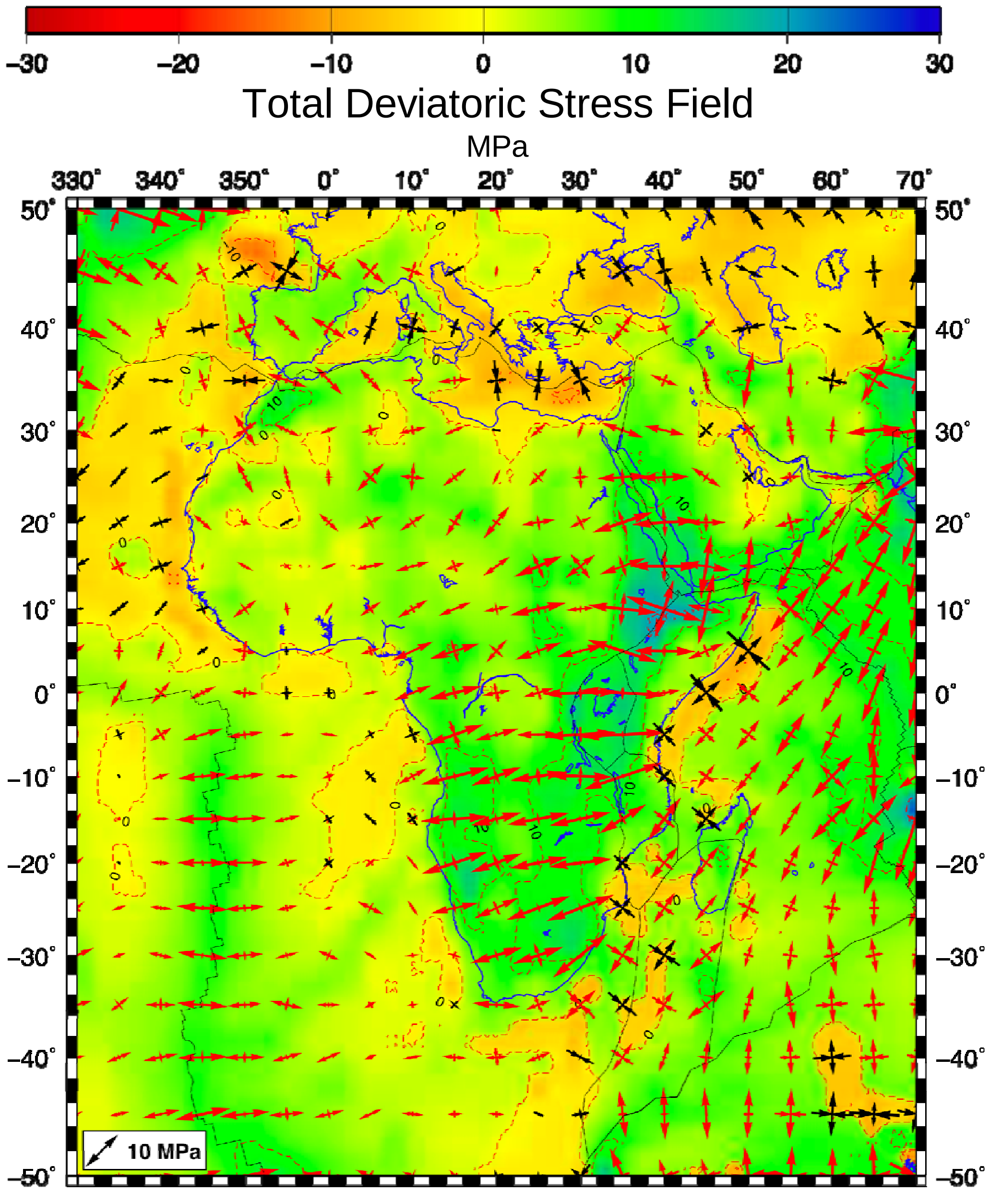
Comparison with a Mantle Flow Model





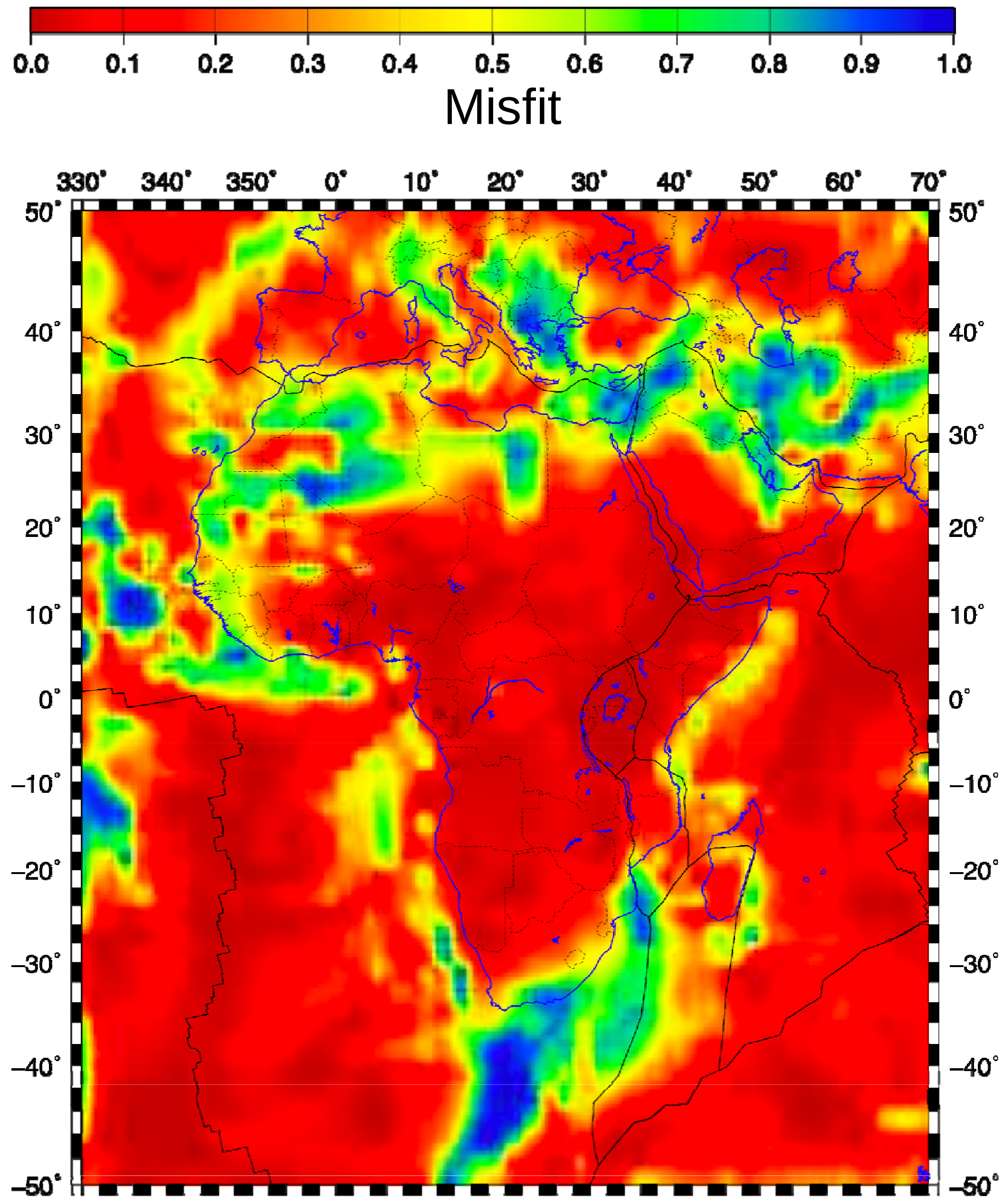
Total Deviatoric Stress Field

- Combination of buoyancy and boundary forces
- Results:
  - Up to ~20 MPa in East Africa
  - E-W tension over most of Africa
  - Largest stresses in MER
  - Higher stresses correlate with trace of the EAR, with magnitudes decreasing southward.
  - Stress magnitudes high outside of the EAR in southern Africa: may explain off-rift seismicity?



Total Stresses vs. Strain Rates

- Result:
  - Improved fit overall
  - Better in areas with strain data
  - Worse in areas w/o strain data
  - E-W extension improves fit across EAR and ridges
  - Large misfit in southern EAR

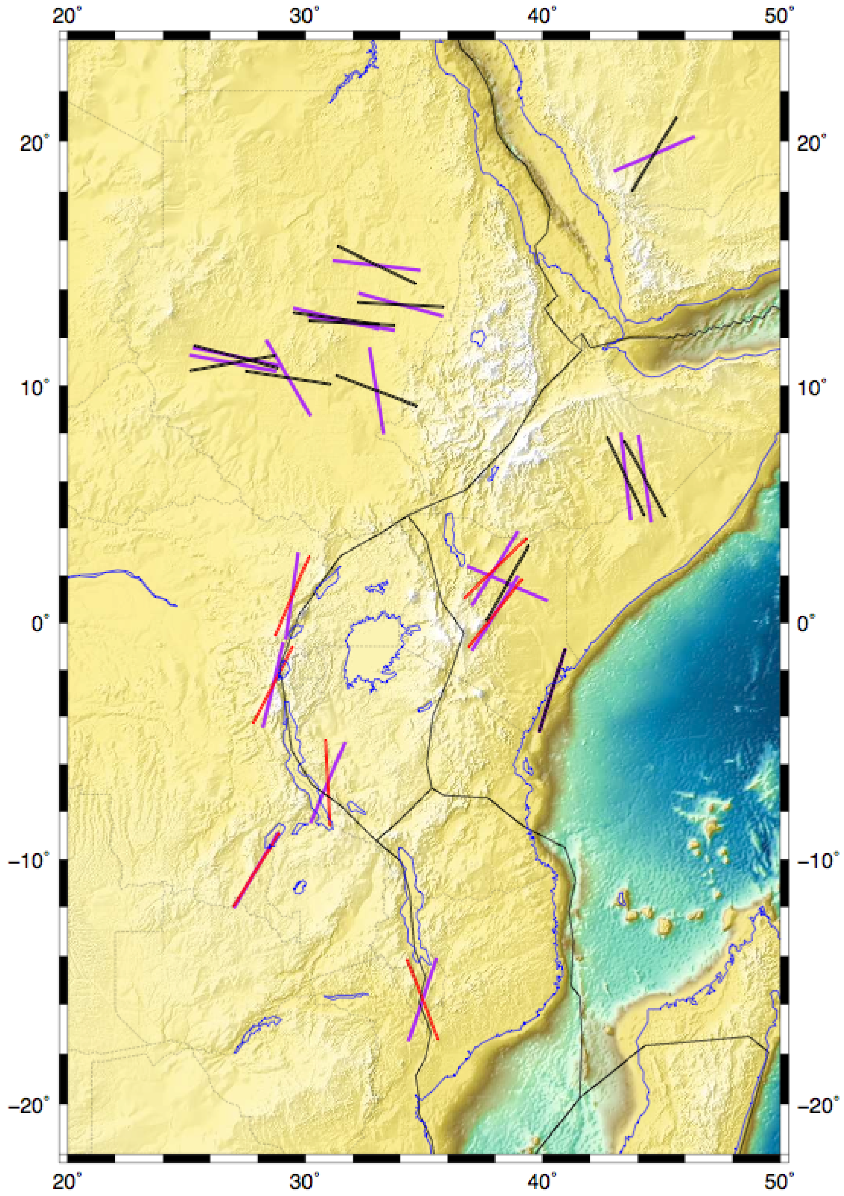


Comparison with World Stress Map

→ World Stress Map (2008)
  - SH_max - maximum horizontal compressive component

→ Red = WSM AB normal faulting
→ Black = WSM AB undefined
→ Purple = this work

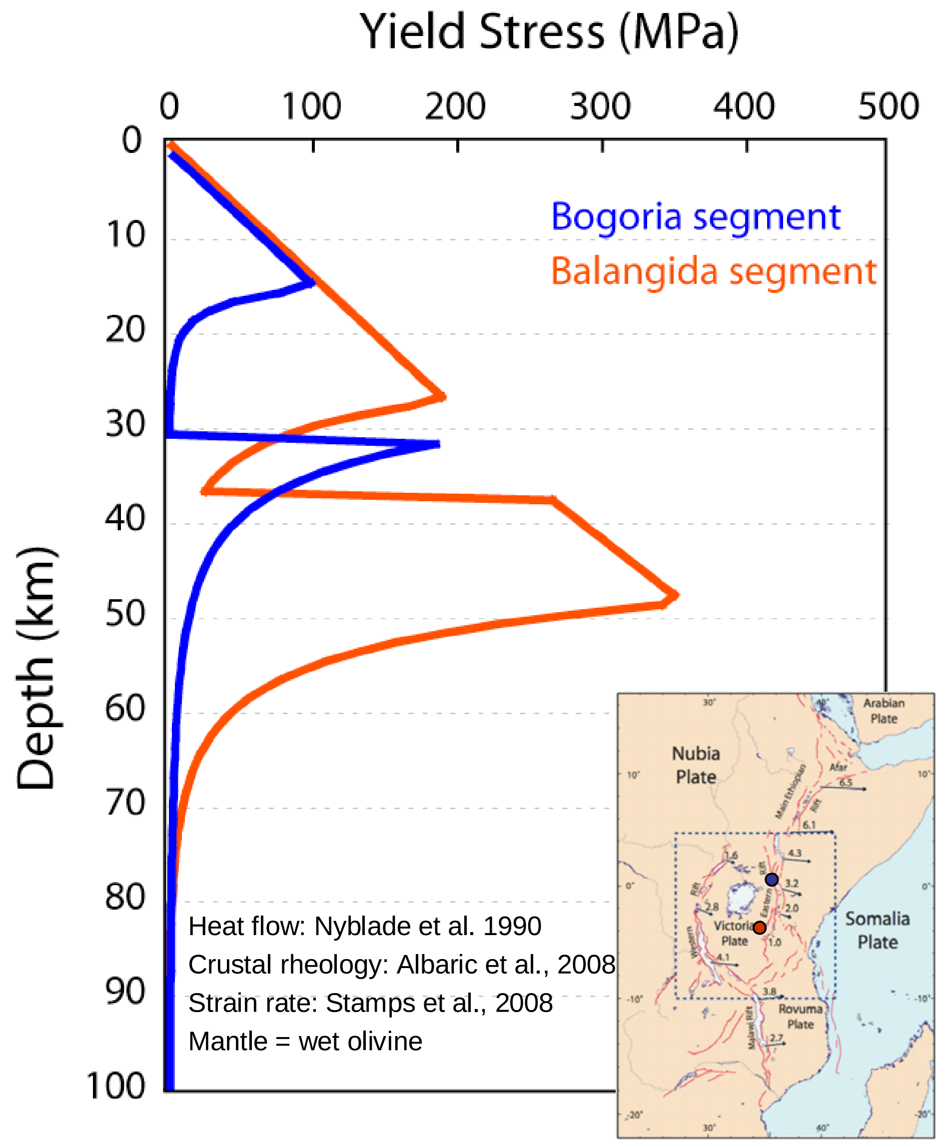
- Style and directions of deviatoric stresses consistent with focal mechanisms and SHmax direction



Stamps et al., (in review) Lithospheric buoyancy forces in Africa from a thin sheet approach, International Journal of Earth Sciences special edition on Continental Rifting

Comparison with Lithospheric Strength

- GPE Stresses ~10 MPa in EAR
  - ~1.5 TN/m 150 km lithosphere
  - ~1.0 TN/m 100 km lithosphere
- Total Stresses ~15 MPa in EAR
  - ~2.3 TN/m 150 km lithosphere
  - ~1.5 TN/m 100 km lithosphere
- Integrated lithospheric strength
  - Bogoria segment (warm) ~4 TN/m
  - Balangida segment (cold) ~9 TN/m
- Buoyancy + boundary stresses
  - Not sufficient to rupture cold EAR
  - Sufficient if mantle lithosphere "removed"



Conclusions

- A first-order kinematic model for the EAR consistent with:
  - 3 plates between Nubia and Somalia: Victoria, Rovuma, Lwandle
  - EAR motions consistent over past 3.2 Ma
  - Localized strain along narrow rift structures that isolate large, mechanically strong, lithospheric blocks.
  - Requires confirmation from more detailed geodetic studies.
- A new total deviatoric stress field for Africa:
  - Dominated by GPE, with ~30% contribution from mantle flow
  - Tensional, ~E-W over most of Africa, ~15 MPa in EAR
  - Good agreement with independent stress and strain observations
  - GPE + mantle flow not sufficient to rupture cold lithosphere in East Africa…
- Additional contribution from magma buoyancy (+ heat advection), cf. Buck, 2002?

Differences in Misfits

- Improved fit:
  1. western branch
  2. eastern branch
  3. Congo basin
  4. Main Ethiopian Rift
- Better in areas with strain data
- Worse in areas w/o strain data
- E-W extension improves fit across EAR and ridges