Regional analysis of necking domains in young, incipient and failed rifted margins from deformable plate tectonic models and geophysical data

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Introduction, Geological Setting and Aim

- The Red Sea is a young ocean basin in the process of transitioning from continental extension to seafloor spreading (e.g., Shi et al., 2018).
- However, the extent of the transition from active rift to oceanic spreading, and whether the crust in the central Red Sea is continental or oceanic has been controversial.
- Rift initiation estimates fall between 33 Ma (Tubbs et al., 2014) or 23 Ma (Bosworth et al., 2005).
- The aim of this project is to shed light on the time, extent and kinematics of rifting and breakup through the use of gravity inversion and deformable plate tectonic models.

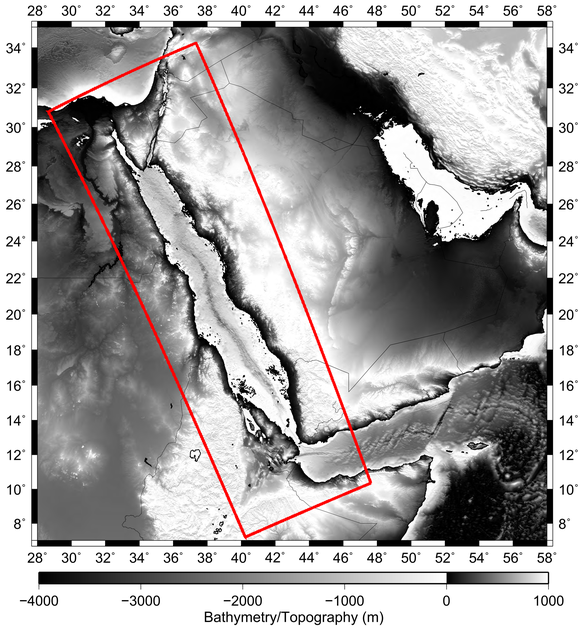

Figure 1 – Study area location with the domain used for the gravity inversion shown in red.

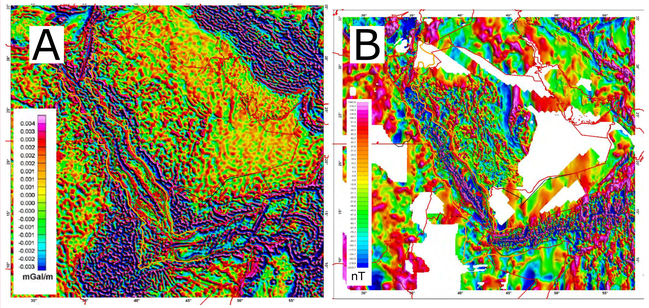

Fig. 2 - A) First vertical derivative of the residual Bouguer gravity. 3D terrain corrected gravity reduced from Sandwell and Smith, free air data v23.1 (Sandwell et al., 2014). B) Reduced to pole magnetics (merged shipboard data, Quesnel et al., (2009) and EMAG2 v3, Meyer et al., 2017). Processing completed using Oasis Montaj (Geosoft).

Gravity Inversion

Methods

- A regional constrained 3-D gravity inversion was performed over the Red Sea using the GRAV3D inversion algorithm from Li and Oldenburg (1996; 1998).
- The inversion was performed using Free Air gravity observations (Andersen et al., 2010) and a reference model that included topography/bathymetry and interpolated depth to basement constraints from well data, seismic refraction surveys (e.g., Shi et al., 2018), and global sediment thickness compilations (Laske and Masters, 1997).
- The topography/bathymetry data used were from the 2014 global 30-arcsec gridded bathymetric dataset of the General Bathymetric Chart of the Oceans (GEBCO; http://www.gebco.net/).
- The model parameterisation for GRAV3D consisted of flattened cubes, each with lateral dimensions of 5 km × 5 km and 500 m thick. The total mesh depth was set to 35 km and a reference density of 2850 kg/m^3 was assigned.
- Model cells above sea-level offshore and above the topography onshore were null cells that did not contribute to the calculation of the predicted gravity anomaly values.
- Cells corresponding to water were kept invariant, cells corresponding to sediments were required to have densities increasing with depth, subject to geologically constrained bounds, and the remaining parts of the model were allowed to vary as much as necessary.
- From the resulting density anomaly model, a constant density iso-surface was extracted from the model to act as a proxy for the depth to the Moho across the region. A density anomaly of 170 kg/m^3 (corresponding to an absolute density of 3020 kg/m^3) was chosen for the Moho proxy.
- The crustal thickness map was obtained by taking the difference between the Moho proxy map and the interpolated depth to basement map.

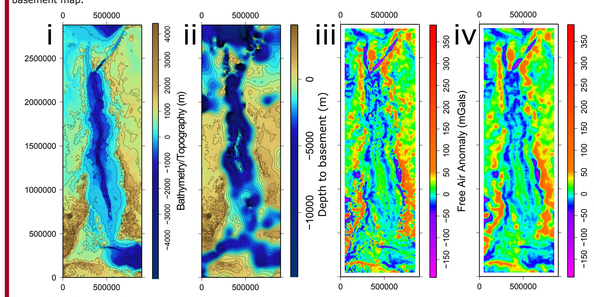

Figure 3 – i-iii) Gravity inversion model inputs and iv) predicted free air anomaly.

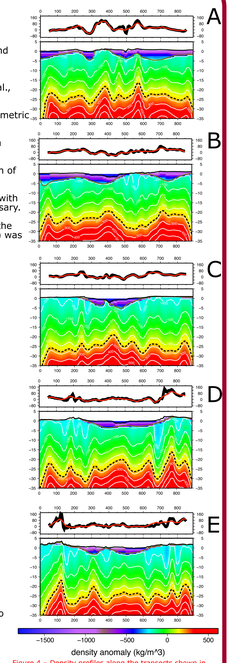

Figure 4 – Density profiles along the transects shown in Fig. 4 from the final model.

Preliminary results

- Depth to Moho is generally 15 to 20 km down the centre of the Red Sea and into the Gulf of Aden although there is a Moho deepening toward the Afar region.
- Depth to Moho steepens sharply towards the present day coastline of the Red Sea.
- Moho depth along the edges of the Sinai block also appear quite deep.
- Most of the crust under the Red Sea is approximately 15 to 25 km thick.
- Crustal thickness in thinnest in the northern Red Sea, thickening toward the Afar region moderately.

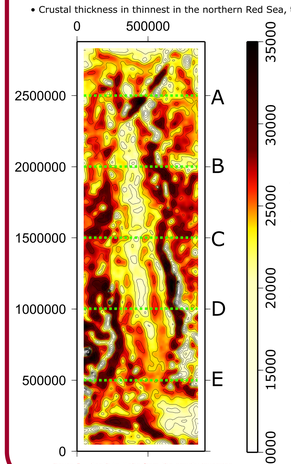

Figure 5 – Depth to Moho from the gravity inversion

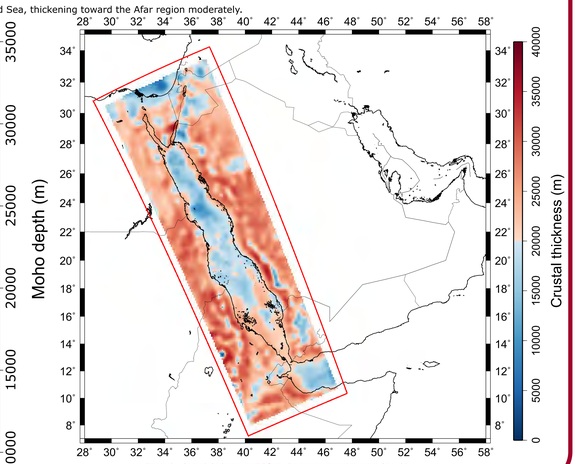

Figure 6 – Crustal thickness model from the gravity inversion using GRAV3D

Deformable plate tectonic models

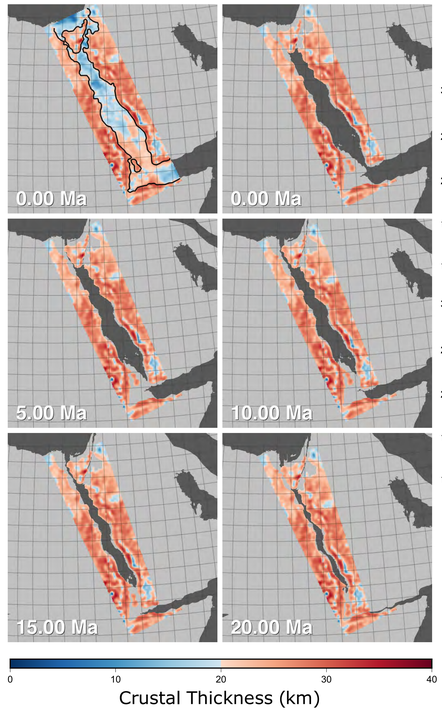

Figure 7 – "Cookie-cut" reconstruction in GPlates of the crustal thickness obtained through the gravity inversion.

Methods

- Models were built in GPlates 2.0 using methodology and theory described in Gurnis et al. (2018) and deployed in Welford et al. (2018).
- All models were run from 100 Ma to present and assume a uniform, region-wide, crustal thickness of 35 km at 100 Ma.
- Plate velocities derived through the poles of rotation relative to one another drive deformation Gurnis et al. (2018).

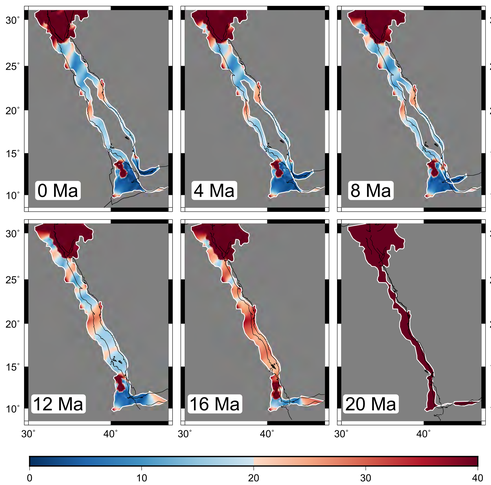

Figure 8 – Preliminary results of GPlates deformable plate modelling using necking lines defined from the gravity inversion results (Fig. 7).

Preliminary results

- New poles derived for Sinai and Danakil micro-continental fragments provide a tight pre-rift configuration.
- The deformable models predict crust on the margins of the Red Sea of comparable thickness to that indicated by the gravity inversion (c. 15-25 km).
- However, a notable area of mismatch between the deformable model and gravity inversion predictions is apparent around the Sinai area (northern Red Sea).
- This suggests that further refinement of the model inputs is required

Conclusions

Outstanding issues

- Poles of rotation and necking lines for the Danakil and Sinai micro-continental fragments need to be refined further to more representatively reproduce deformation styles in these areas.
- Further development of including transforms (e.g., Dead Sea) in GPlates deformable models is required.
- Further investigation of the age of rifting/necking in the Red Sea area and the impact magmatism plays in thickening the crust is also needed.

Take away points

- New constrained gravity inversion and deformable plate modelling results have provided insights into the structure and evolution of the Red Sea and the location and variation in the necking domain geometry.
- Deformable plate modelling has shown that currently published poles of rotation do not fully account for the observed structure as shown through the gravity inversion.
- Further investigations are needed to test rift/breakup ages and necking domain assumptions, in addition to further integrating geophysical datasets.

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References