A rheological model of the rift–drift transition in the Red Sea

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Formation of a new extensional plate boundary: Propagating ridge / rift system

Original system of $n$ plate boundaries

New system of $n + 3$ plate boundaries

- **Rift**
- **Propagating Ridge**
- **Existing Plate Boundaries**
- **Triple Junction**
The rift-drift transition zone

Formation of a new spreading segment
The rift-drift transition zone

Formation of a new spreading segment
The rift-drift transition zone

Formation of a new spreading segment
Rheology of the Lithosphere: Rifting

Constitutive Law for the K-V Element:
\[ \sigma = Y_K \varepsilon_K + \left( \eta_T^* \dot{\varepsilon}_K \right)^{1/n} \]

\( Y_K = 33 \text{ GPa} \)

\( \eta_T^* = \text{Pseudoviscosity [Pa}^n\text{s]} \)

\( \eta_T = \left( \eta_T^* \right)^{1/n} \dot{\varepsilon}_K^{(1-n)/n} \)

\( n = 3 \)

\( \gamma = \eta_T / \eta_S \Rightarrow \eta_T^* = \gamma^n \eta_S^* \)  
Acceptable value for \( \gamma \): \( \gamma = 0.1 \)

\( T = 1000 \text{ K}, \ P = 1 \text{ GPa}, \text{ dry olivine} \Rightarrow \eta_S^* = 7.64 \times 10^{44} \text{ Pa}^3\text{s} \Rightarrow \eta_T^* = 7.64 \times 10^{41} \text{ Pa}^3\text{s} \)

Assuming steady creep: \( \dot{\varepsilon}_s = 10^{-18} \text{ s}^{-1} \) and that stress changes at a much lower rate than strain:

\[ \dot{\varepsilon}(t) - \dot{\varepsilon}_s(t) = \frac{1}{\gamma^n \eta_S^*} \left[ \sigma^{1-n} - \frac{(1-n)Y_K}{\gamma^n \eta_S^*} t \right]^{\frac{n}{1-n}} \]

\[ \eta = \frac{1}{2\dot{\varepsilon}} \left\{ \frac{(1-n)Y_K}{\gamma^n \eta_S^*} t + \gamma^{1-n} \left[ \eta_S^* (\dot{\varepsilon} - \dot{\varepsilon}_s) \right]^{\frac{1-n}{n}} \right\} \]
Calibration of rheological parameters: The post-rift stage

Linear anelastic relaxation test:

\[ \dot{\varepsilon}(t) = -\left(\varepsilon_0 / \tau\right)e^{-t/\tau} \]

Non-linear anelastic relaxation test:

\[ \dot{\varepsilon}(t) = -\frac{1}{\eta_r^* \left[ Y_k \varepsilon(t) \right]^n} \]

\( n \neq 1, \text{ odd integer} \)

Dry rheology; \( \gamma = 0.1 \)

is in agreement with geophysical/geological observation
The study area
Evidence of post-rift anelastic relaxation: 1 – Finite strains around the Red Sea

$$\varepsilon_{yy}(\zeta, t) = \ln \left[ 1 - \frac{\omega_0 R \sin(\zeta / R)}{L_0} (t - t_0) \right]$$

- Black line: Kinematic strain as a function of the distance $\zeta$ from the Euler pole of relative motion between Nubia and Arabia;
- Red line: Finite transversal strain, obtained from observed $\beta$ factors, along the passive continental margins facing the oceanized region of the Red Sea;
- Green line: Finite transversal strain along the active rifting region of the northern Red Sea;
- Violet line: Recovered strain
Evidence of post-rift anelastic relaxation: 2 – Seismicity
Evidence of post-rift anelastic relaxation: 3 – Geology (Strike-slip faults)
Evidence of post-rift anelastic relaxation: 3 – Geology (Reverse faults and folds)
Evidence of post-rift anelastic relaxation: 3 – Geology (Reverse faults and folds)
Evidence of post-rift anelastic relaxation:

3 – Geology (reverse faults)
Evidence of post-rift anelastic relaxation:
3 – Geology (Strike-slip & reverse faults)
Evidence of post-rift anelastic relaxation: 3 – Geology (Strike-slip & reverse faults)
Numerical Experiment: Rifting Stage Model

Mass conservation: \( \Phi = \oint_D \rho v \cdot dS = 0 \)

Equations of motion (Navier-Stokes): \( \rho \ddot{v}_i = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \eta \left( \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) + \lambda \frac{\partial v_k}{\partial x_k} \delta_{ij} \right] + \rho g_i \)

Energy conservation: \( \rho c_p \dot{T} - \alpha T \dot{p} = \Phi + k \nabla^2 T \)

Equation of state: \( \rho = \rho_0 \left[ 1 - \alpha (T - T_0) \right] \)
Numerical Experiment: Rifting Stage Model

\[ \eta = 10^{23} \text{ Pa s} \]

Lithosphere mantle: \[ \eta = \frac{1}{2\dot{\varepsilon}} \left\{ \frac{(1-n)Y_K}{\gamma^n \eta_s^*} t + \gamma^{1-n} \left[ \eta_s^* (\dot{\varepsilon} - \dot{\varepsilon}_s) \right]^{1-n} \right\}^{\frac{1}{1-n}} ; \quad n = 3 \]

Asthenosphere: \[ \eta = A^{-1/n} \exp\left( \frac{H}{nRT} \right) \dot{\varepsilon}^{1-n} ; \quad n = 3.5 \]
Numerical Modelling: Velocity Field

$t = 0$ Myrs, $15$ mm yr\(^{-1}\)

$t = 15$ Myrs, $15$ mm yr\(^{-1}\)

$T$ [K]

[Image of velocity field diagram]
Numerical Modelling: Velocity Field $-v_x$

$t = 0$ Myrs

$t = 15$ Myrs

$v_x$ [cm yr$^{-1}$]
Numerical Modelling: Velocity Field – $v_y$

$t = 0$ Myrs

$t = 15$ Myrs

$v_y$ [cm yr$^{-1}$]
Numerical Modelling: Velocity Field – $v(x,0)$

Blue = 0 Myrs; Red = 5 Myrs; Green = 10 Myrs; Orange = 15 Myrs.

Offset of the rift axis at $t = 0, 5, 10, 15$ Myr (dashed lines).
Numerical Modelling: Stress 2nd Invariant

$t = 0$ Myrs

$t = 15$ Myrs
Numerical Modelling: Stress
Future research: Post-rift Stage Model

Working hypotheses:

• Stress is not relaxed instantaneously along the rift zone;
• Stress is relaxed by propagation of an ultra-slow stress wave;
• Ultra–slow stress waves are solitons that travel at a velocity of 40–50 km/Myr;
Conclusions

- The lithosphere mantle accumulates strain energy during the rifting stage. The best-fitting non-linear rheology requires a transient viscosity 1–2 orders of magnitude less than the steady-state viscosity;
- After break-up, this energy is released by anelastic relaxation. During the strain recovery, the passive margins experience post-rift tectonic inversion.
Thank You