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

Presentation based on:

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

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Presentation based on:

Main paper (Zwaan et al. 2020 in Tectonics):

Supplementary material to Zwaan et al. (2020) in Tectonics:

Additional analogue modelling work:

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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 ($\pm 25$ 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

• **Problem:** 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](https://doi.org/10.1016/j.jafrearsci.2019.103649))

• **Goal:** New large-scale structural and tectonic characterization of the Western Afar Margin

• **Methods:**
  • 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:

- 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
Earthquake analysis

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

- T-axes from focal mechanisms

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Earthquake analysis

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

- T-axes from focal mechanisms
  - Indicate various current extension directions!

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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

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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)

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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

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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 → → →

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**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 to local rotation of Danakil Block

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**Phase 1:**

- Nubia-Arabia rotation axis (31.7°N, 24.6°E)
- Gulf of Suez
- Arabian plate
- Nubian plate
- WAM
- α = 37° (50°N)
- α = 56°

**Phase 2:**

- Rotational opening
- Red Sea
- Gulf of Aden
- Ethiopian Plateau
- Somali Plateau
- Addis Ababa

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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)
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)
Conclusion
(and Outlook)
Conclusion

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

Introduction – Results/Discussion – Conclusion – References

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References


