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

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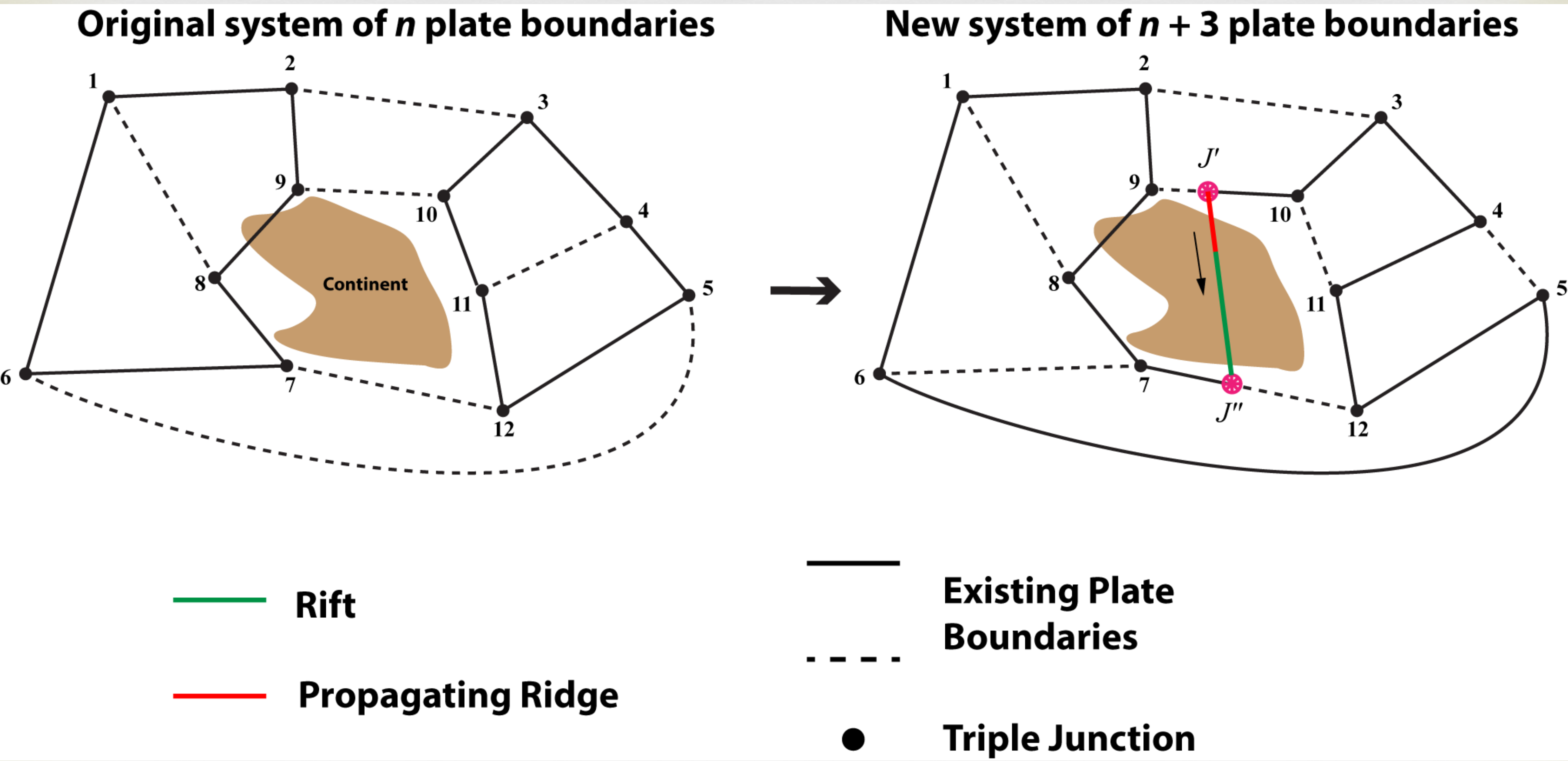
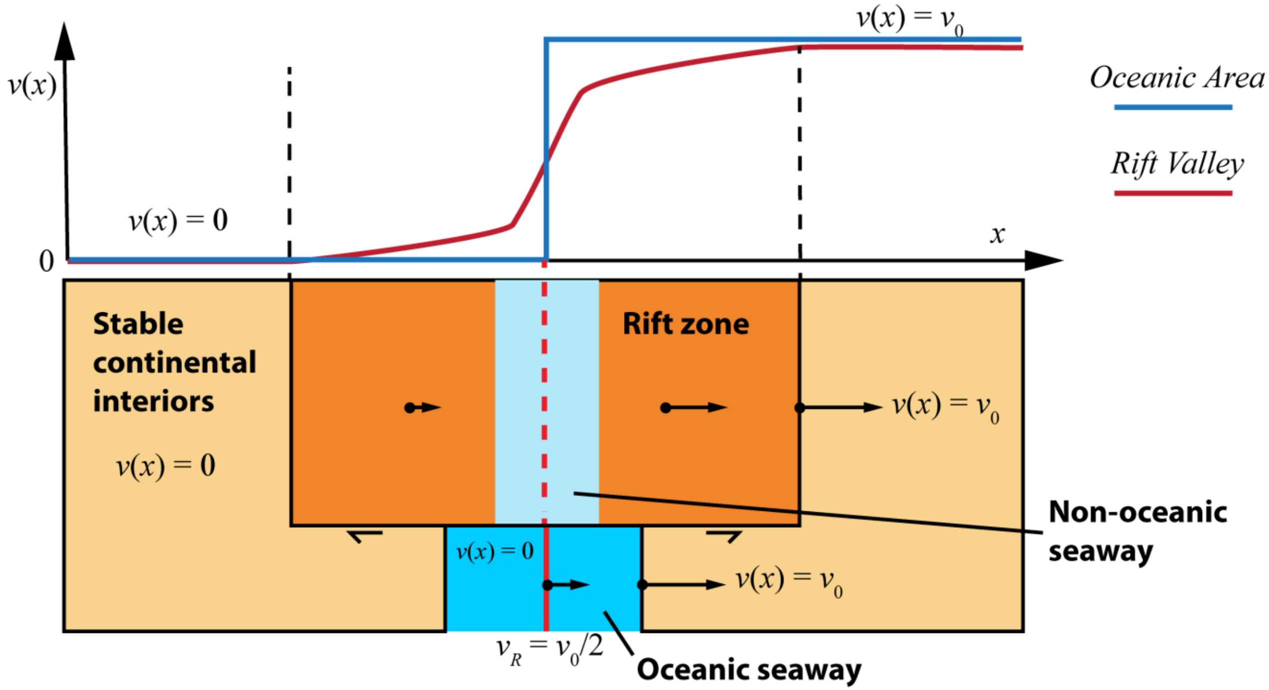
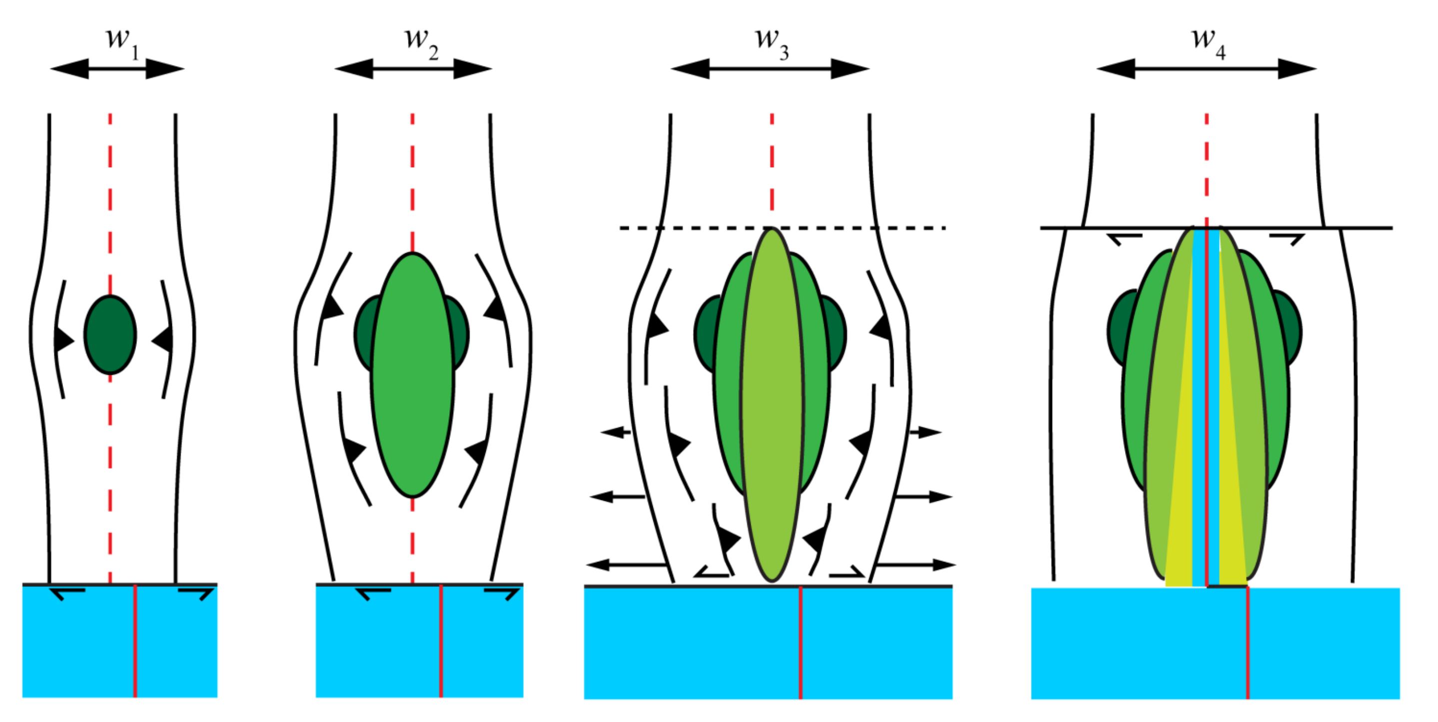
Formation of a new extensional plate boundary: Propagating ridge / rift system



The rift-drift transition zone



Formation of a new spreading segment



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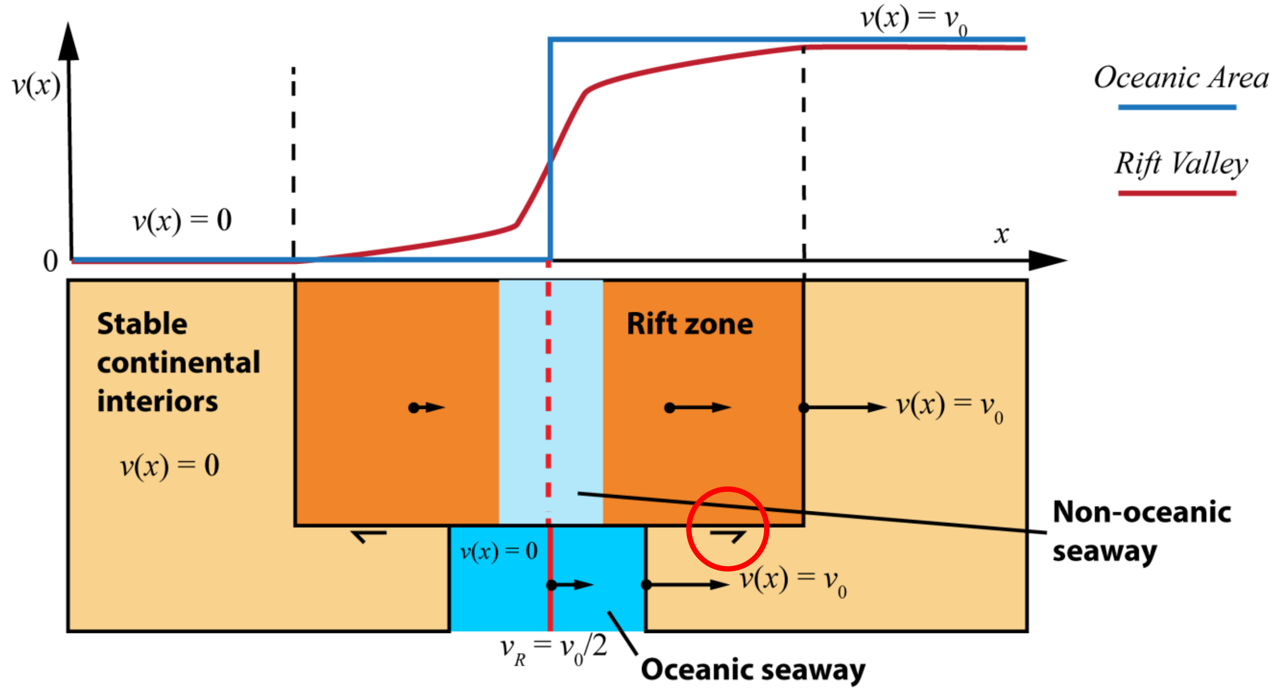

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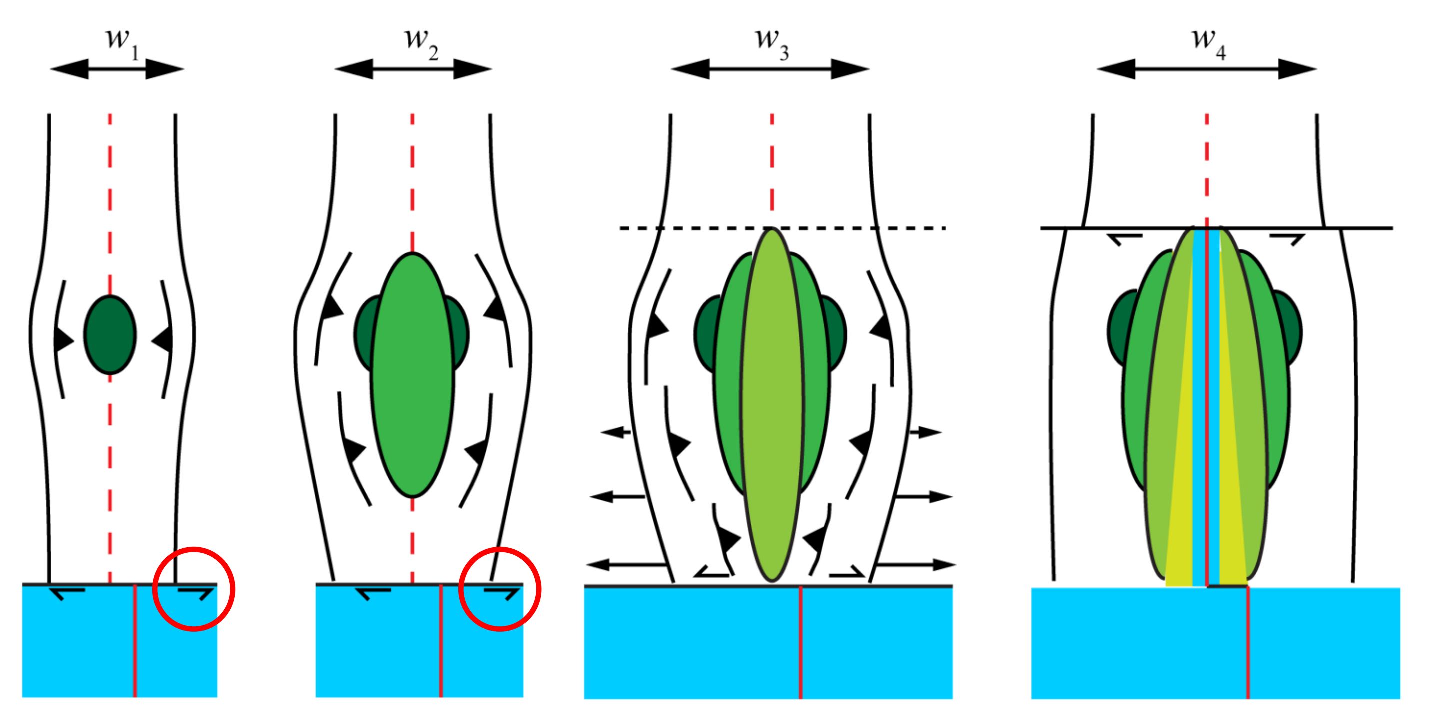

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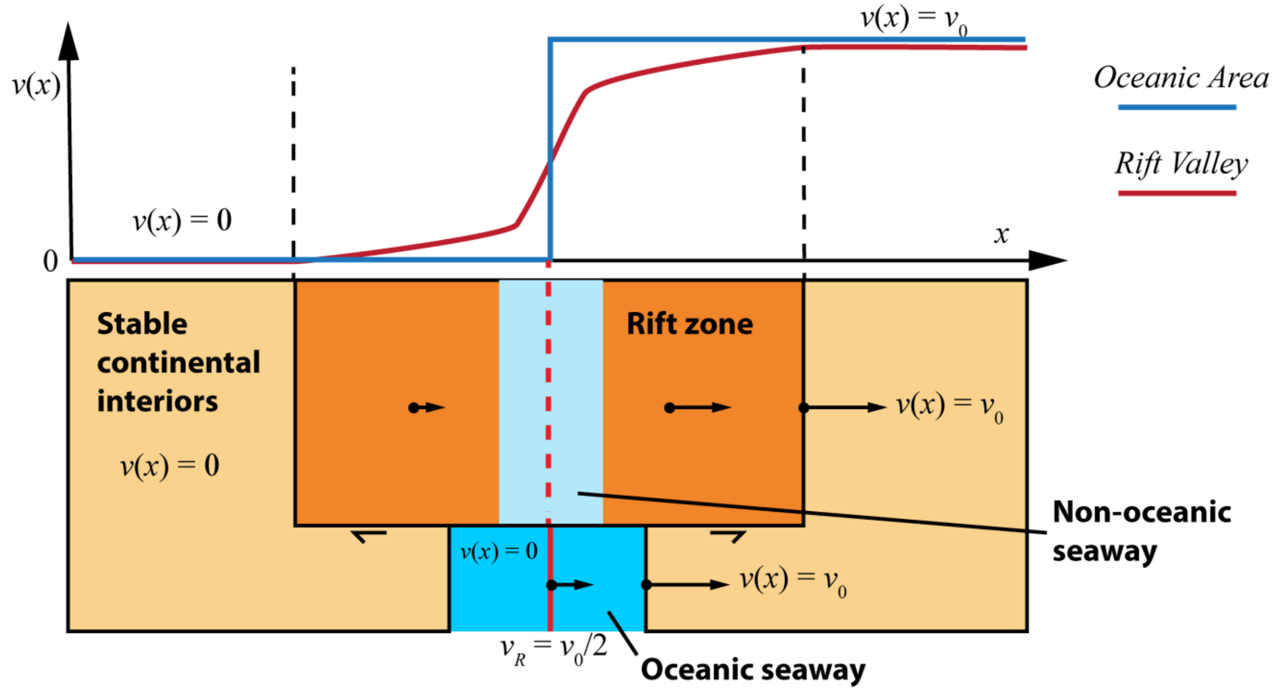

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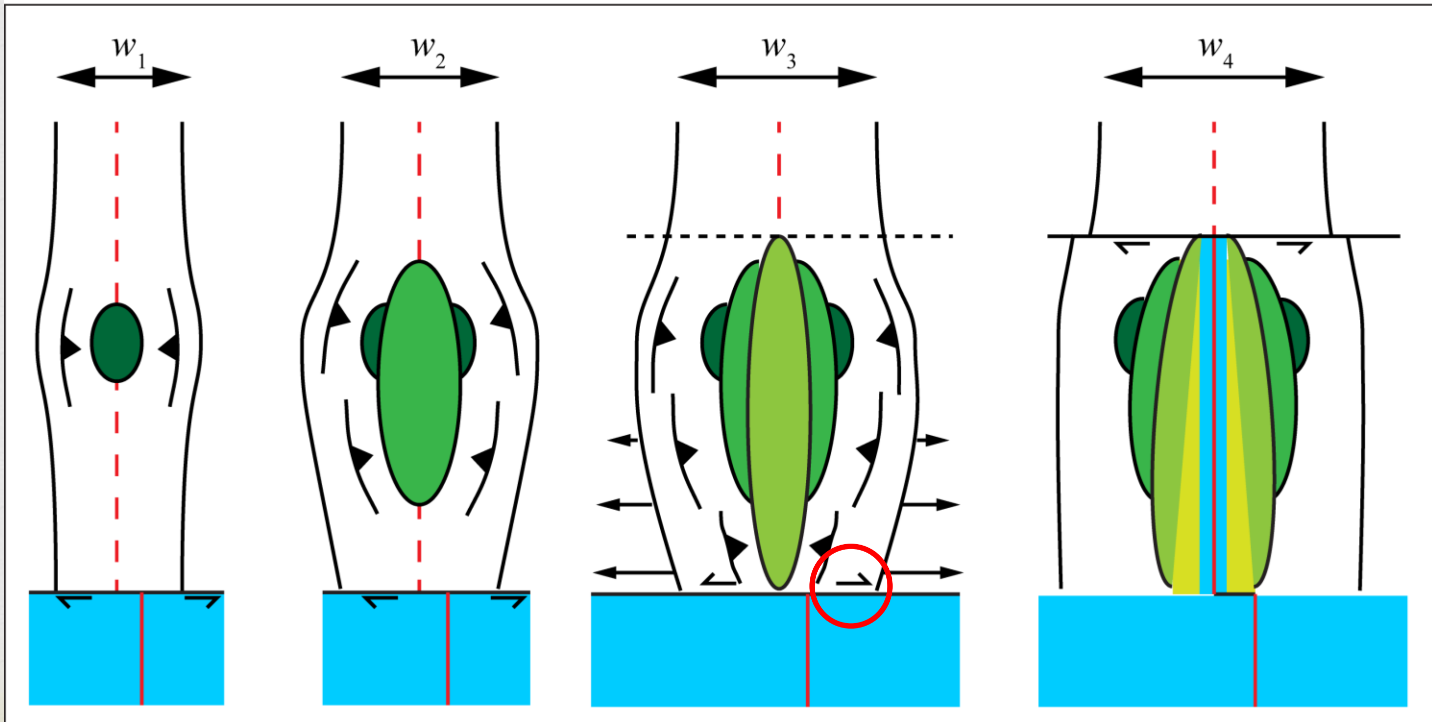
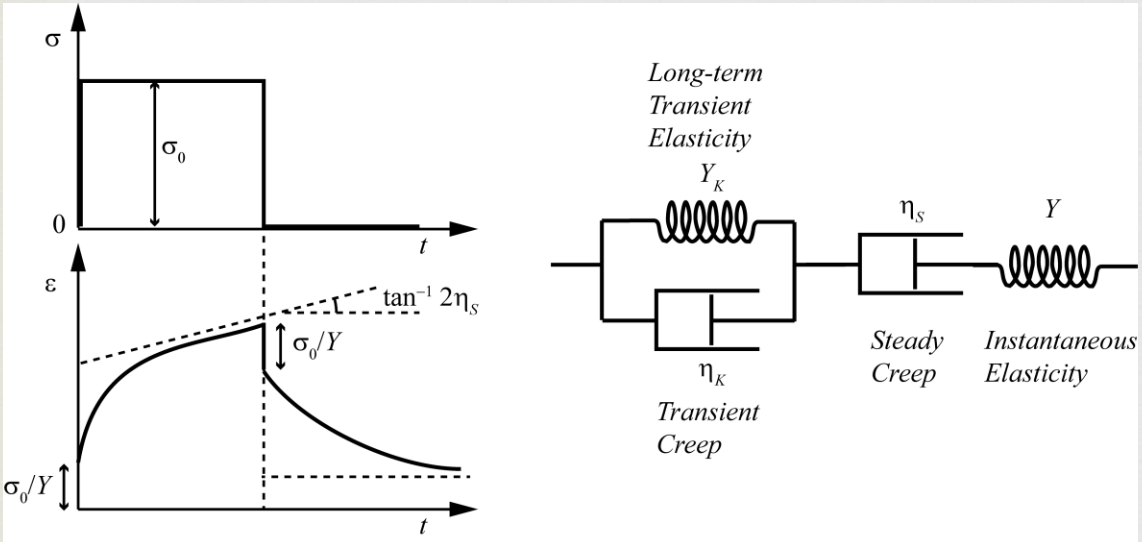


Rheology of the Lithosphere: Rifting



Constitutive Law for the K-V Element:

$$\sigma = Y_K \varepsilon_K + \left(\eta_T^* \dot{\varepsilon}_K\right)^{1/n}$$

$Y_K = 33$ GPa

$\eta_T^* =$ Pseudoviscosity [Pa^{n}s]

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

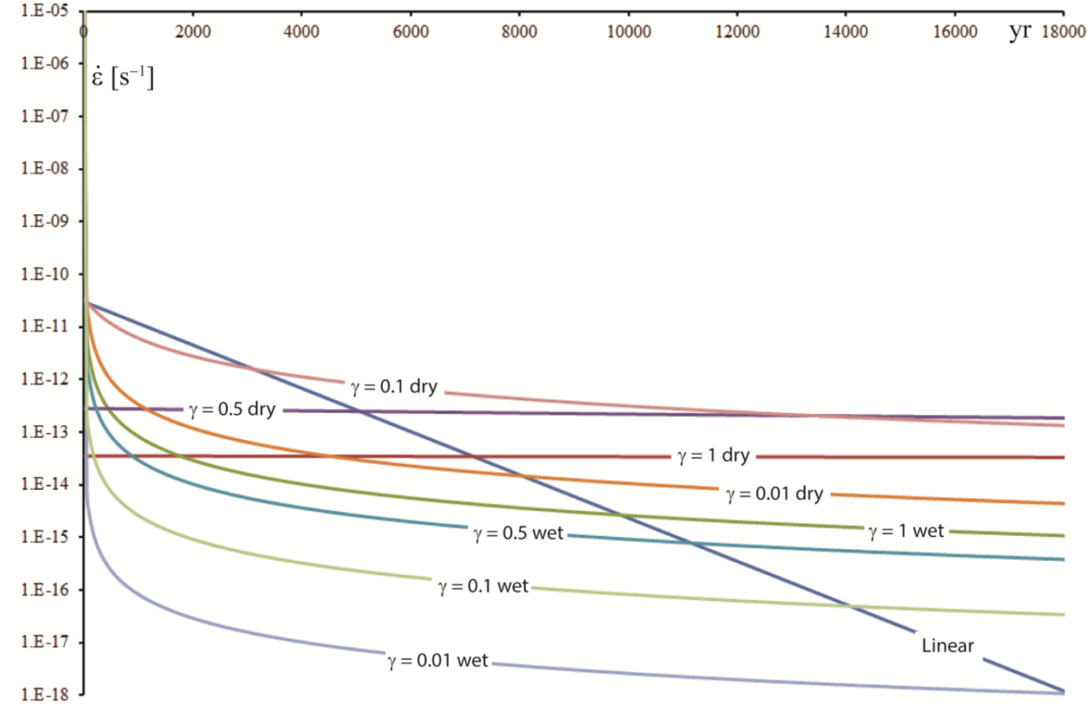
$n = 3$

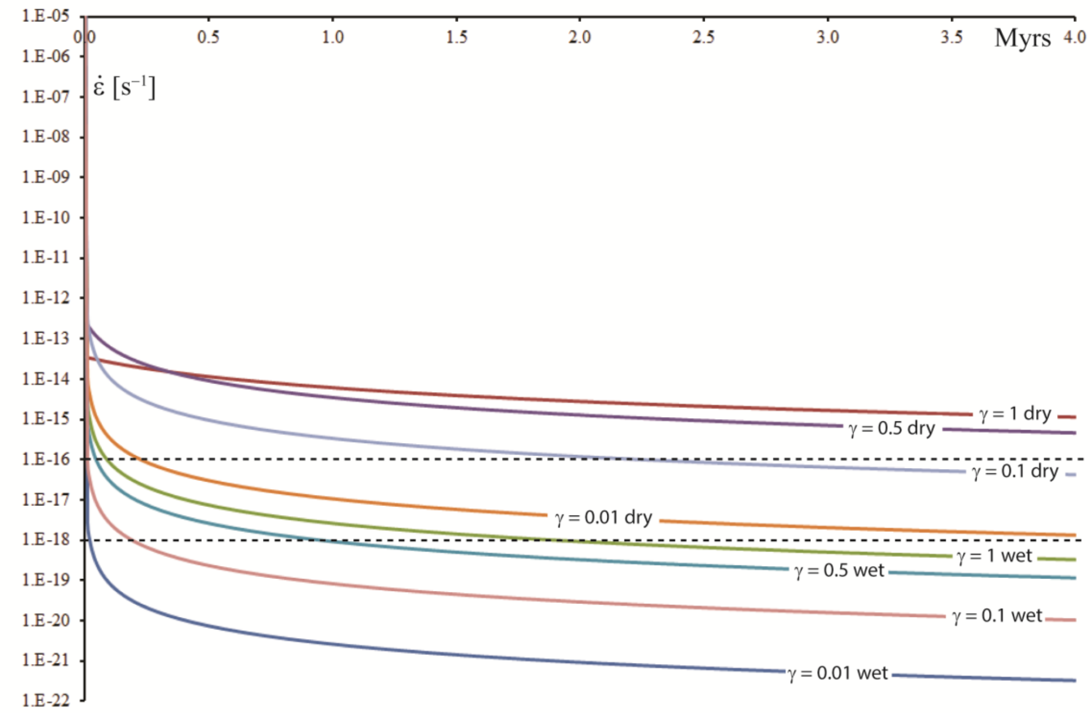
$\gamma = \eta_T / \eta_S \Rightarrow \eta_T^* = \gamma^n \eta_S^*$ Acceptable value for γ: $\gamma = 0.1$

$T = 1000$ K, $P = 1$ GPa, dry olivine $\Rightarrow \eta_S^* = 7.64\times10^{44}$ Pa^{3}s $\Rightarrow \eta_T^* = 7.64\times10^{41}$ Pa^{3}s

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

$$\dot{\varepsilon}(t) - \dot{\varepsilon}_S(t) = \frac{1}{\gamma^n \eta_S^*}\left[\sigma^{1-n} - \frac{(1-n)Y_K}{\gamma^n \eta_S^*} t\right]^{\frac{n}{1-n}} \qquad \eta = \frac{1}{2\dot{\varepsilon}}\left\{\frac{(1-n)Y_K}{\gamma^n \eta_S^*} t + \gamma^{1-n}\left[\eta_S^*\left(\dot{\varepsilon} - \dot{\varepsilon}_S\right)\right]^{\frac{1-n}{n}}\right\}^{\frac{1}{1-n}}$$





Calibration of rheological parameters: The post-rift stage

Linear anelastic relaxation test:

$$\dot{\varepsilon}(t) = -(\varepsilon_0 / \tau) e^{-t/\tau}$$

Non-linear anelastic relaxation test:

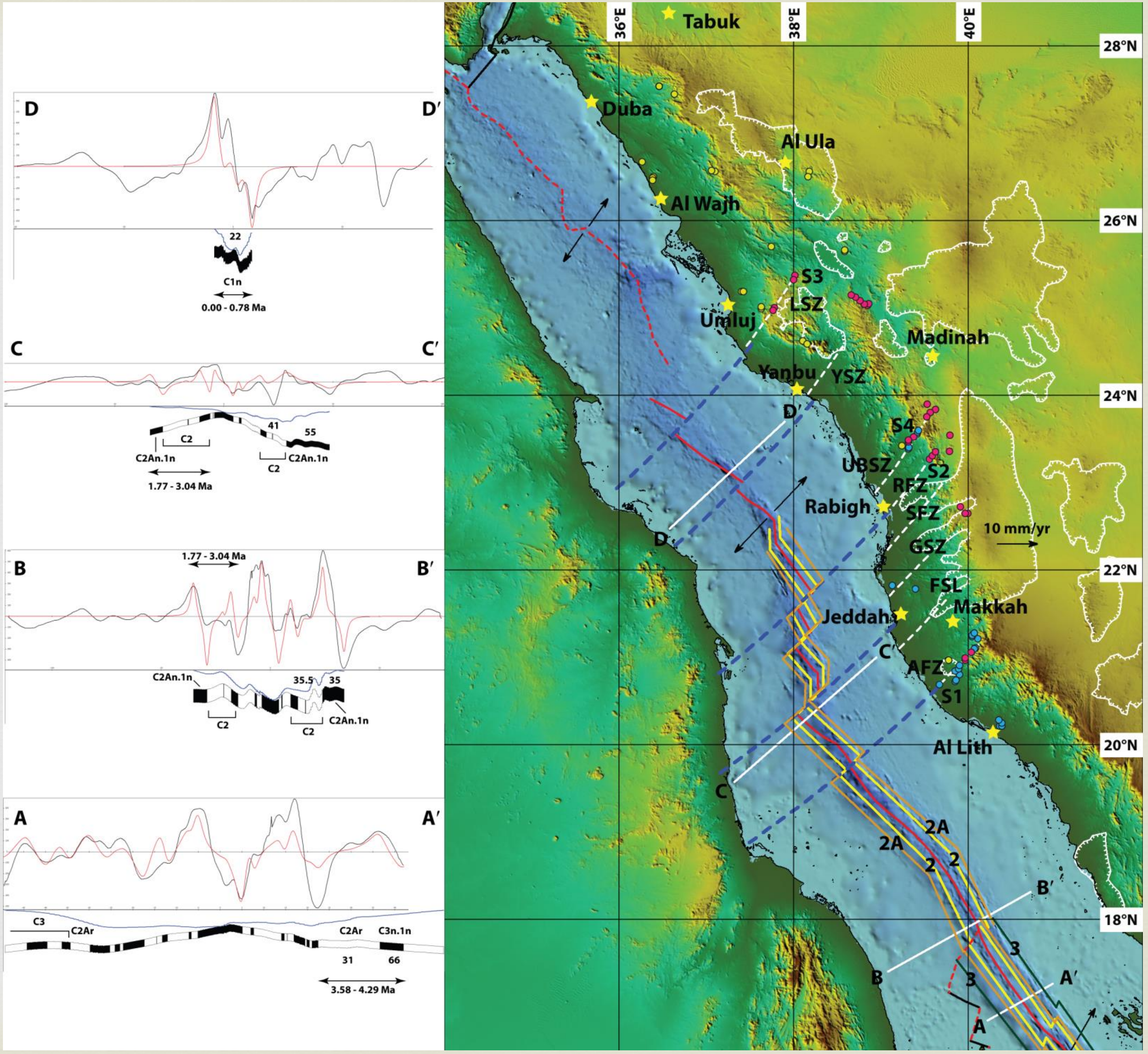
$$\dot{\varepsilon}(t) = -\frac{1}{\eta_T^*}\left[Y_K \varepsilon(t)\right]^n$$

$n \neq 1$, odd integer

$\Downarrow$

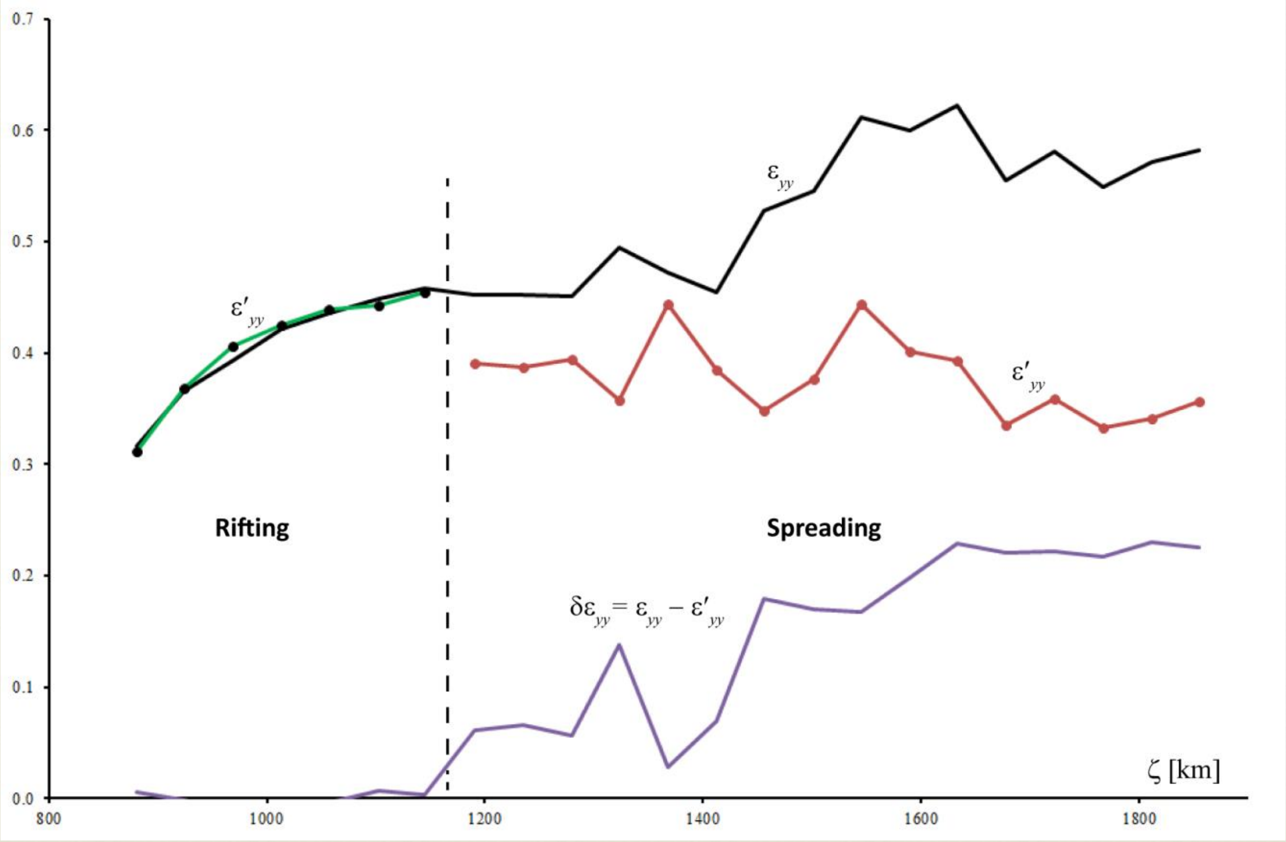
Dry rheology ; $\gamma = 0.1$
is in agreement with
geophysical/geological observation

The study area



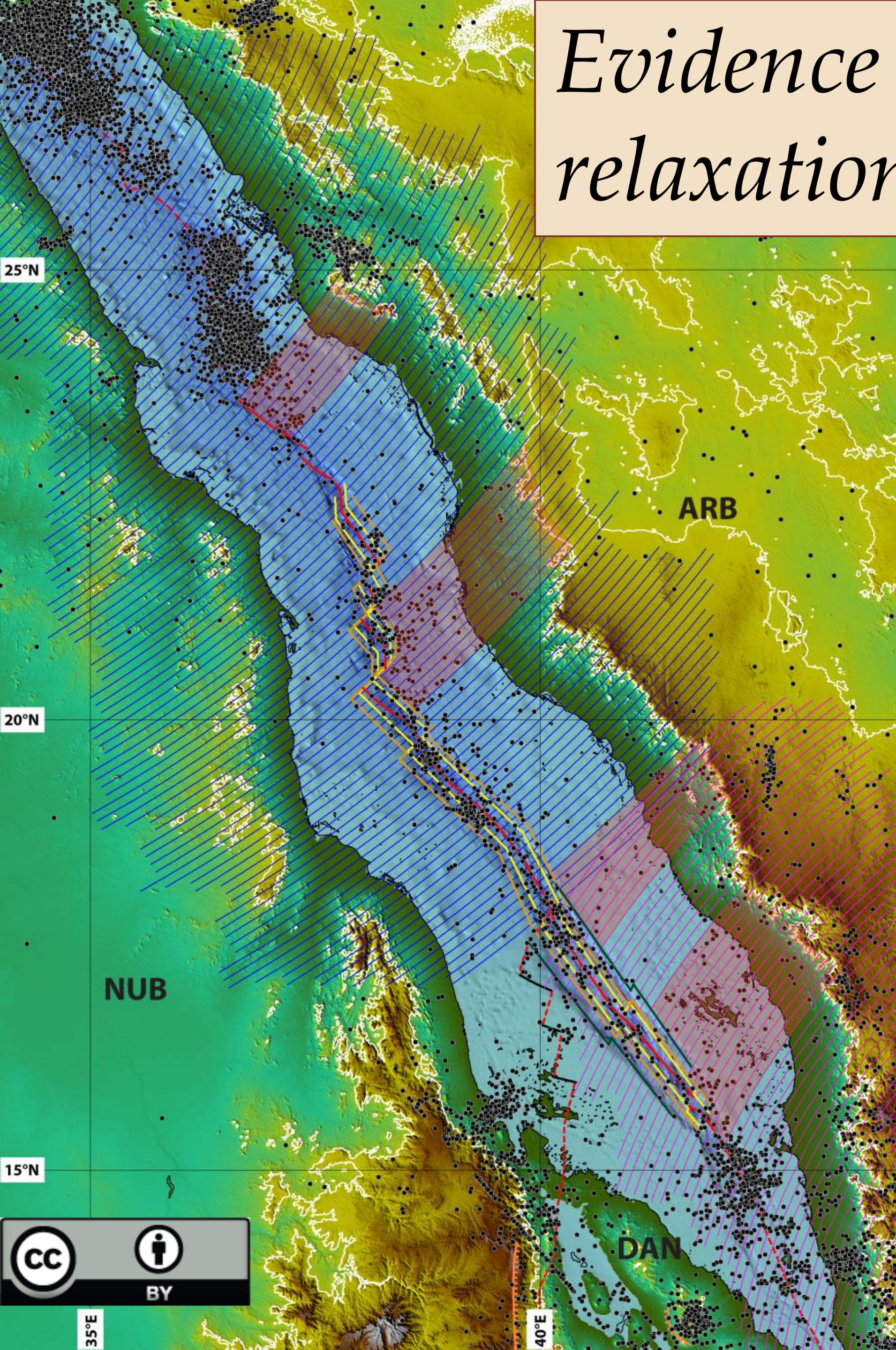
Evidence of post-rift anelastic relaxation: 1 – Finite strains around the Red Sea

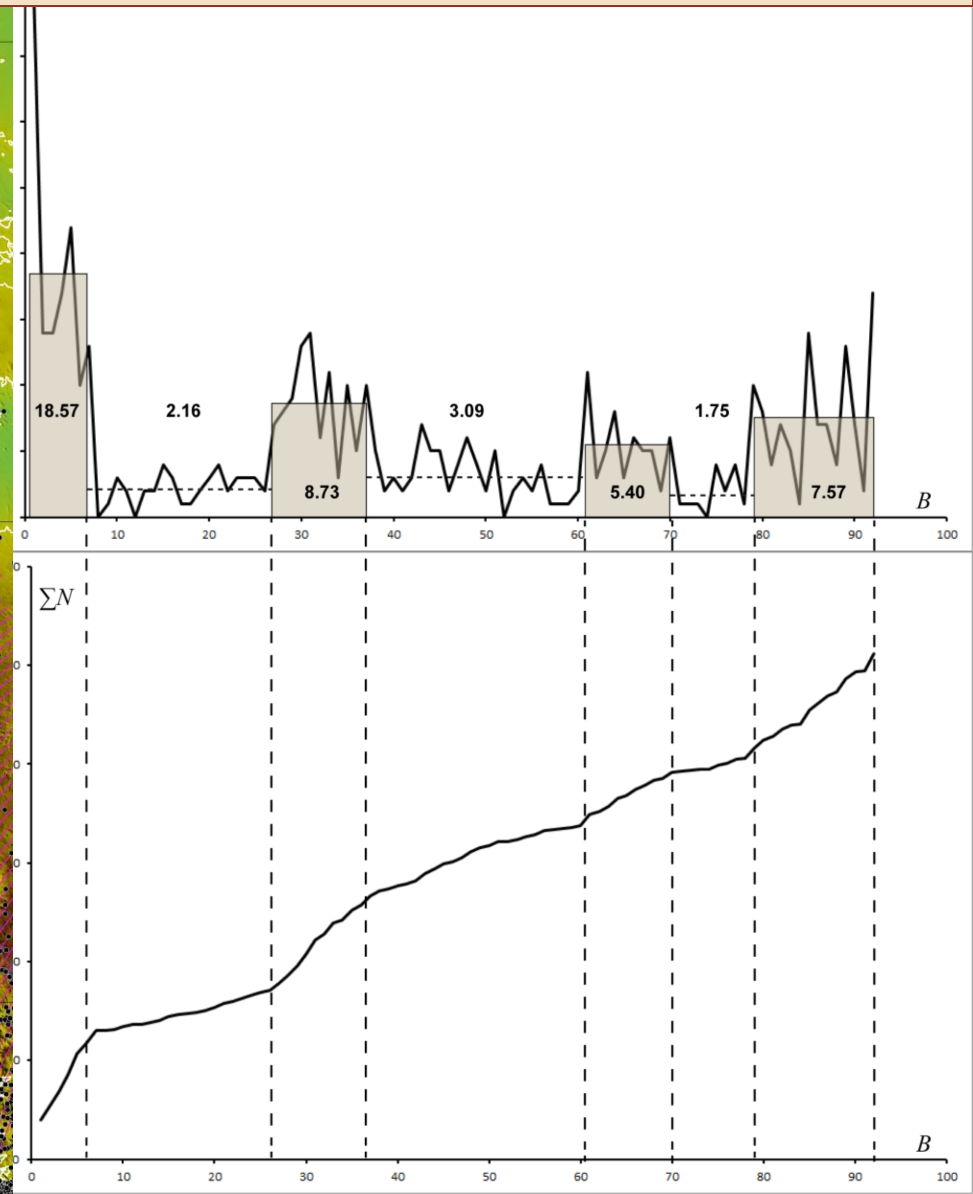
$$\varepsilon_{yy}(\zeta,t)=\ln\left[1-\frac{\omega_0 R\sin(\zeta/R)}{L_0}(t-t_0)\right]$$



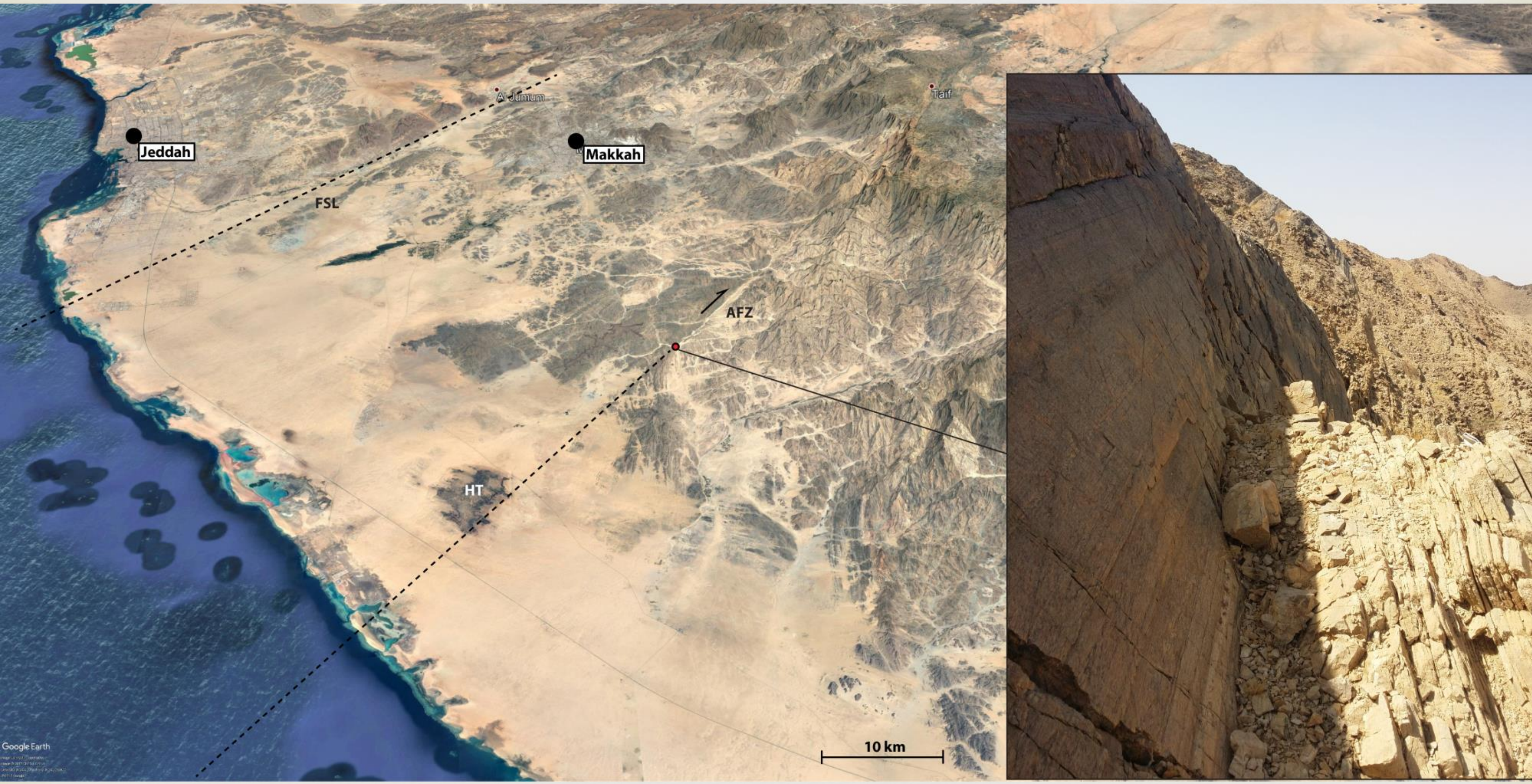
- ✓ Black line: Kinematic strain as a function of the distance ζ from the Euler pole of relative motion between Nubia and Arabia;
- ✓ Red line: Finite transversal strain, obtained from observed β factors, along the passive continental margins facing the oceanized region of the Red Sea;
- ✓ Green line: 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

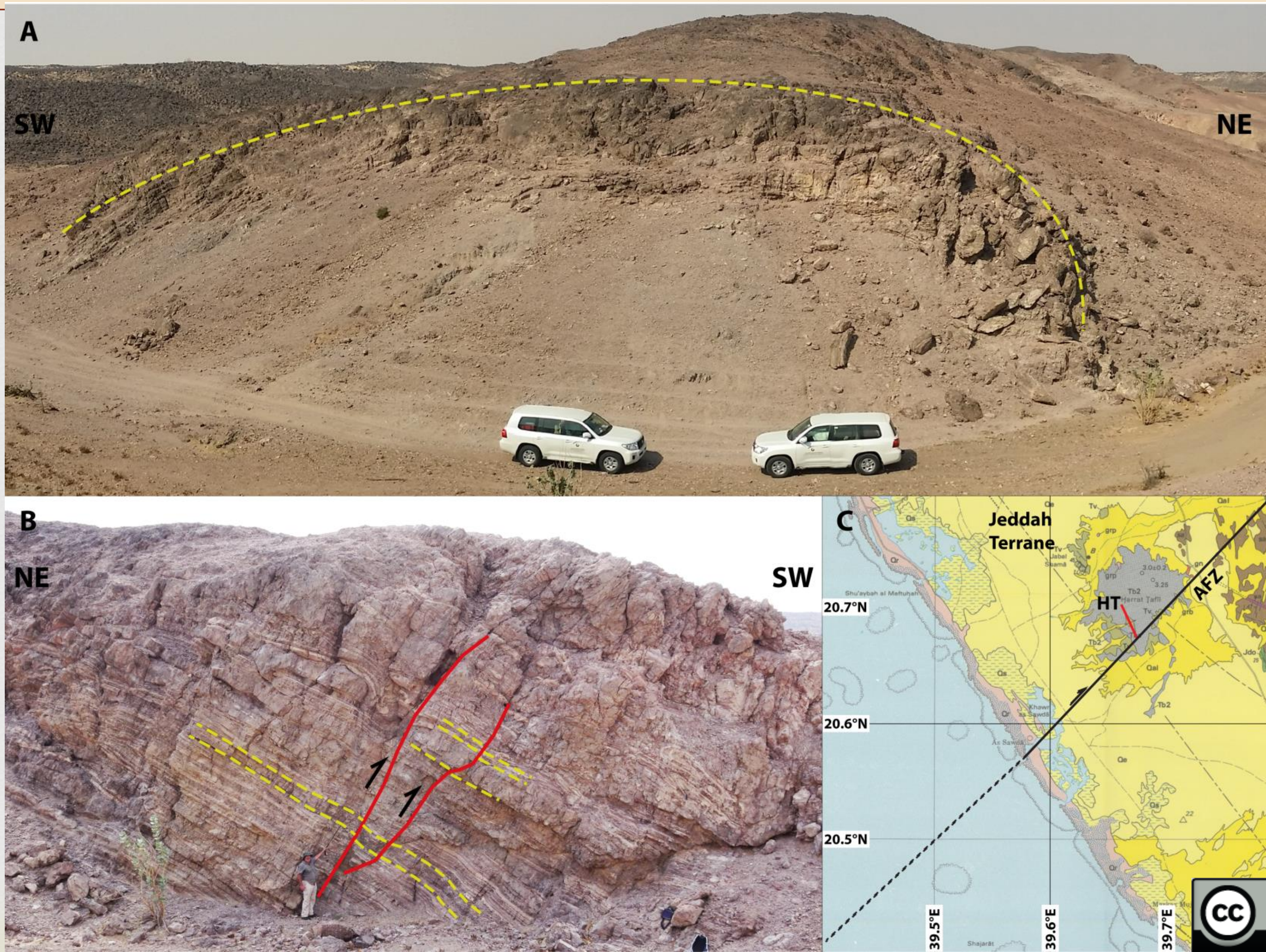




Evidence of post-rift anelastic relaxation: 3 – Geology (Strike-slip faults)



Evidence of post-rift anelastic relaxation: 3 – Geology (Reverse faults and folds)



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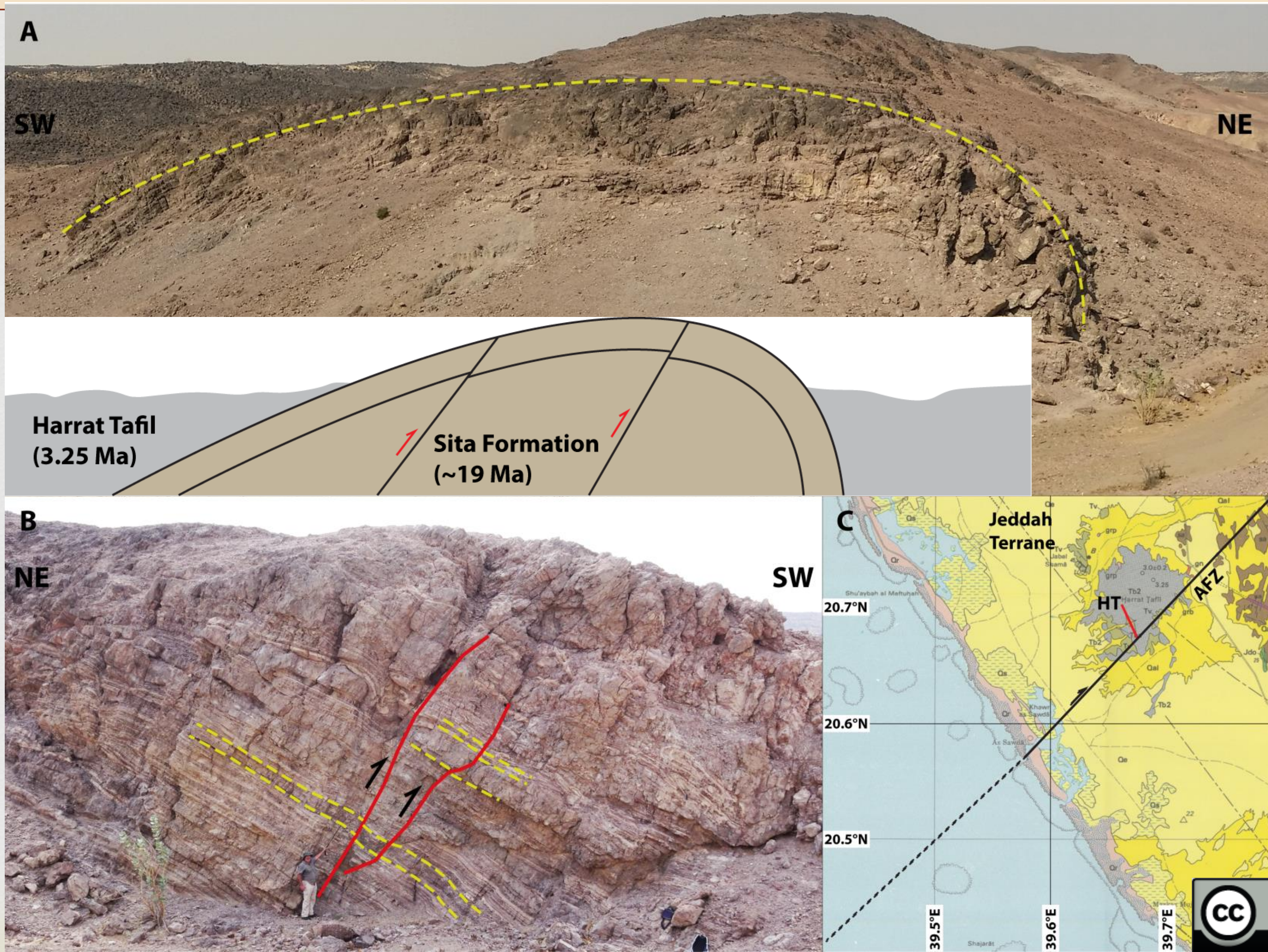

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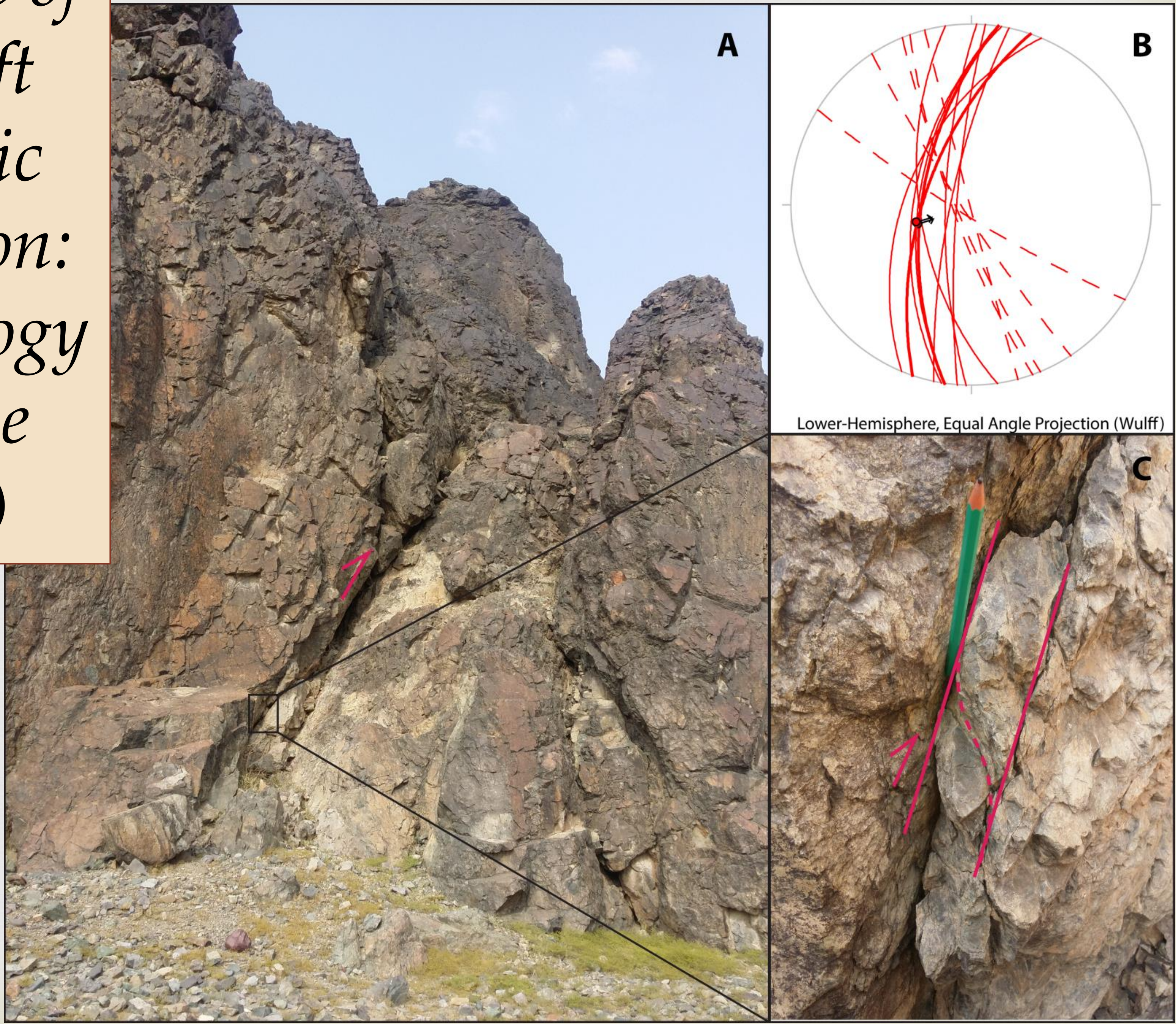
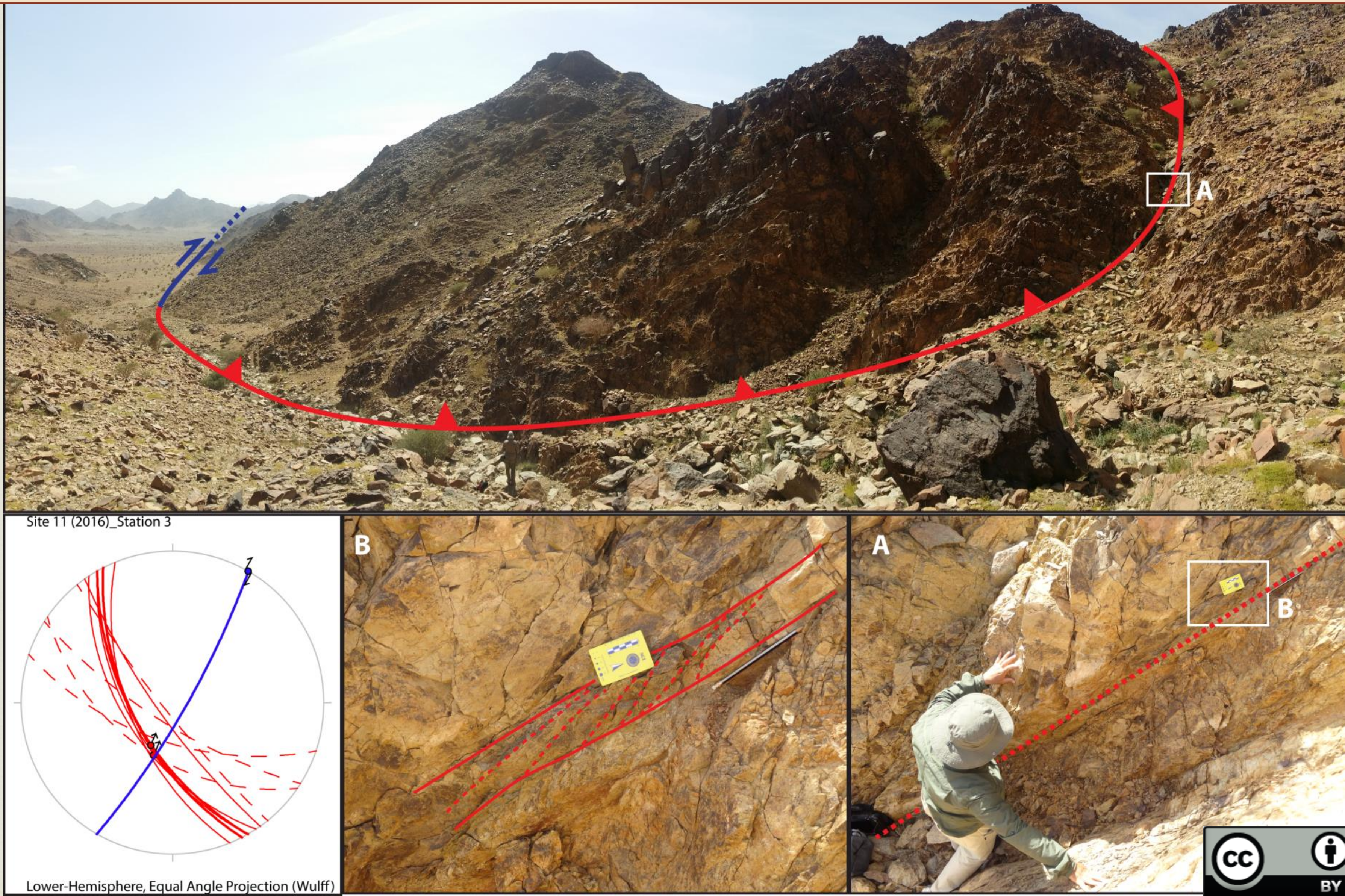


Evidence of post-rift anelastic relaxation: 3 – Geology (Strike-slip & reverse faults)



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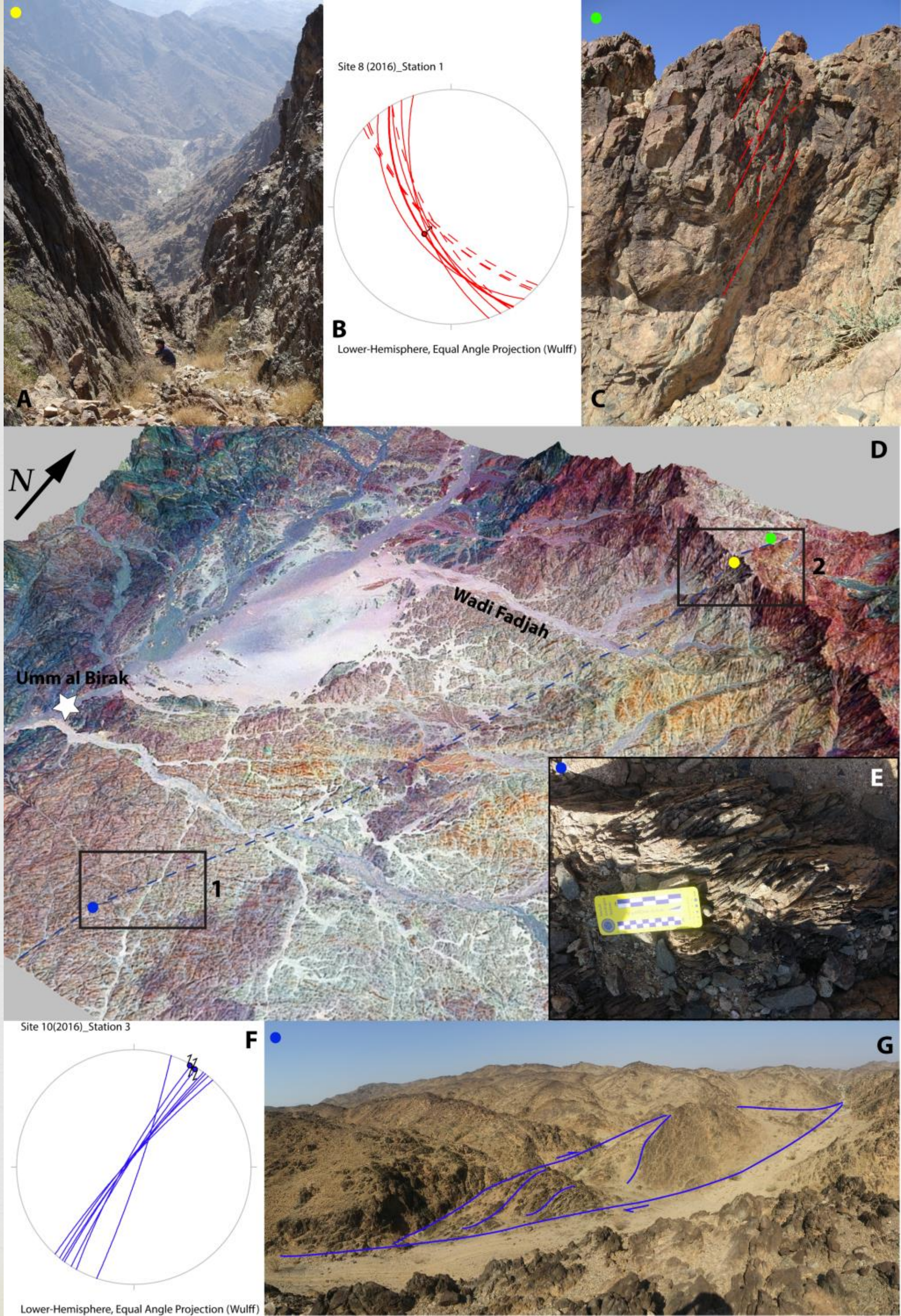
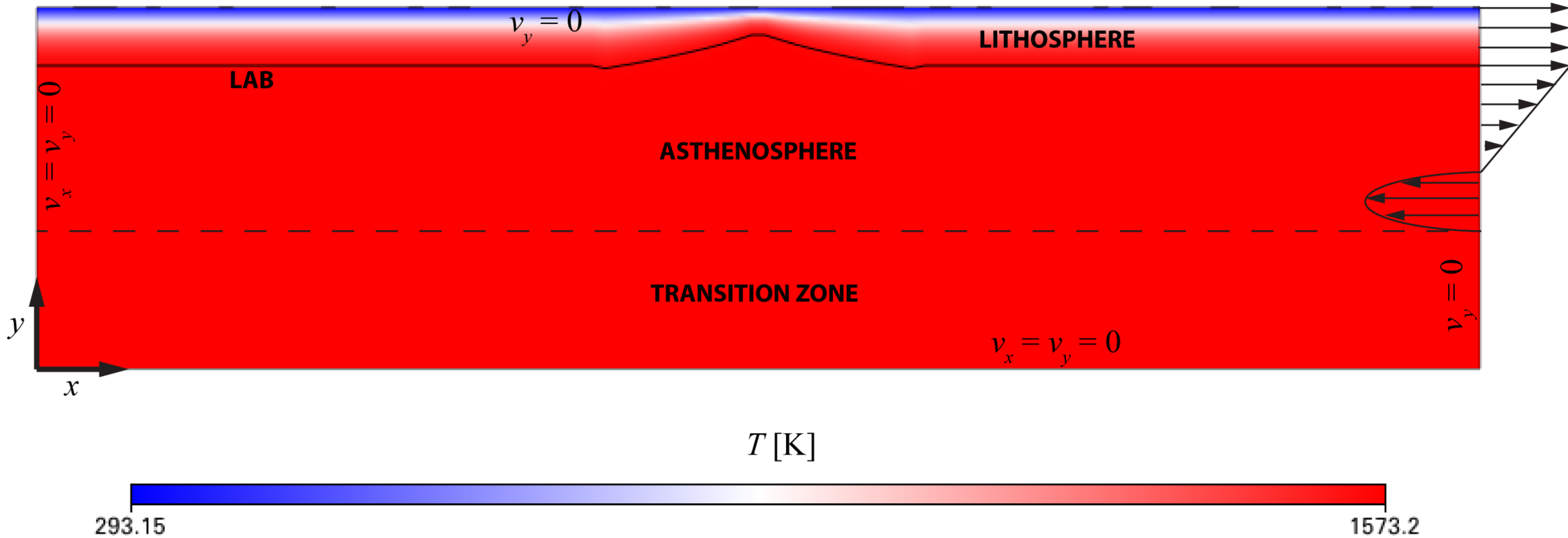


Numerical Experiment: Rifting Stage Model



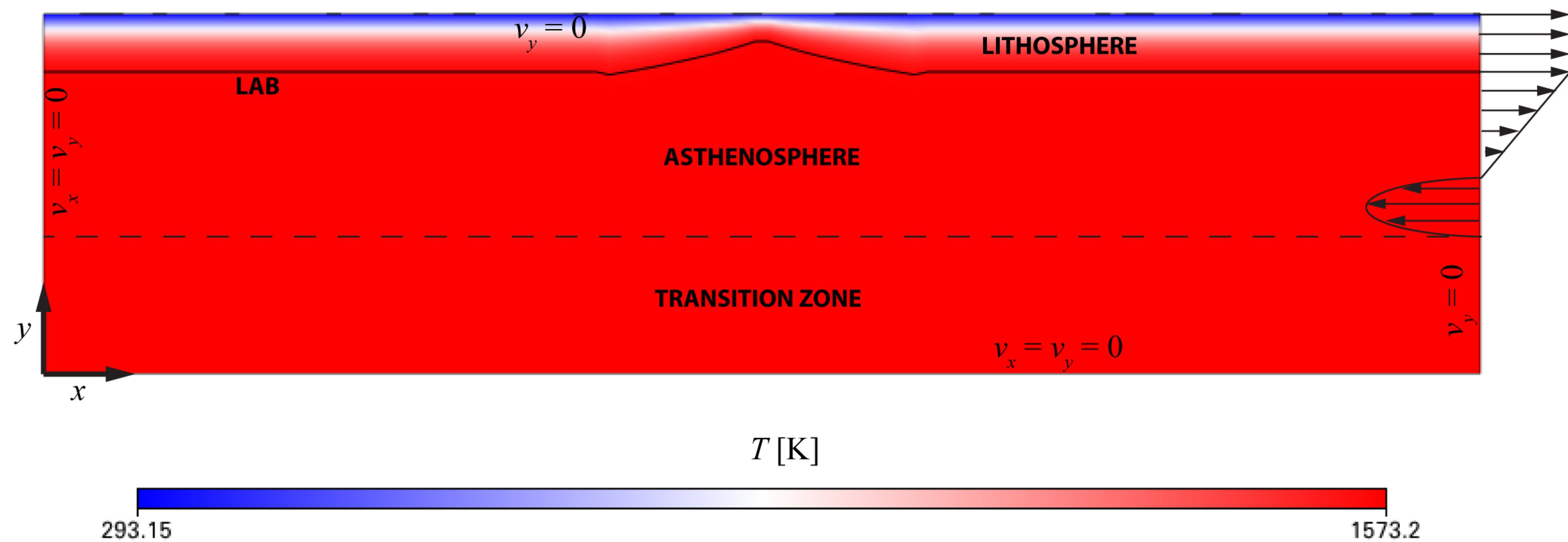
Mass conservation: $\Phi = \oint_{\mathbf{D}} \rho \boldsymbol{v} \cdot d\boldsymbol{S} = 0$

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

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

Equation of state: $\rho = \rho_0\left[1 - \alpha\left(T - T_0\right)\right]$

Numerical Experiment: Rifting Stage Model

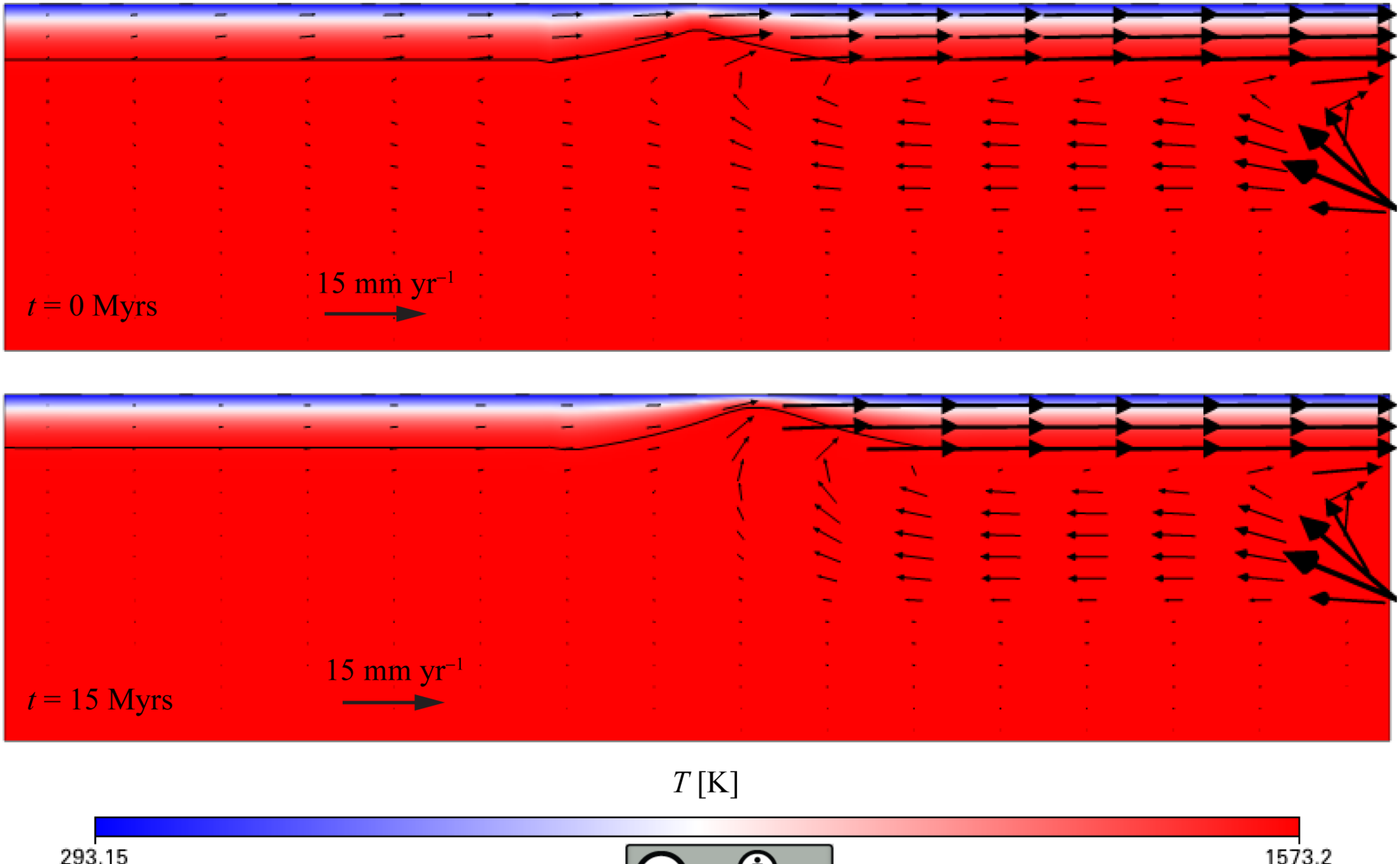


Lithosphere mantle: $\eta = \frac{1}{2\dot{\varepsilon}}\left\{\frac{(1-n)Y_K}{\gamma^n \eta_S^*}t + \gamma^{1-n}\left[\eta_S^*\left(\dot{\varepsilon}-\dot{\varepsilon}_S\right)\right]^{\frac{1-n}{n}}\right\}^{\frac{1}{1-n}}$; $n=3$

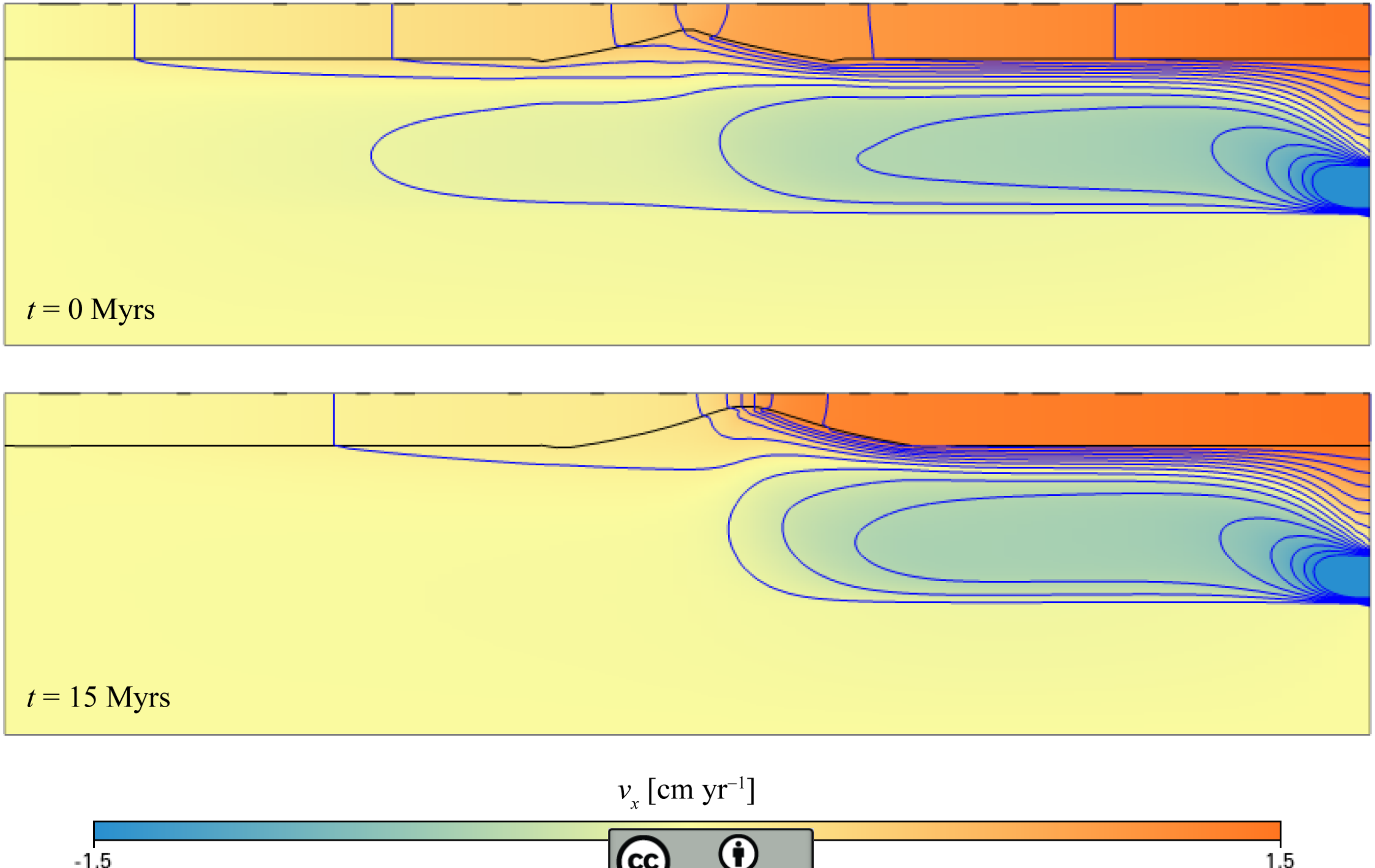
Asthenosphere: $\eta = A^{-1/n} exp\left(H/nRT\right)\dot{\varepsilon}^{\frac{1-n}{n}}$; $n=3.5$

Transition zone: $\eta = 10^{23}$ Pa s

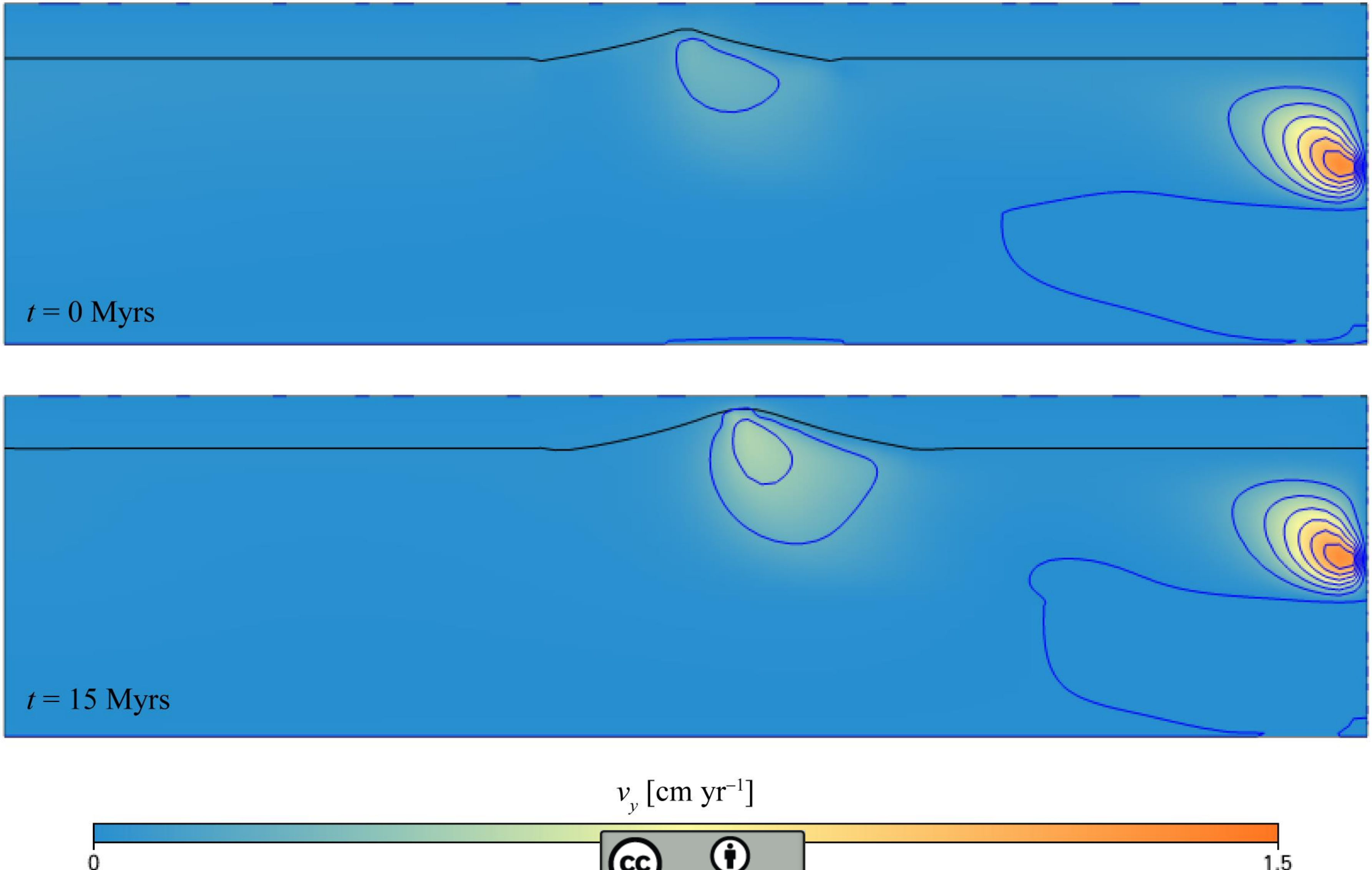
Numerical Modelling: Velocity Field



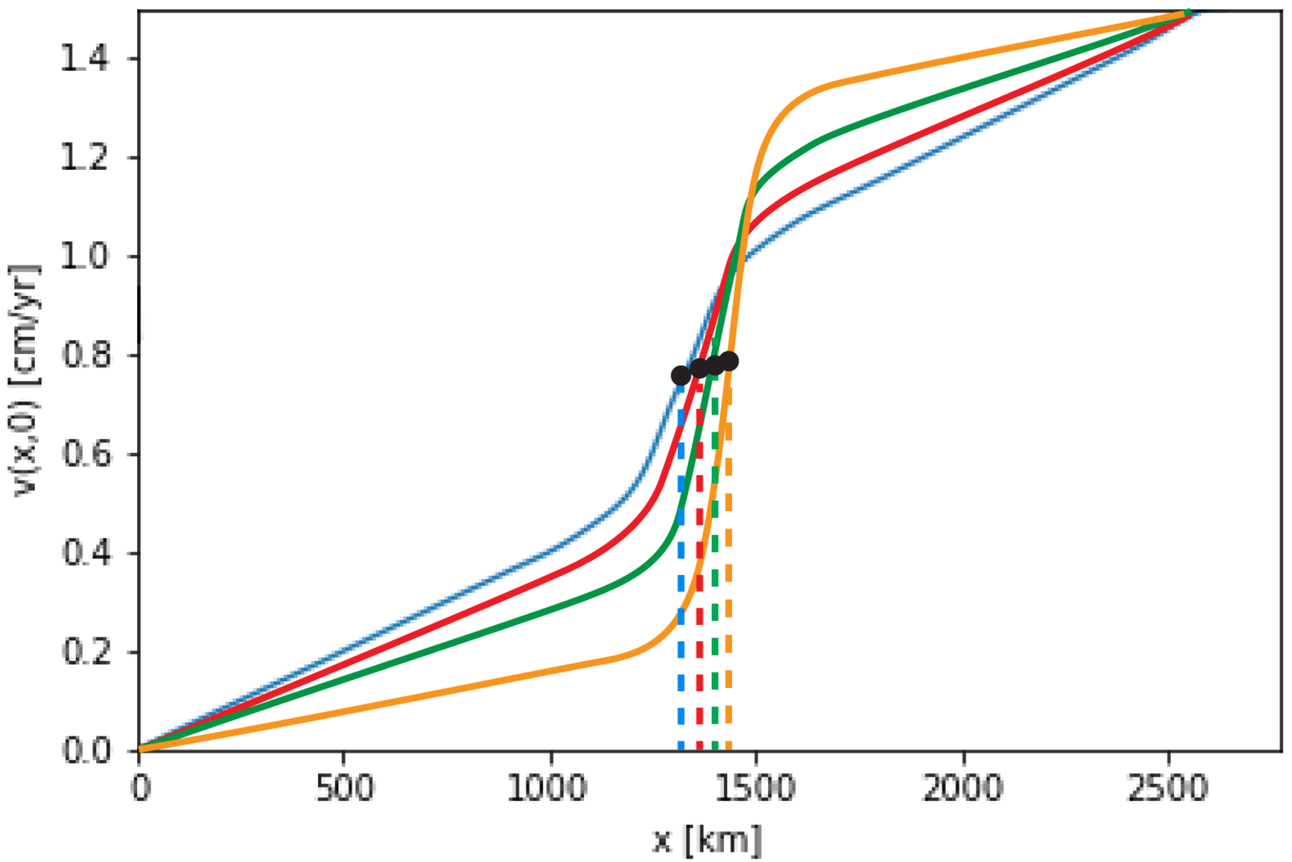
Numerical Modelling: Velocity Field $- v_x$



Numerical Modelling: Velocity Field $-v_y$



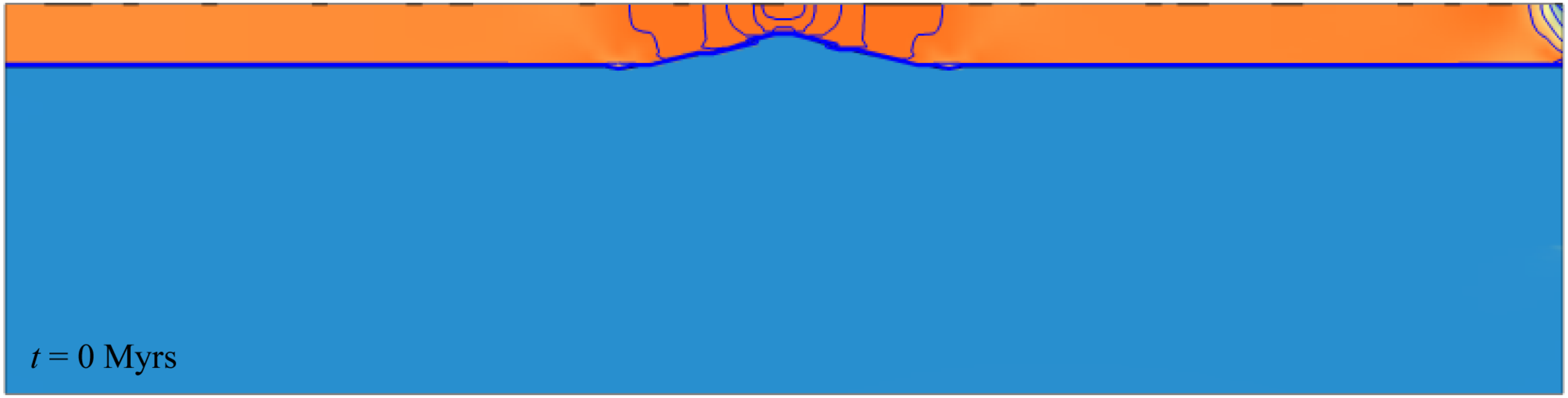
Numerical Modelling: Velocity Field – $v(x,0)$

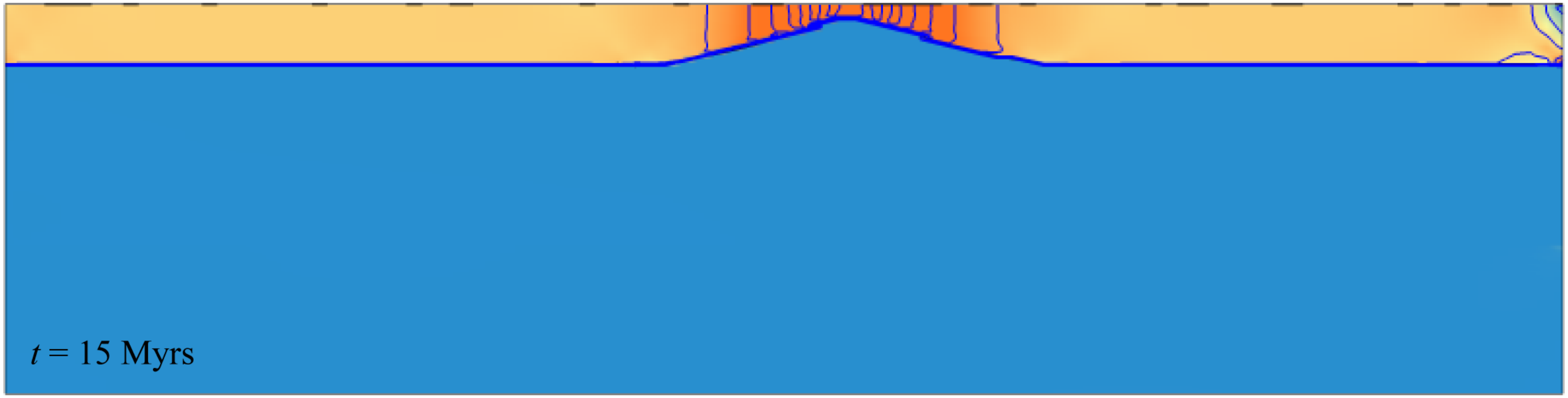


Blue = 0 Myrs;
Red = 5 Myrs;
Green = 10 Myrs;
Orange = 15 Myrs.

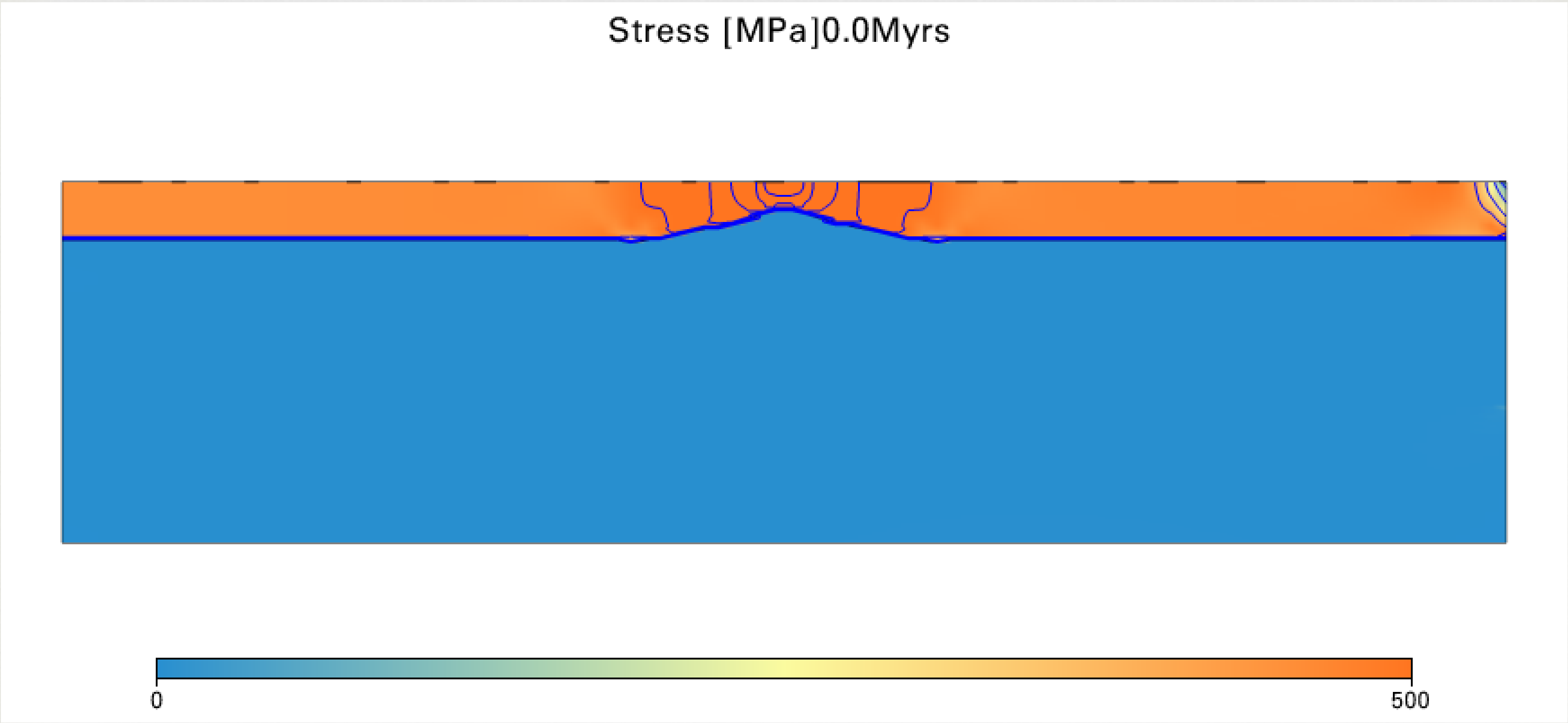
Offset of the rift axis at t = 0, 5, 10, 15 Myr (dashed lines).

Numerical Modelling: Stress 2nd Invariant





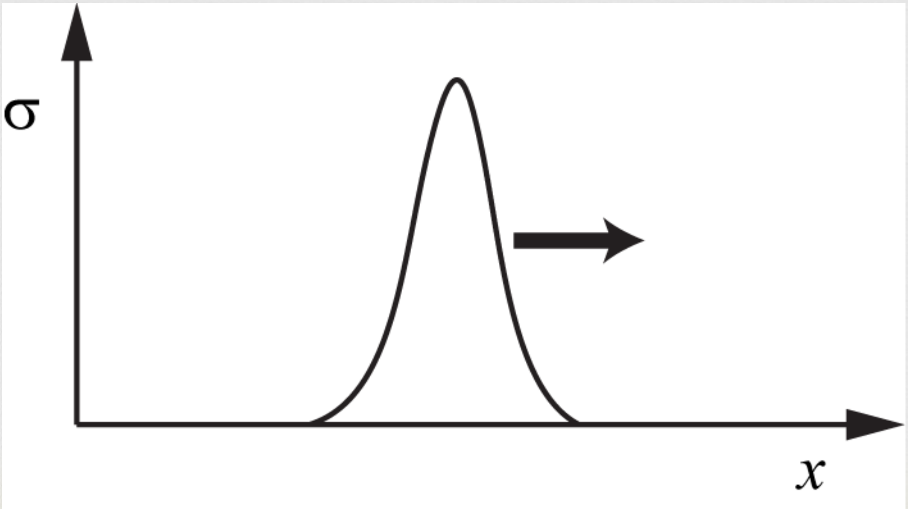
Numerical Modelling: Stress



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