Multiphase rotational extension and marginal flexure along a developing passive margin: the Western Afar Margin, East Africa

Authors:

Frank Zwaan
Giacomo Corti
Derek Keir
Federico Sani
Ameha Muluneh
Finnigan Illsley-Kemp
Mauro Papini

Presentation based on:

Zwaan et al. (2020) Tectonics
Zwaan et al. (in review) Tectonophysics
(details on next page)

Contact: frank.zwaan@geo.unibe.ch

FNSNF Fonds national suisse Schweizerischer Nationalfonds Fondo nazionale svizzero Swiss National Science Foundation

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Addis Ababa University

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Presentation based on:

Main paper (Zwaan et al. 2020 in Tectonics):
Zwaan, F., Corti, G., Keir, D., Sani, F., Muluneh, A., Illsley-Kemp, F., Papini, M. (2020). Structural analysis of the Western Afar Margin, East Africa: evidence for multiphase rotational rifting. Tectonics. http://doi.org/10.1029/2019TC006043

Supplementary material to Zwaan et al. (2020) in Tectonics:
Zwaan, F., Corti, G., Keir, D., Sani, F., Muluneh, A., Illsley-Kemp, F., Papini, M., 2020. Geological data from the Western Afar Margin, East Africa. GFZ Data Services. http://doi.org/10.5880/fidgeo.2020.017

Additional analogue modelling work:
Zwaan, F., Corti, G., Keir, D., Sani, F. (in review). An analogue modeling study of marginal flexure in Afar, East Africa: implications for passive margin formation. Tectonophysics.

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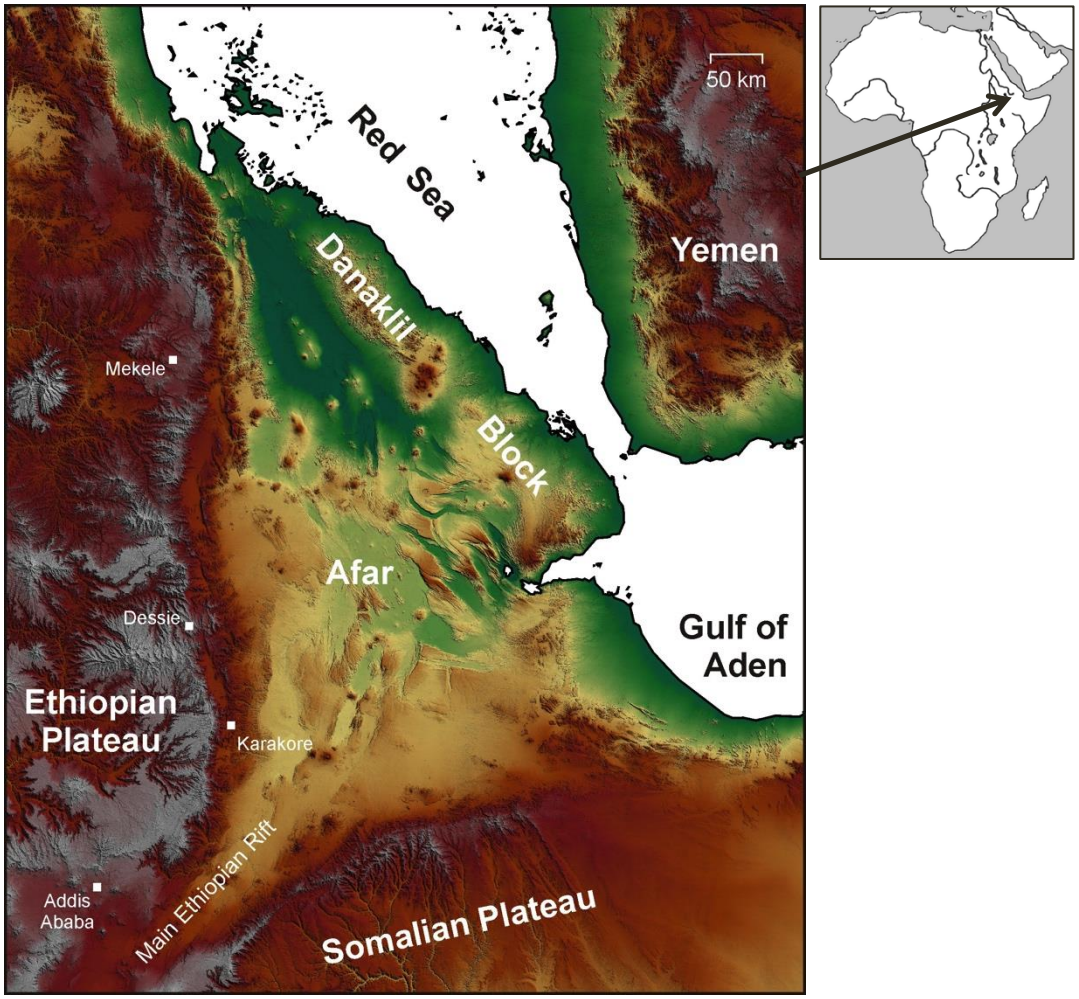
Introduction

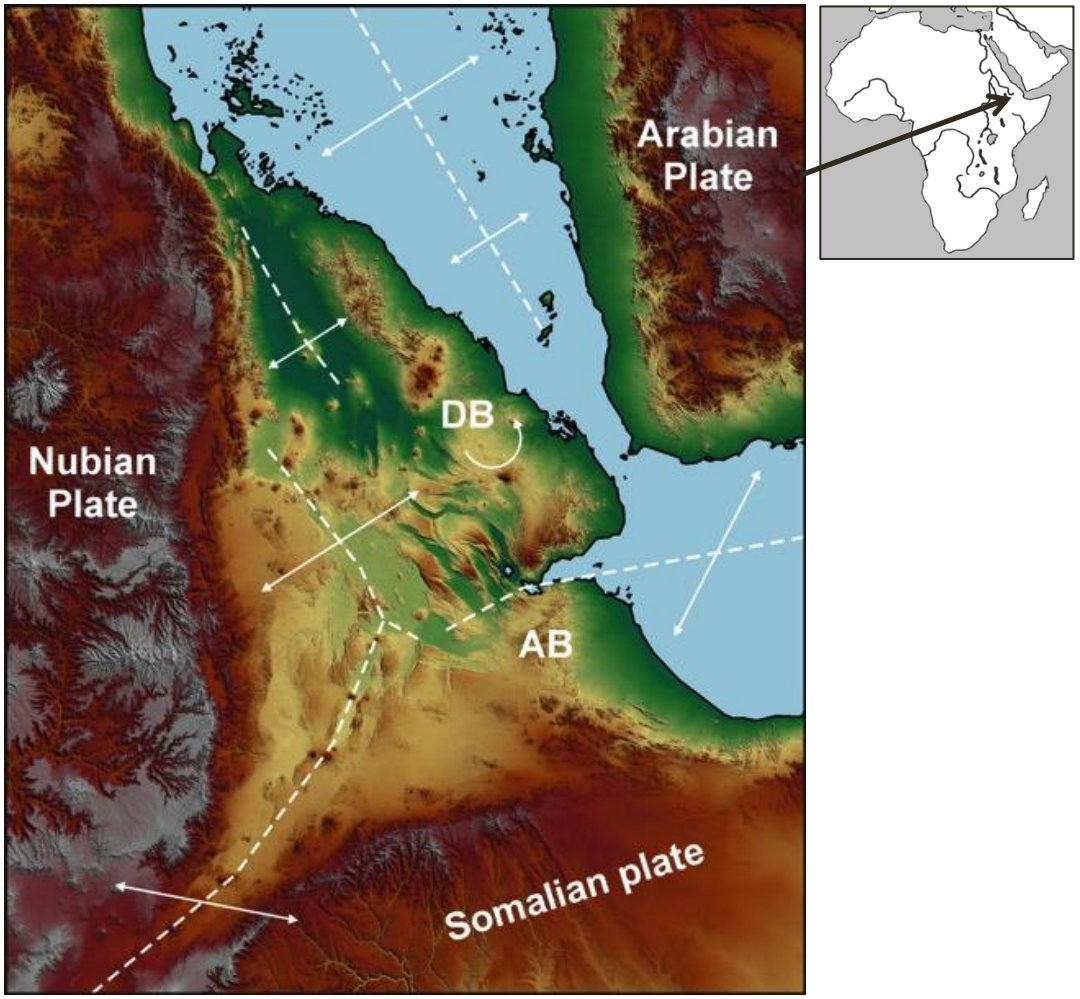
Afar

- Triangular depression in East Africa (± 25 Ma)
- Part of the East African Rift System



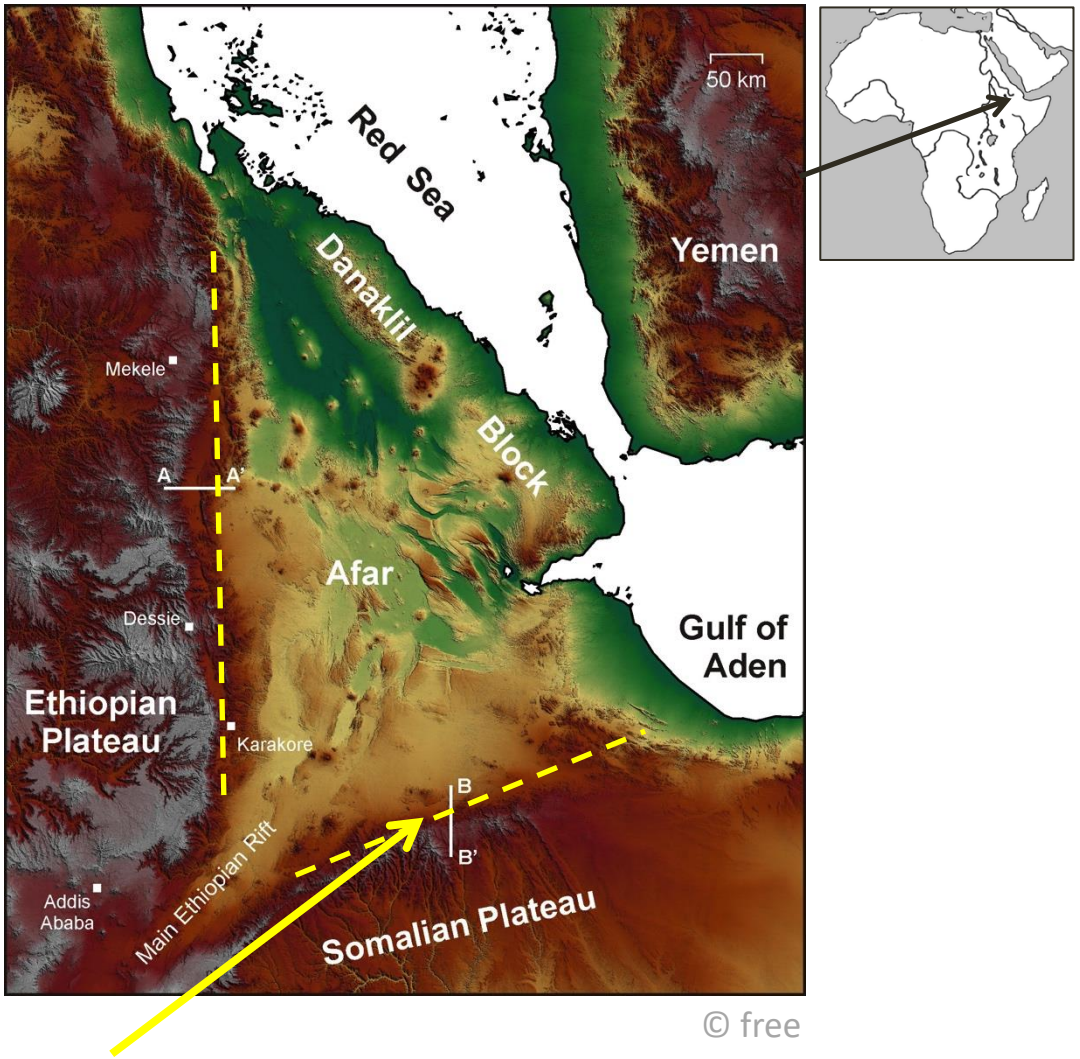
Afar

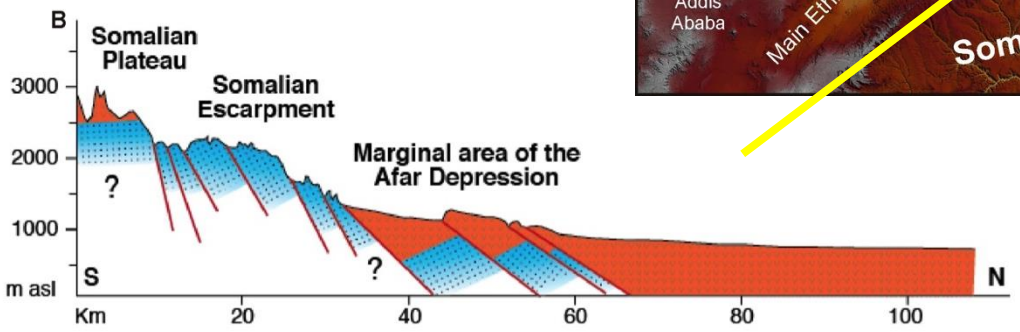
- Triangular depression in East Africa (± 25 Ma)
- Part of the East African Rift System
- Triple junction
- Lots of volcanism + active continental break-up: unique location for the study of rifting processes (!)



Afar margins

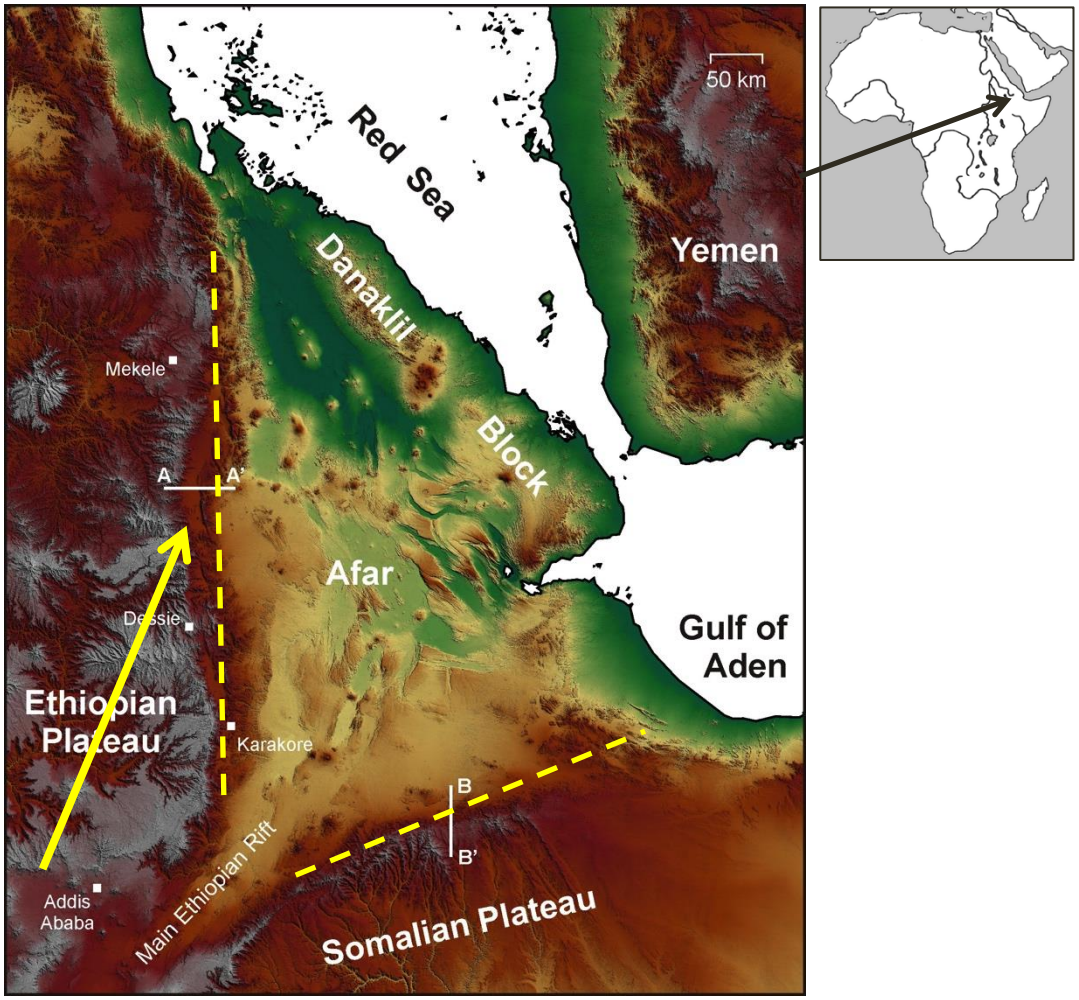
- (Developing) passive margins
- Somalian margin: Synthetic faulting (i.e. towards Afar)

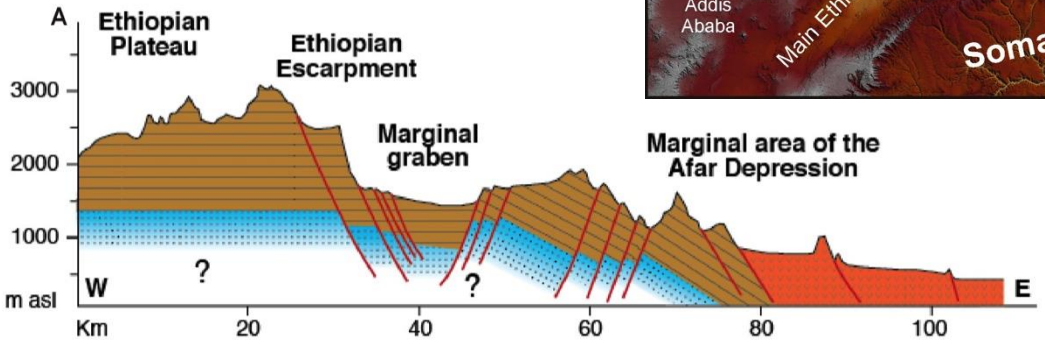




Afar margins

- (Developing) passive margins
- West. Afar Margin:
  - "Flexure"
  - Escarpment fault
  - Antithetic faulting (away from Afar)
  - Marginal grabens





Research aims

- **<u>Problem:</u> Western Afar Margin (WAM) is poorly understood**
  - Various contrasting tectonic scenarios are proposed
    (see Zwaan et al. 2020 in JAES: https://doi.org/10.1016/j.jafrearsci.2019.103649)

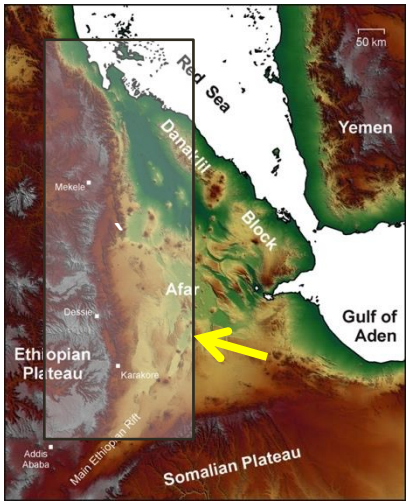
- **<u>Goal:</u> New large-scale structural and tectonic characterization of the Western Afar Margin**

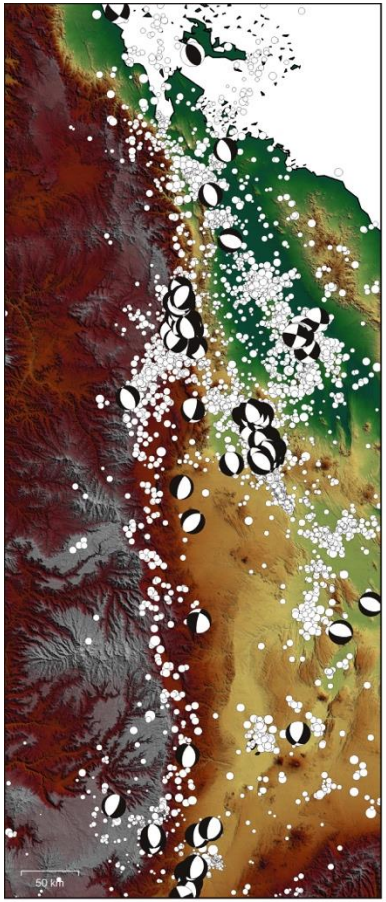
- **<u>Methods:</u>**
  - Earthquake analysis
  - Large-scale fault interpretation (satellite data)
  - New fieldwork
  - Analogue models (see outlook/conclusion)

Results/Discussion

Earthquake analysis

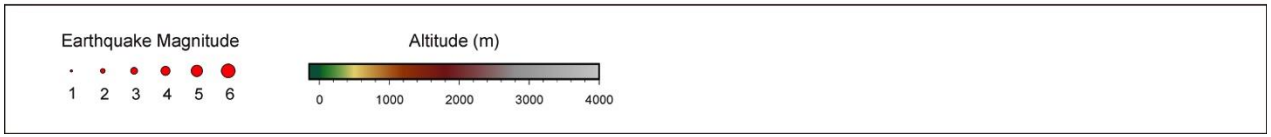
- Significant seismic activity along the WAM





Earthquake data and focal mechanisms from :

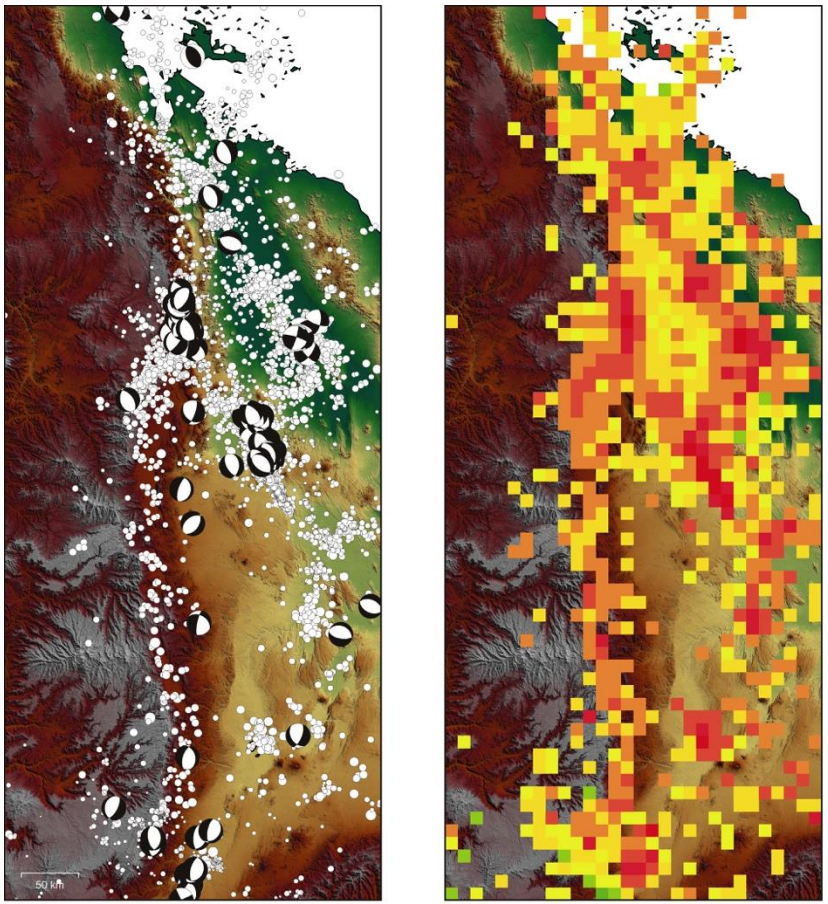
- Keir et al (2006) in JGR
- Ebinger et al. (2008)in GJI
- Keir et al. (2009) in Geology
- Belachew et al. (2011) in JGR
- Illsley-Kemp et al. (2018a) JGR
- Illsley-Kemp et al. (2018b) G3
- GCMT (https://www.globalcmt.org/)

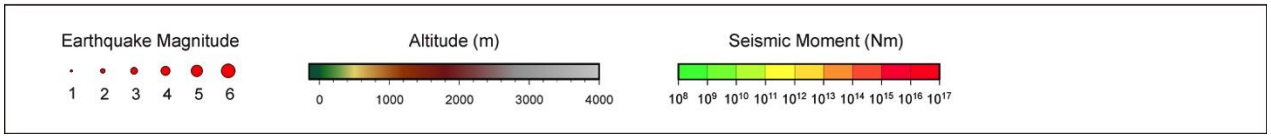


Earthquake analysis

- Significant seismic activity along the WAM
  - Consistent SMR along the margin

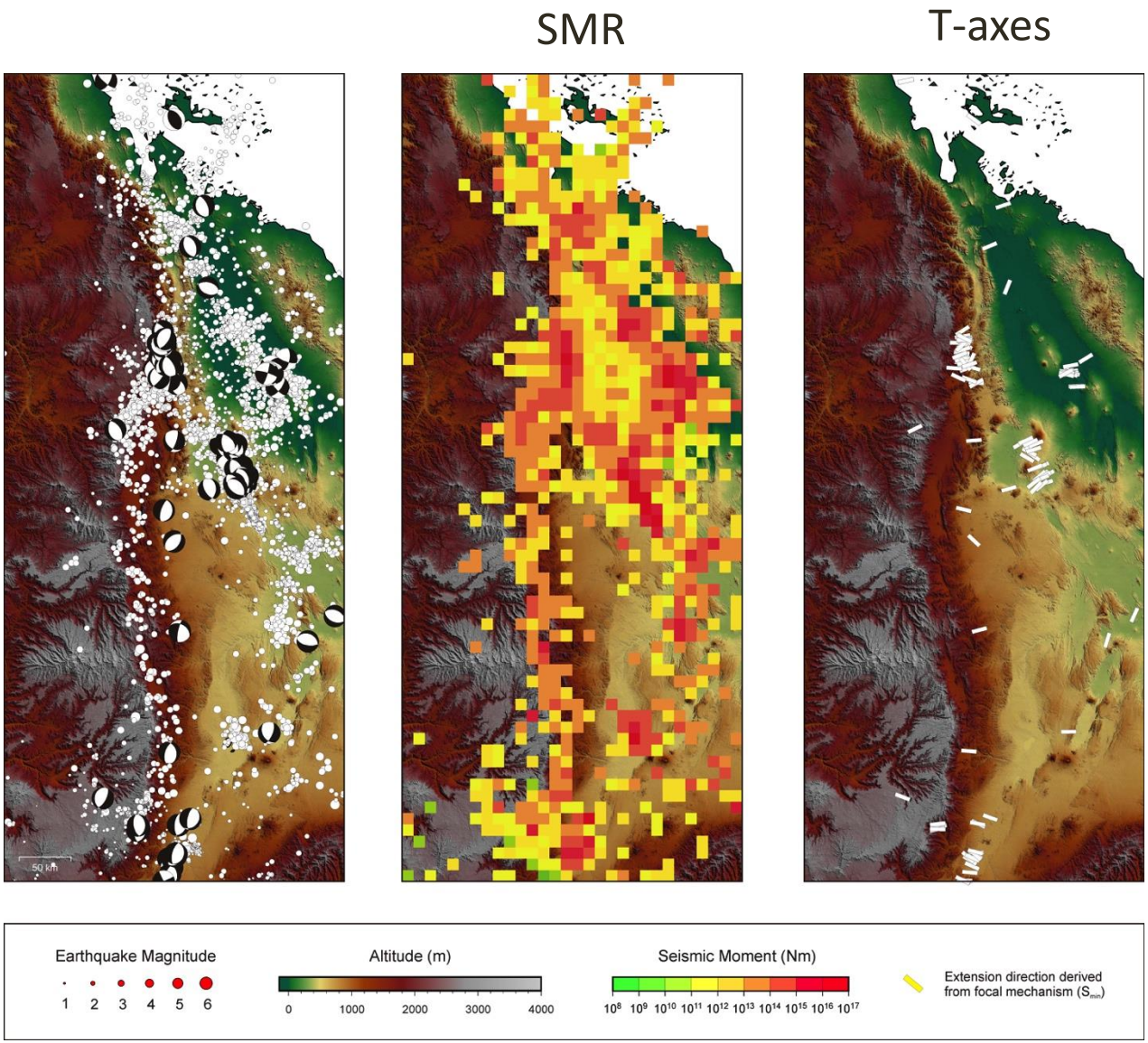
SMR = Seismic Moment Release





Earthquake analysis

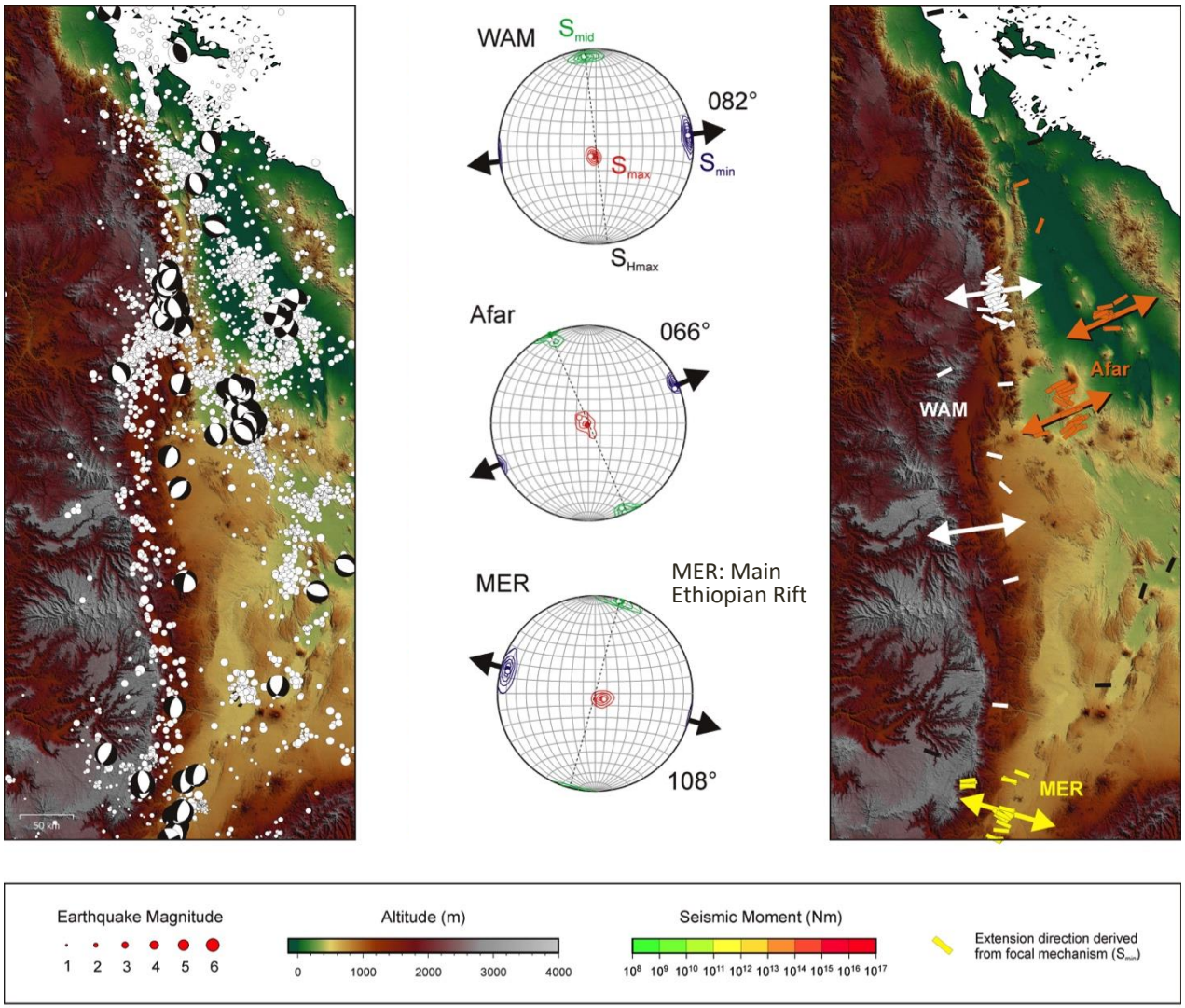
- Significant seismic activity along the WAM
  - Consistent SMR along the margin
- T-axes from focal mechanisms



Earthquake analysis

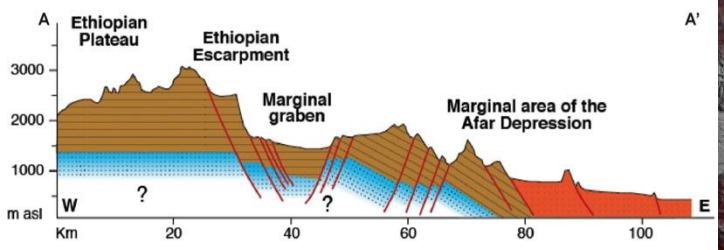
- Significant seismic activity along the WAM
  - Consistent SMR along the margin
- T-axes from focal mechanisms
  - Indicate various <u>current</u> extension directions!

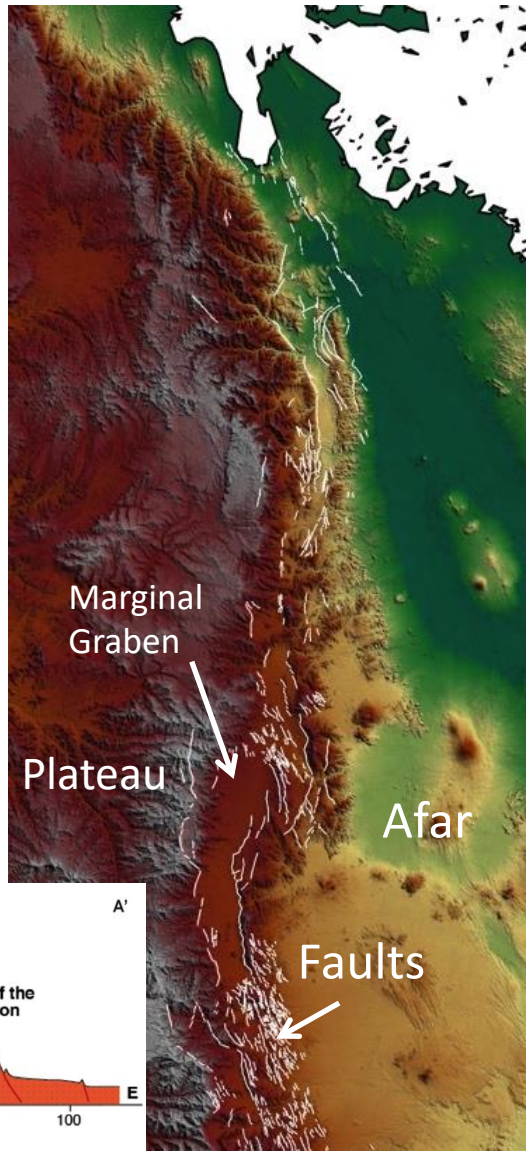
T-axes

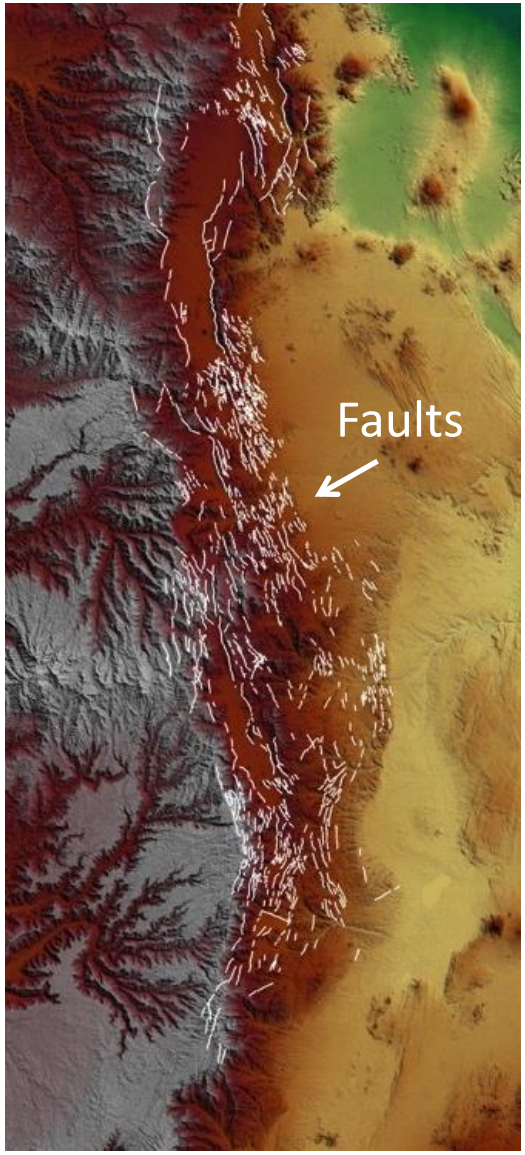


Large-scale structural interpretation

- New fault map: both syn- and antithetic faults
- Marginal grabens
  - Structures generally fit with previous observations

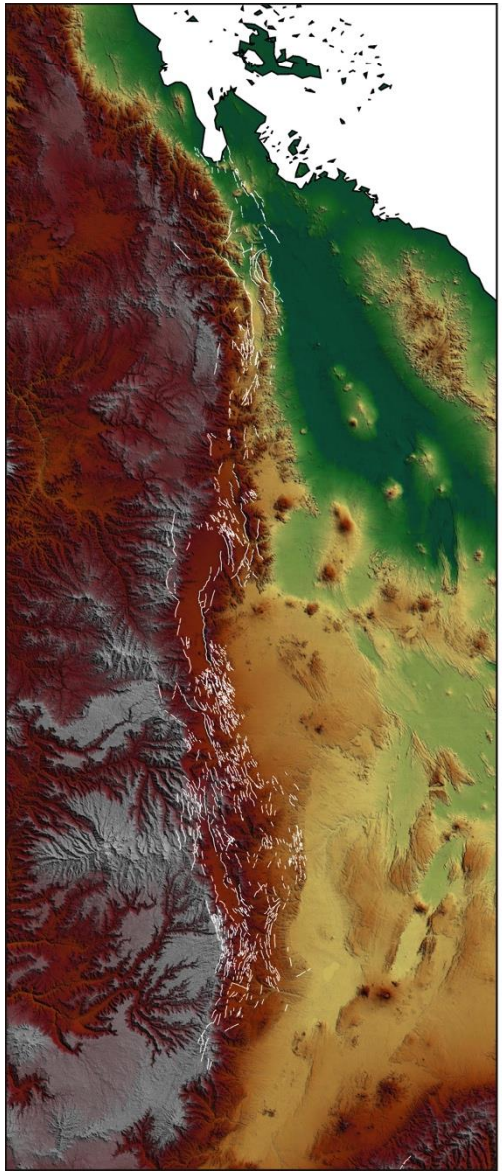


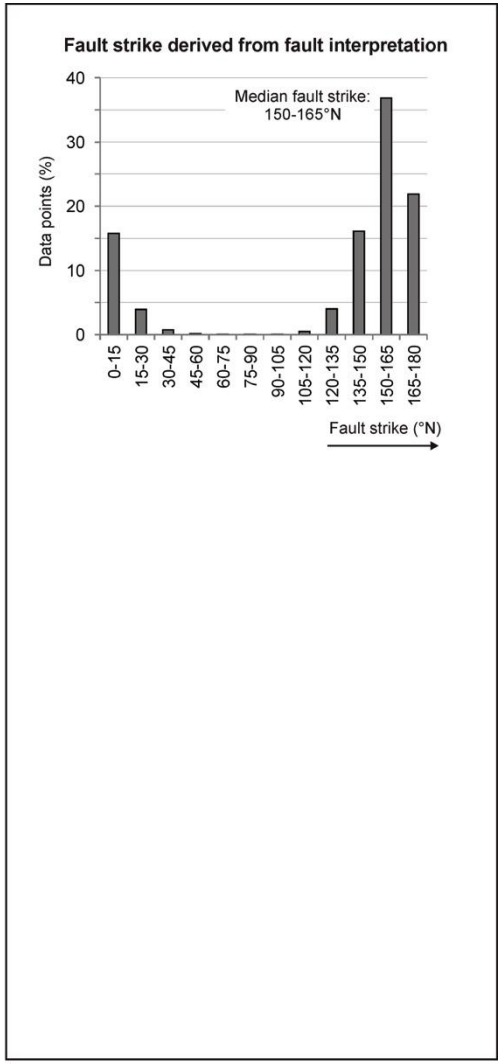


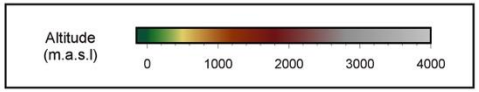


Large-scale structural interpretation

- New fault map: dominant NNW-SSE faults

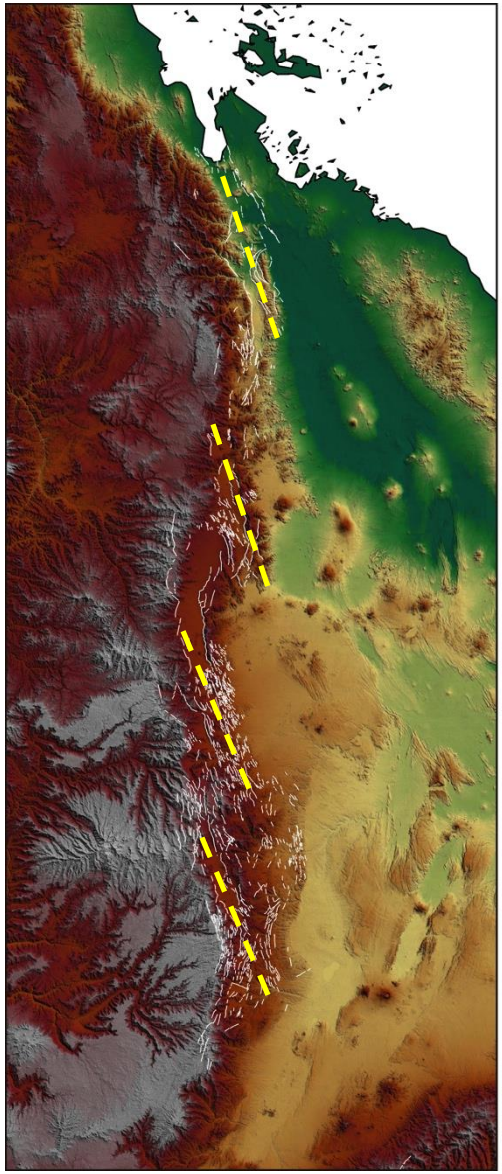


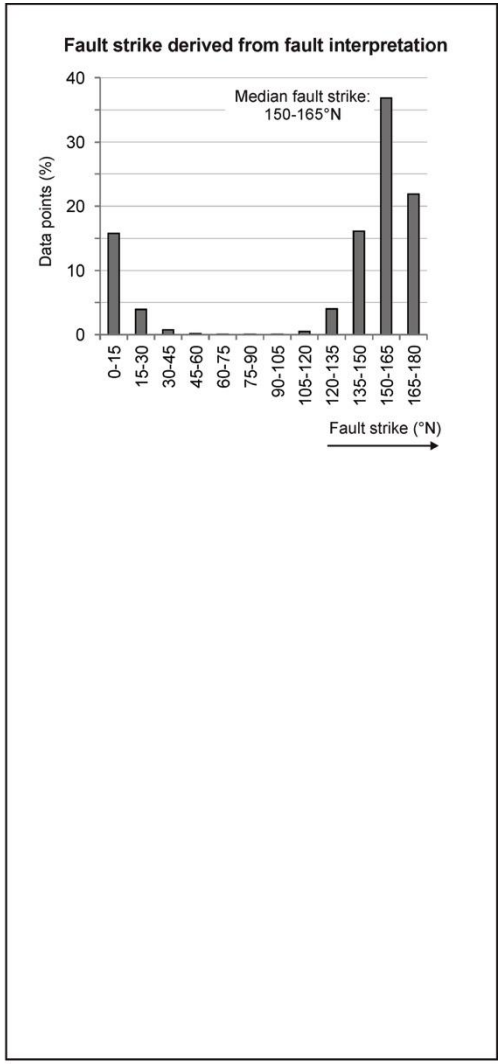


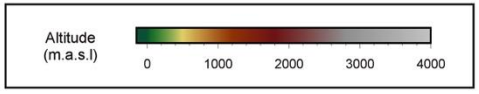


Large-scale structural interpretation

- New fault map: dominant NNW-SSE faults
- En echelon right-stepping grabens/faults/escarpment





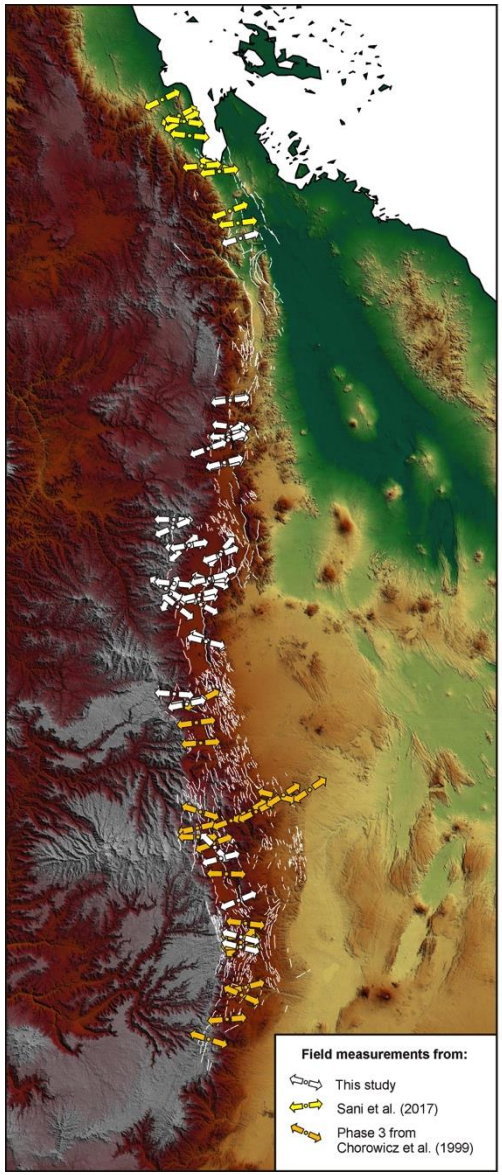


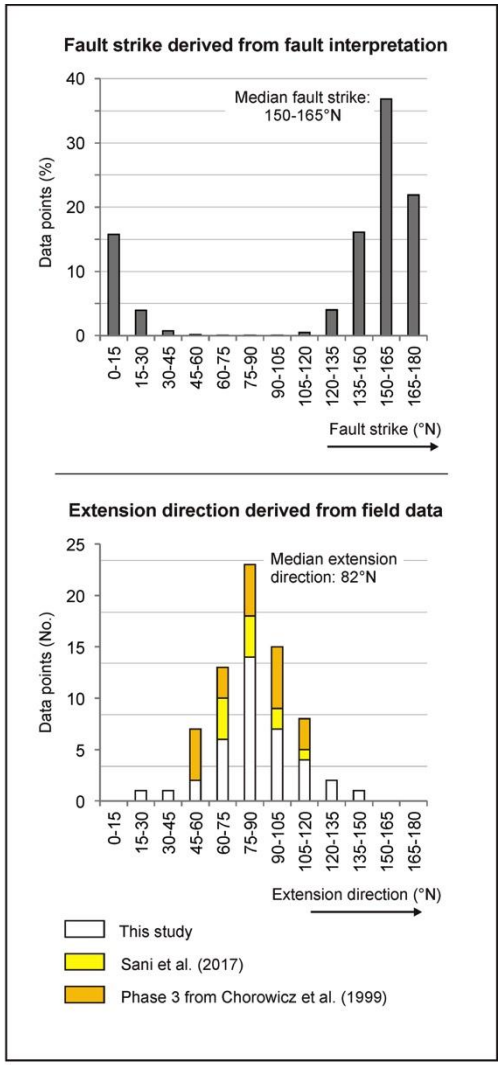
Large-scale structural interpretation

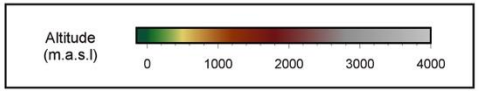
- New fault map: dominant NNW-SSE faults
- Analysis of field measurements

Large-scale structural interpretation

- New fault map: dominant NNW-SSE faulting
- Analysis of field measurements (with Wintensor): dominant ESE-WNW extension (82˚N)



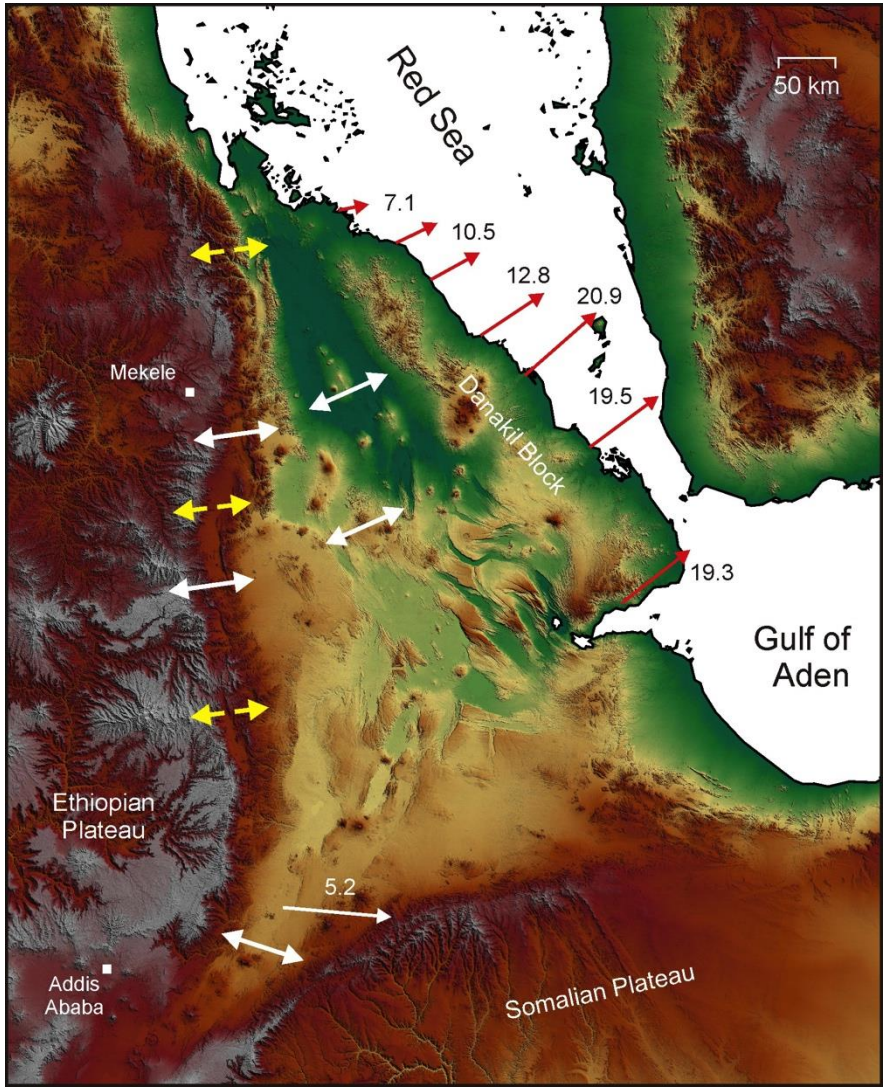




Regional context

Extension directions:

- T-axes (white)
- Fault data (yellow)
- GPS data (red, mm/y)

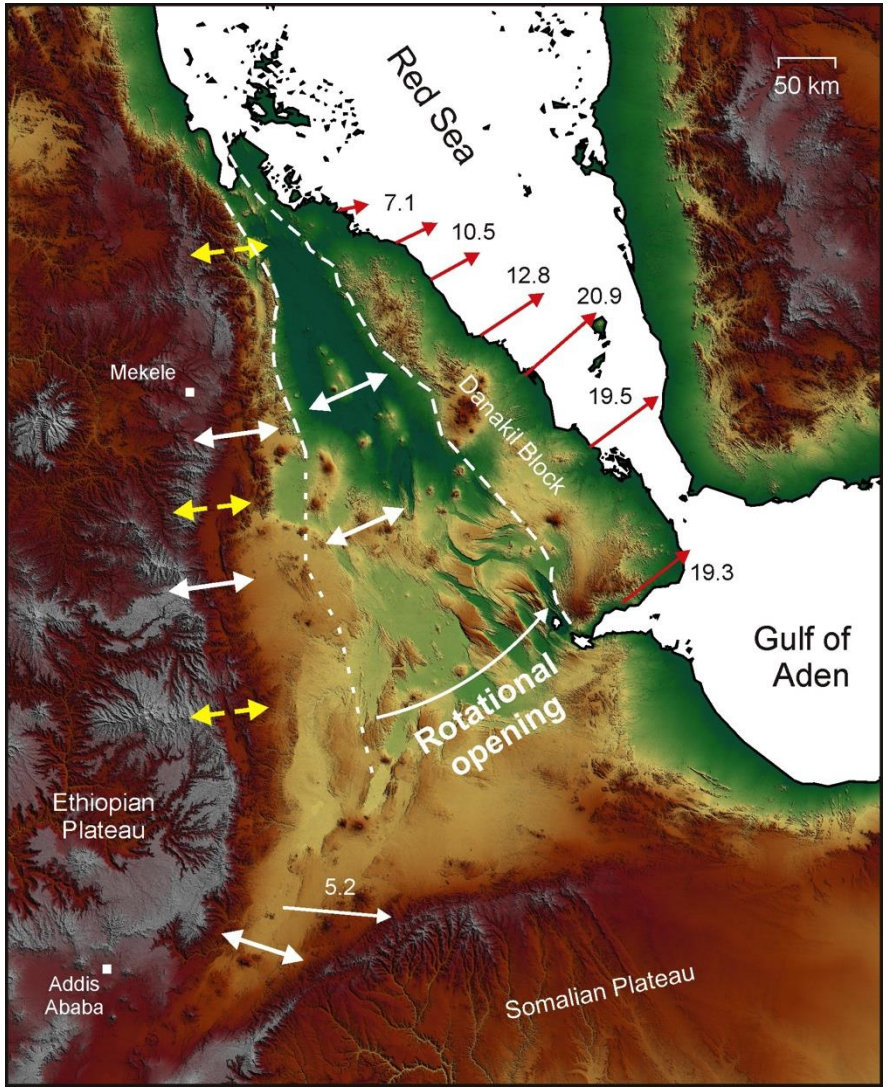


GPS data: McCluskey et al. (2010) in GRS, and Saria et al. (2014) in JGR

Regional context

Data fit with:

- Ongoing rotation of Danakil Block
- Rotational opening of Afar



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GPS data: McCluskey et al. (2010) in GRS, and Saria et al. (2014) in JGR

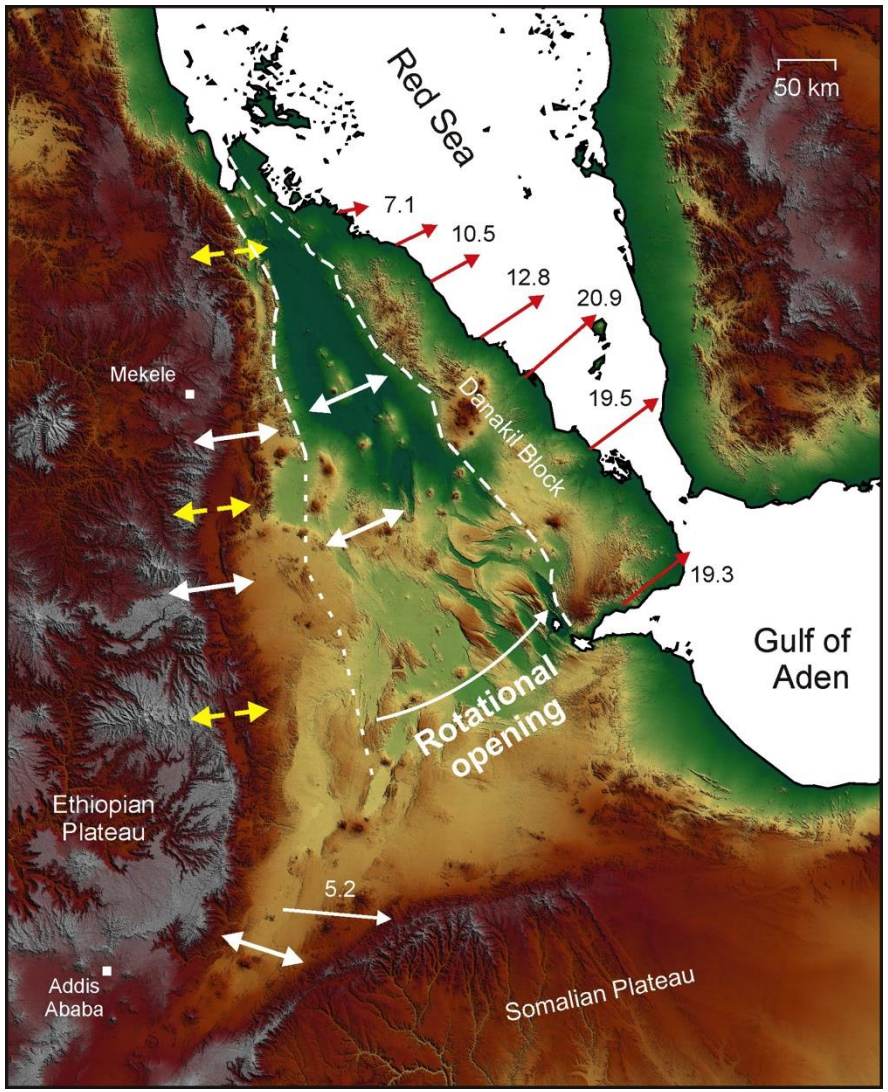
Regional context

Data fit with:

- Ongoing rotation of Danakil Block
- Rotational opening of Afar

Question:

- Any changes in last 25 Myr?
  - E.g. early SSW-NNE extension (Chorowicz et al. 1999 in EGH)



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GPS data: McCluskey et al. (2010) in GRS, and Saria et al. (2014) in JGR

- **Large-scale rotation of the Arabian plate should cause oblique extension along the WAM (!)**
- **Evidence:**
  - Field data from Chorowicz et al. (1999),
  - En echelon arrangement of the WAM, typical of oblique extension →→→

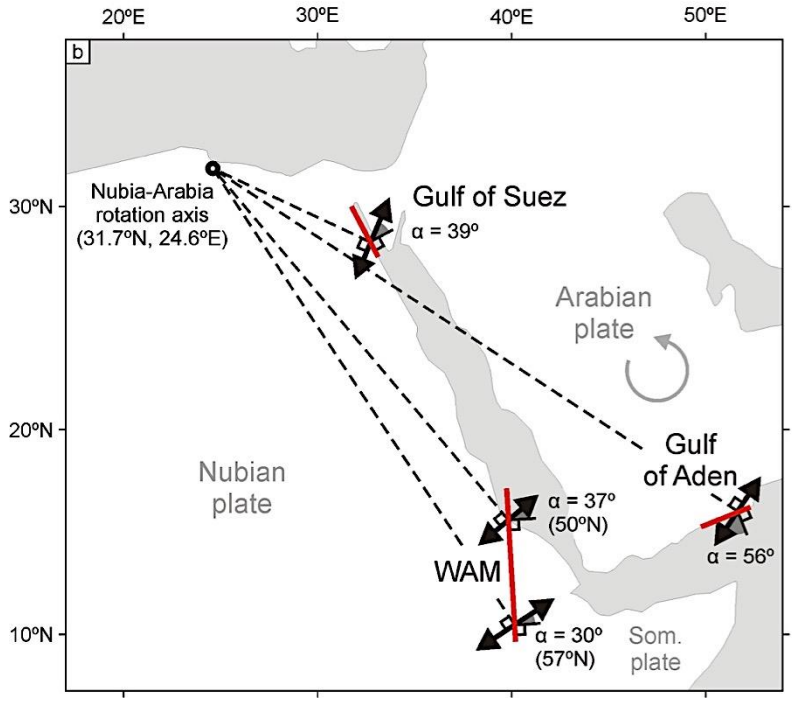
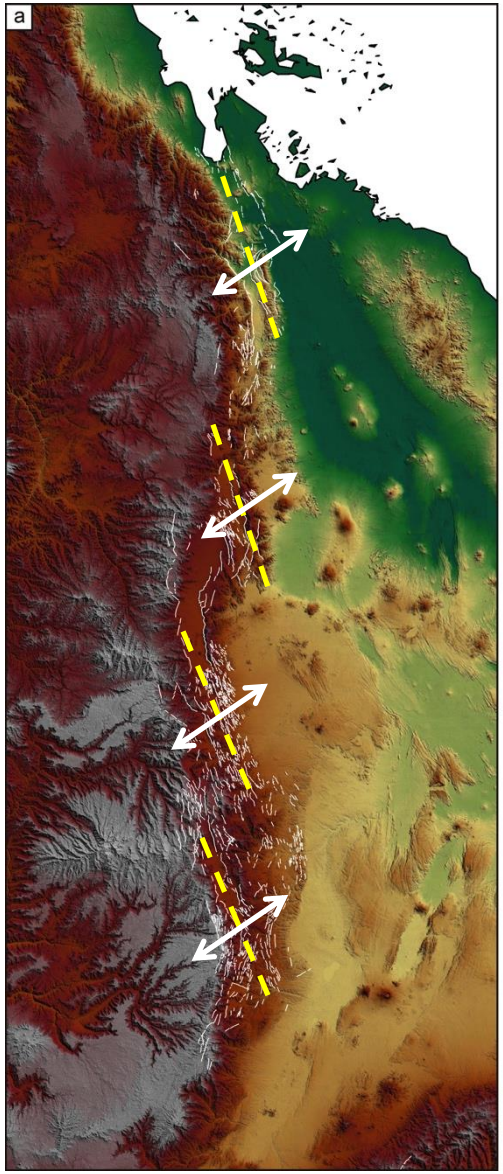
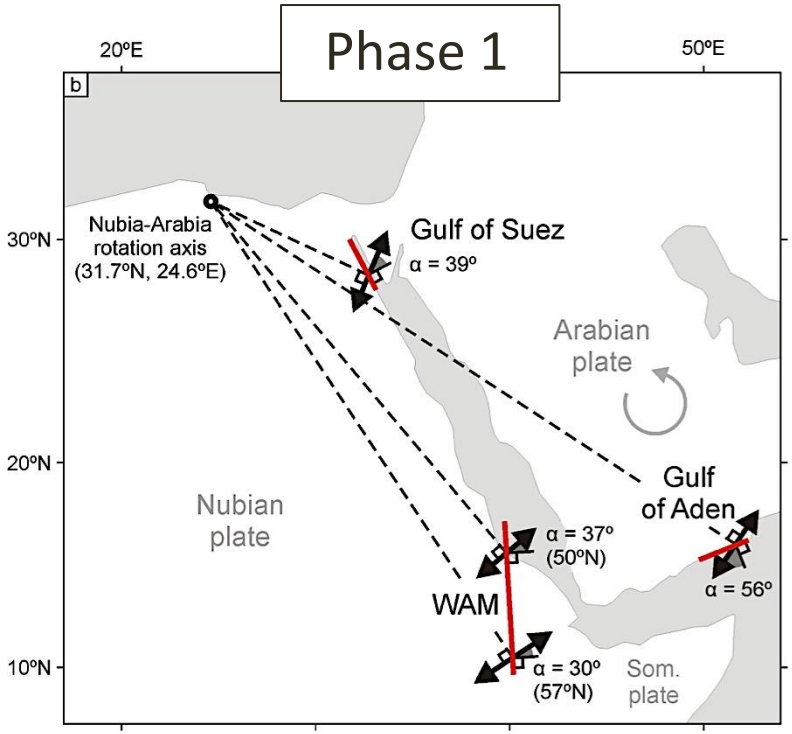


Image based on Smith (1993) in Tectonophysics and ArRajehi et al. (2010) in Tectonics



- **Problem:** we have near-orthogonal extension instead of oblique extension
- **Solution:** Multiphase rotational rifting!
  - **Phase 1:** oblique extension due to large-scale rotation of Arabia
  - **Phase 2:** orthogonal extension due local rotation of Danakil Block



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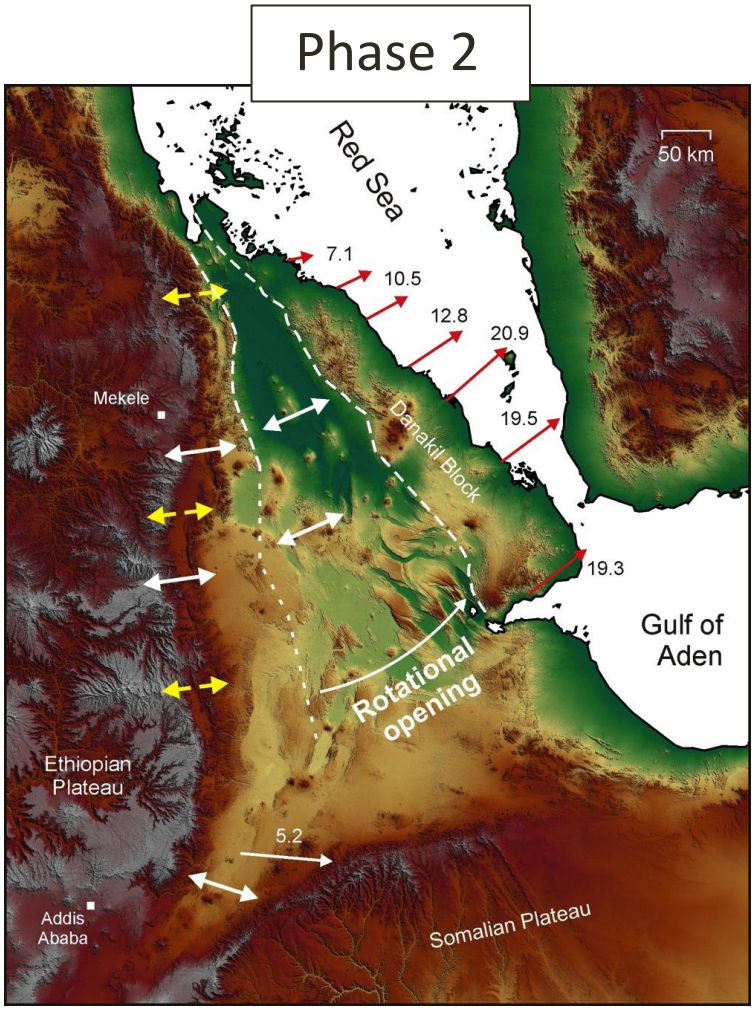

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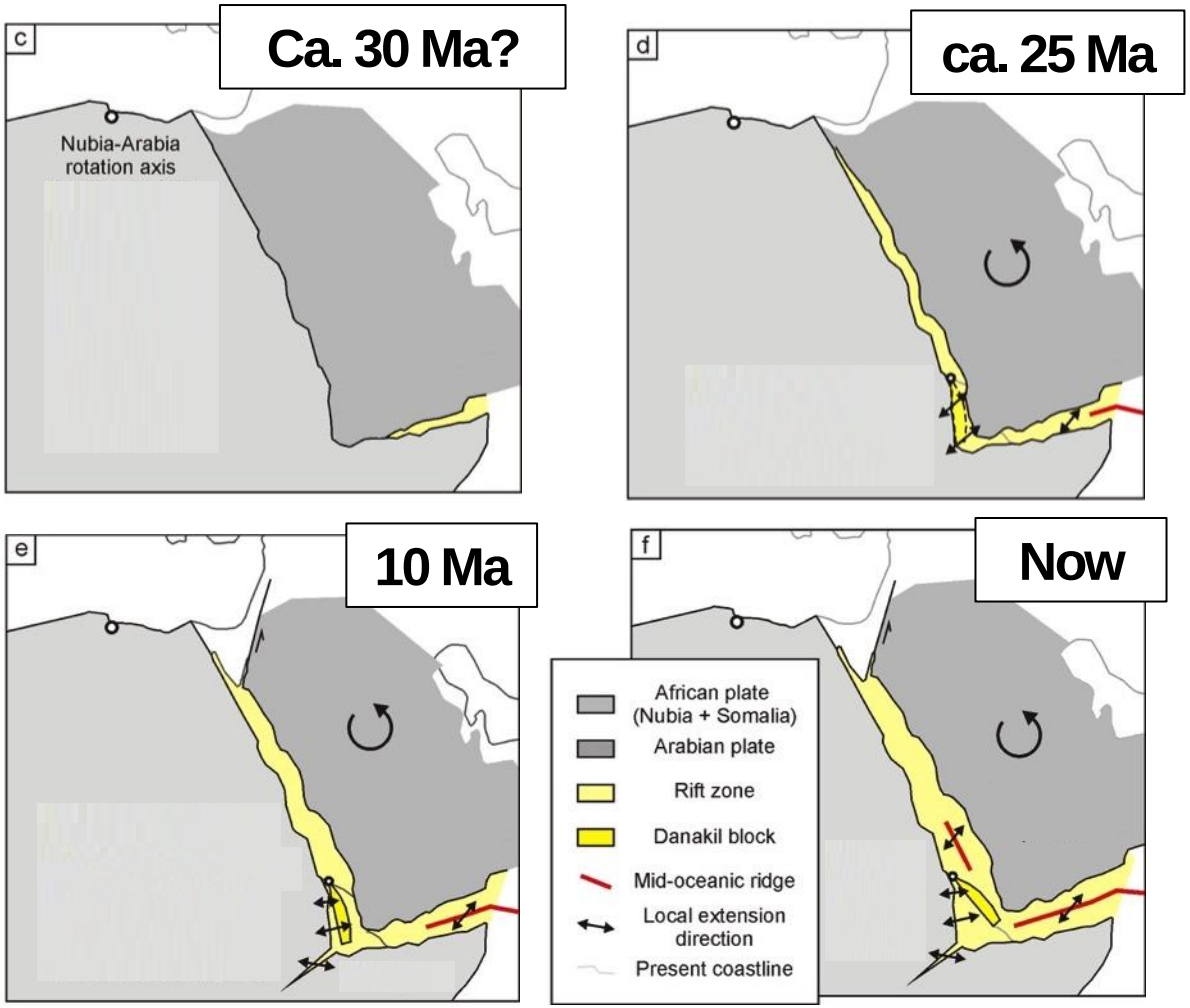
GPS data: McCluskey et al. (2010) in GRS, and Saria et al. (2014) in JGR

Regional context

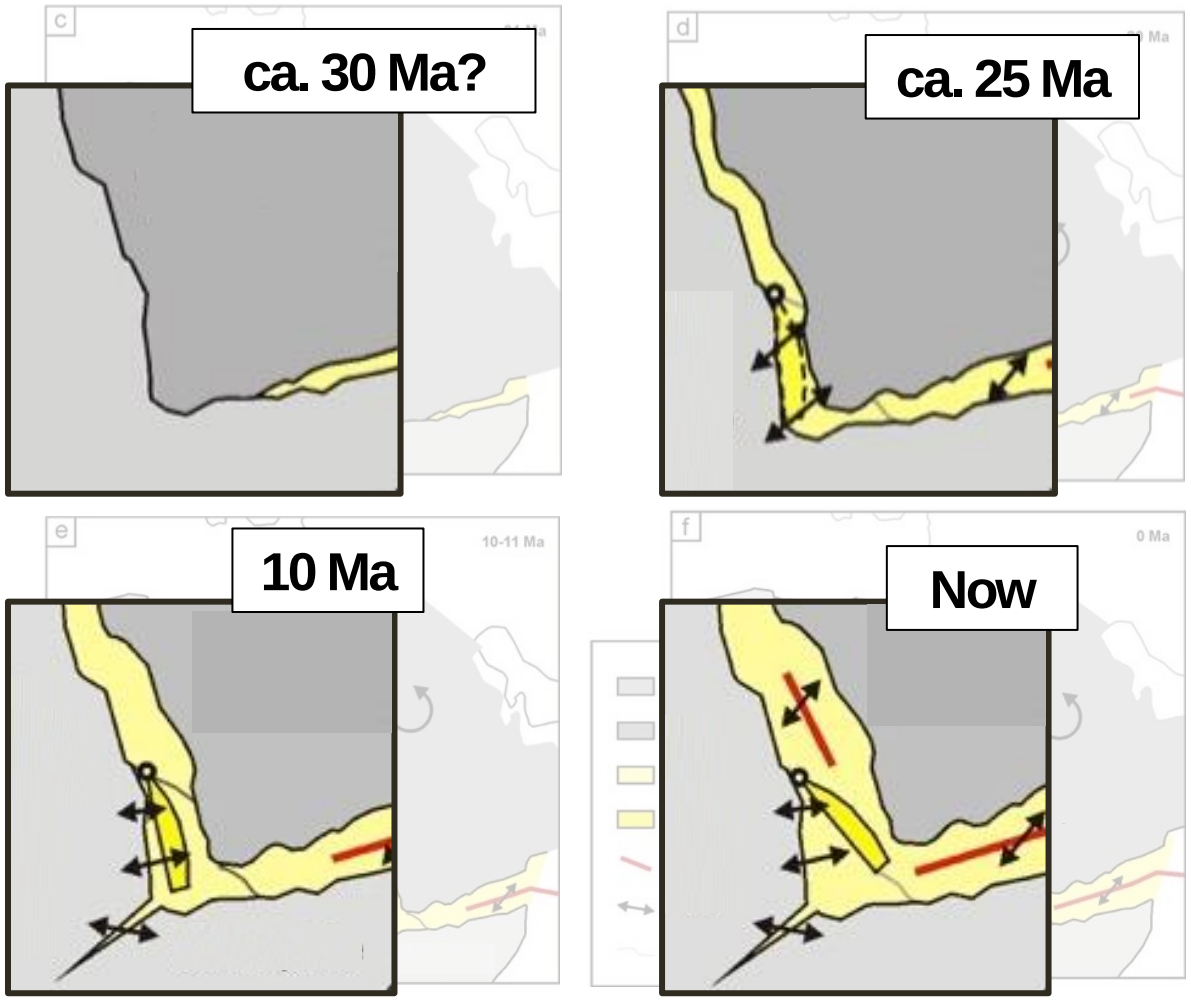
- **Phase 1:** oblique extension due to large-scale rotation of Arabian plate
- **Phase 2:** orthogonal extension due local rotation of Danakil Block since ca. 11 Ma (McCluskey et al. 2010)



Based on Bosworth et al. (2005) in JAES, DArRajehi et al. (2010) in Tectonics, Saria et al. 2014 in JGR and Bosworht (2015) in Springer

Regional context

- **Phase 1:** oblique extension due to large-scale rotation of Arabia
- **Phase 2:** orthogonal extension due local rotation of Danakil Block around 11 Ma (McCluskey et al. 2010)

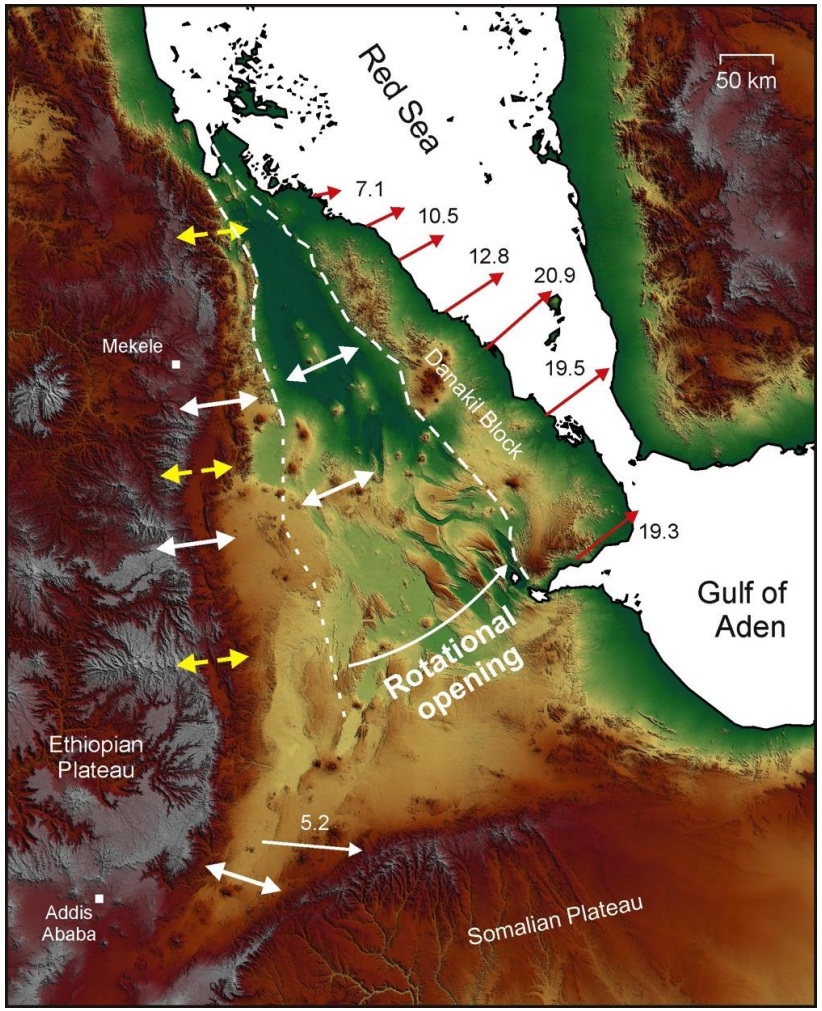


Based on Bosworth et al. (2005) in JAES, DArRajehi et al. (2010) in Tectonics, Saria et al. 2014 in JGR and Bosworht (2015) in Springer

Conclusion
(and Outlook)

Conclusion

- Extension directions from T-axis, field data and GPS analysis are compatible with the current rotational opening of Afar

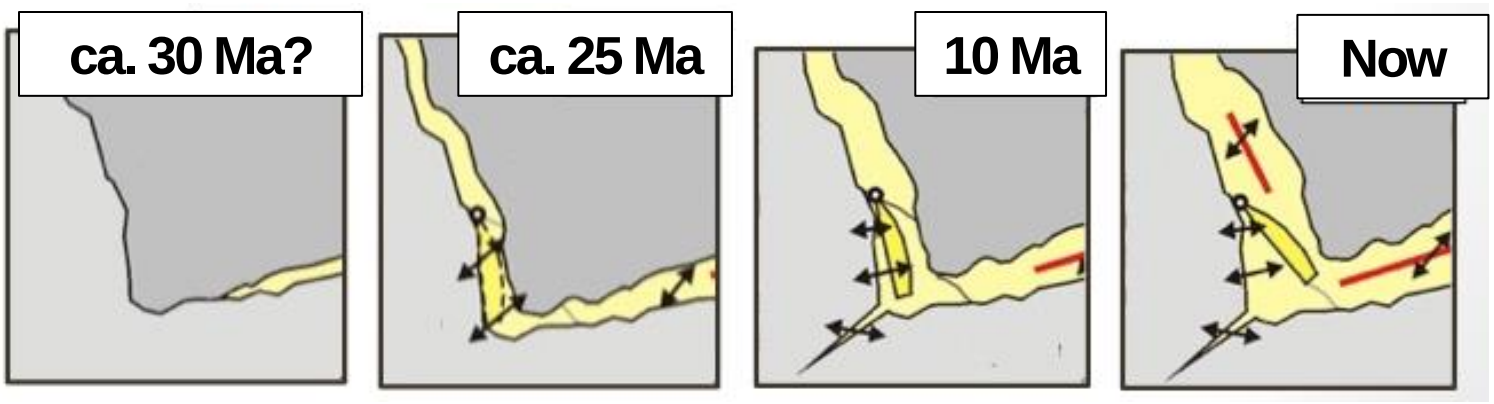


GPS data: McCluskey et al. (2010) in GRS, and Saria et al. (2014) in JGR

Conclusion

- Extension directions from T-axis, field data and GPS analysis are compatible with the current rotational opening of Afar

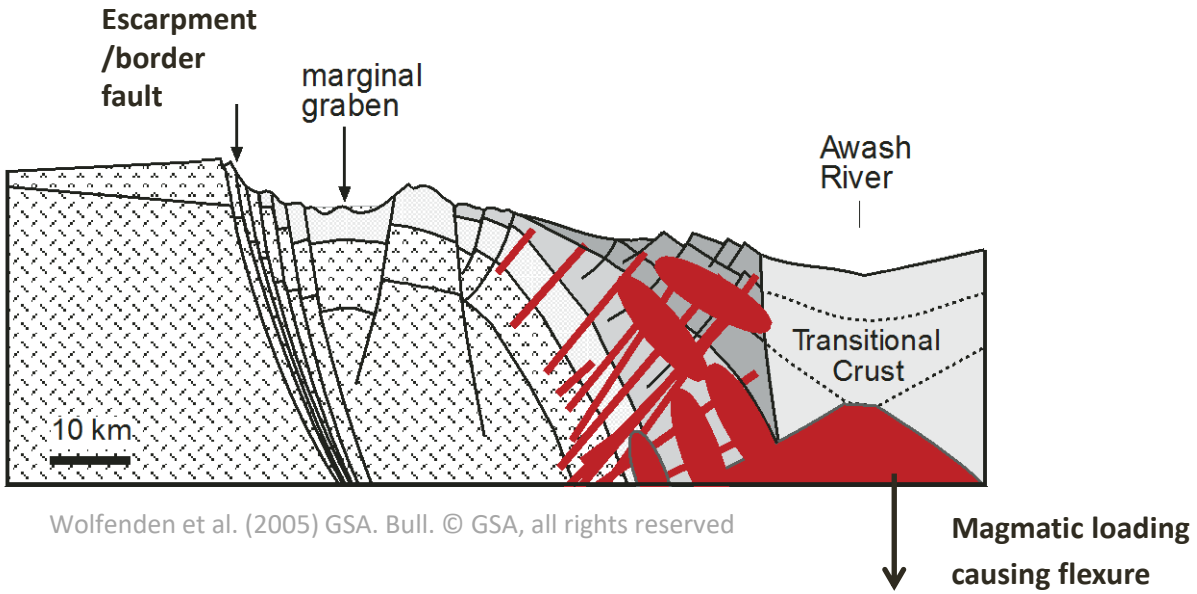
- Fault orientations and published data indicate that early rifting was controlled by Arabian plate rotation
  - current tectonics started with the rotation of the Danakil block around 11 Ma (McCluskey et al. 2010)



Based on Bosworth et al. (2005) in JAES, ArRajehi et al. (2010) in Tectonics, Saria et al. 2014 in JGR and Bosworth (2015) in Springer

Outlook

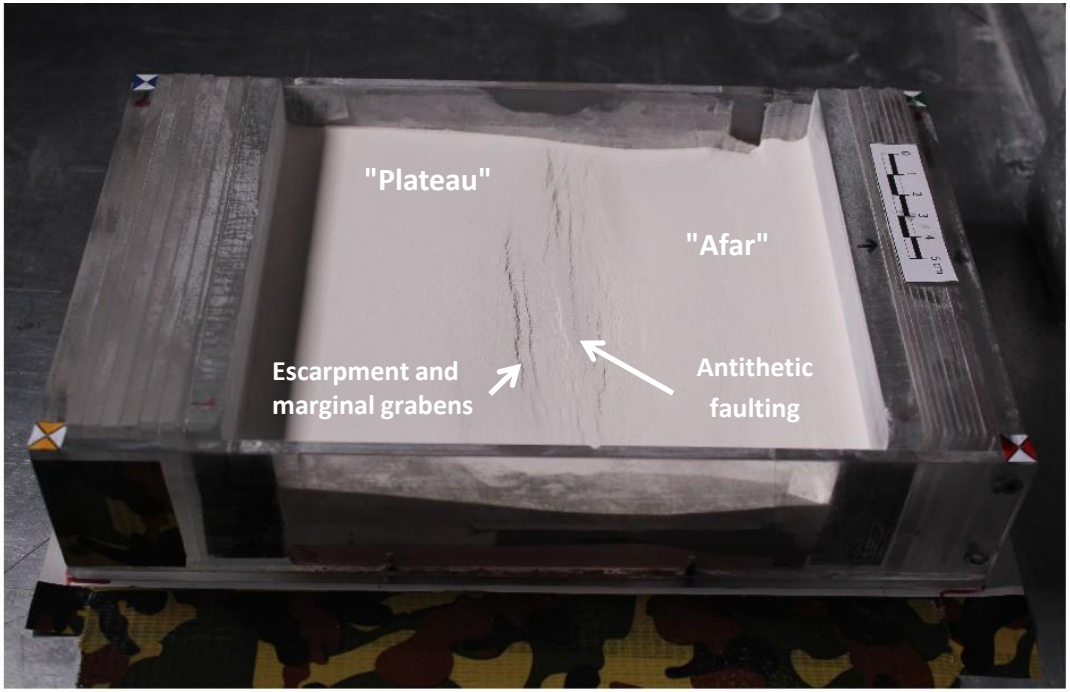
- The WAM has opportunities for modelling marginal flexure.



- Wolfenden et al. (2005) in GSA Bull. propose magmatic loading causing crustal flexure leading to WAM-style structures, which is supported by numerical models: Corti et al. (2015) in Geosphere.
  - **Problem**: numerical models do not reproduce detailed structures

Outlook

- We ran analogue models to test marginal flexure
  - Zwaan et al. (in review by Tectonophysics)
    - Example below: detailed faulting and en echelon marginal grabens due to flexure



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