Modelling thermal lithospheric thickness along the conjugate South Atlantic passive margins implies asymmetric rift initation

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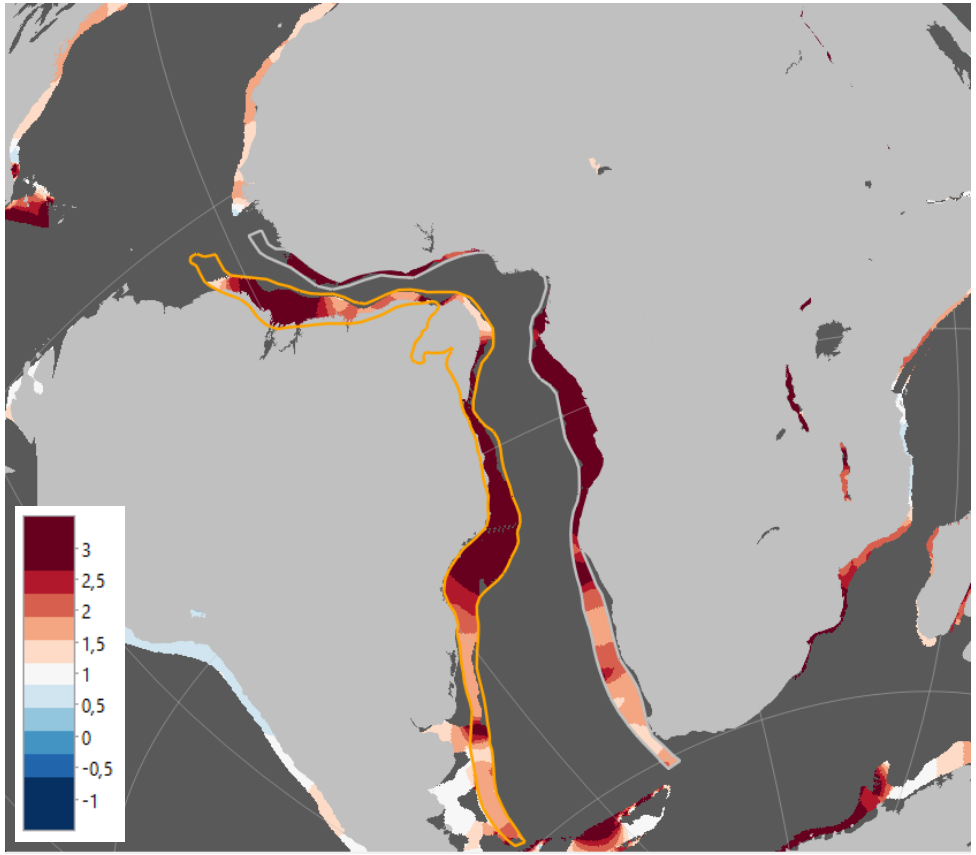
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TS6.1 - Continental Rift Evolution: from inception to break-up, with special attention to the The Afro-Arabian rifting system

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Introduction



Stretching factors for the South Atlantic passive margins of the Müller et al. 2019 model, rotated back to 105 Ma. They represent the length of deformation that occurs and determine the amount of lithosphere that can be thinned during an extensional period.

- Opening of the South Atlantic involved several tectonic processes that are manifested in heterogeneous architecture of passive margins:
  - Volcanic and non-volcanic passive margins
  - Asymmetry of opposed margin pairs
- All rifting models have in common that an initial lithospheric thickness is thinned and stretched prior to rifting
  - Amount of lithospheric thinning is often unknown

✓ We develop a thermal lithospheric thickness model along the South Atlantic passive margins accounting for across-margin gradients of crustal thickness and stretching

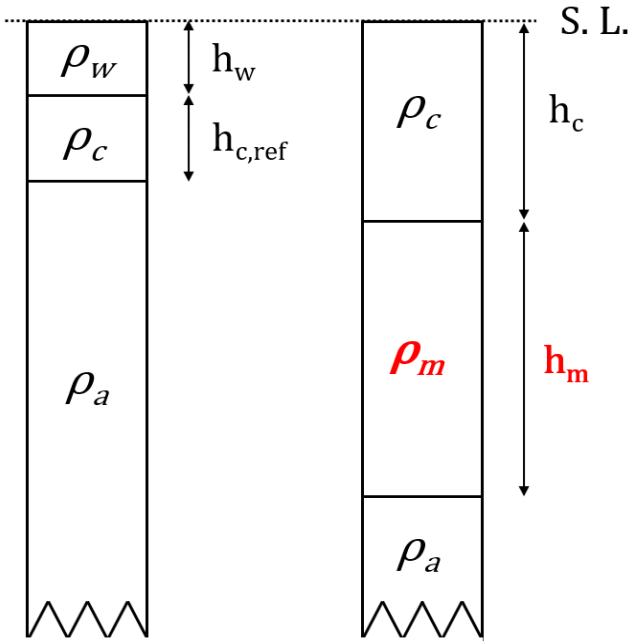
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Initial lithosphere-asthenosphere boundary ($z_{LAB,init}$)

- Defined by isostatic balance of passive margin against Mid Ocean Ridge (MOR)
- Defined for each grid point by variable crustal thickness
- Mantle density iteratively updated

Variable	Name	Value
ρ_w	Density of sea water	1.03 g/cm³
ρ_c	Density of crust	2.809 g/cm³ [1]
ρ_m	Density of lithospheric mantle	Unknown
ρ_a	Density of asthenosphere	3.3 g/cm³ [3]
h_w	Height of sea water	2.5 km [2]
$h_{c,ref}$	Thickness of crust at MOR	7 km [2]
h_c	Thickness of crust	Variable [1]
h_m	Thickness of lithospheric mantle	Unknown

[1]Thickness and density of the crust are taken from Finger et al. 2021.
[2]Thicknesses of MOR reference column are taken from Afonso et al. 2019.
[3]Density of asthenosphere taken from Zoback and Mooney 2010.



Isostatic balance of MOR (left) and passive margin (right). Mantle density and thickness of mantle lithosphere (highlighted in red) are the unknown parameters. Full names of the parameters are given in Table 1.

$$h_m = \frac{\rho_w h_w + \rho_c (h_{c0} - h_c) + \rho_a (h_c - h_w - h_{c,ref})}{(\rho_m - \rho_a)}$$

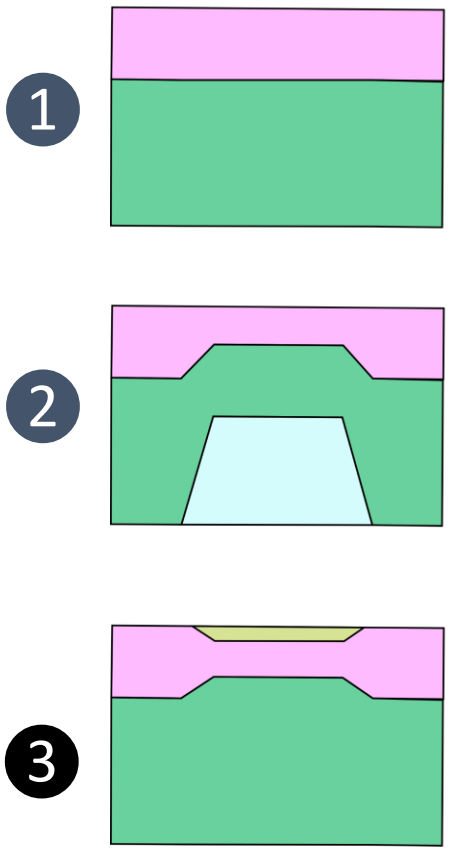
$$z_{LAB,init} = h_c + h_m$$

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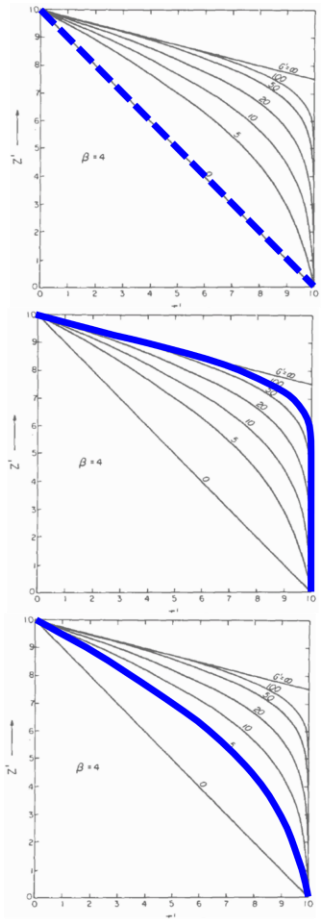
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Stretching the lithosphere

Earth model



Temperature vs. Depth



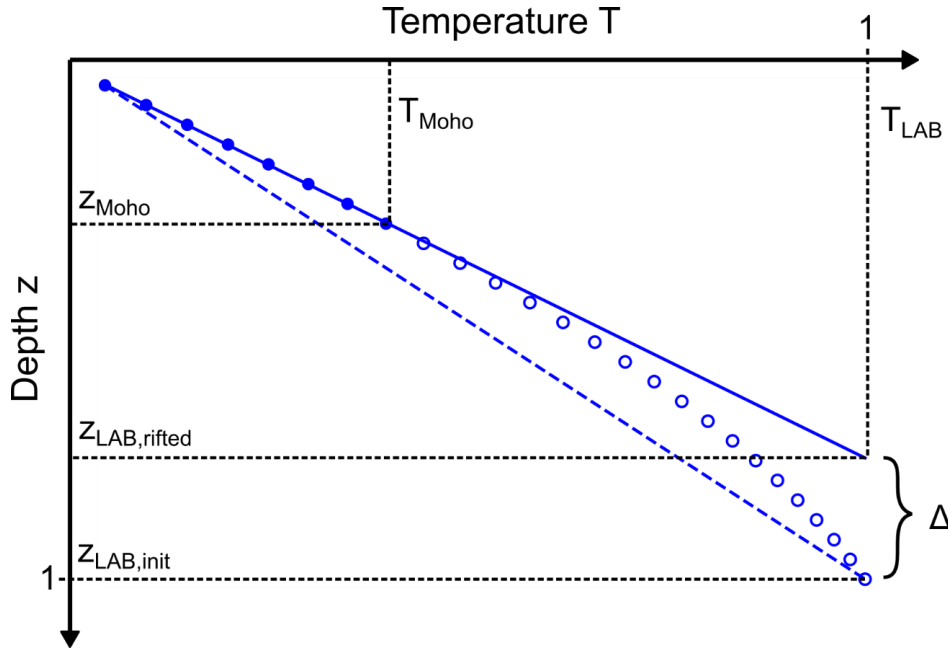
Unthinned lithosphere, linear geotherm

Thinned lithosphere, uplifted geotherm, non-linear displacement

Cooling lithosphere, geotherm relaxes, but still contains non-linear component

Pink: Crust, Green: Mantle Lithosphere, Light blue: Asthenosphere, yellow: Sediments. Adapted from McKenzie 1978 and Jarvis & McKenzie 1980.

LAB after rifting ($z_{LAB,rifted}$)



Dashed line: Initial geotherm before rifting, circles: uplifted geotherm after rifting and cooling, solid blue line: extrapolated linear geotherm based on thermal structure of crust (filled circles). The depth at which the extrapolated geotherm reaches T_{LAB} provides an approximate estimate of z_{LAB}.

- ✓ $z_{LAB,rifted}$ is thermal LAB based on 1D advection and diffusion

Amount of non-linearity in geotherm based on:

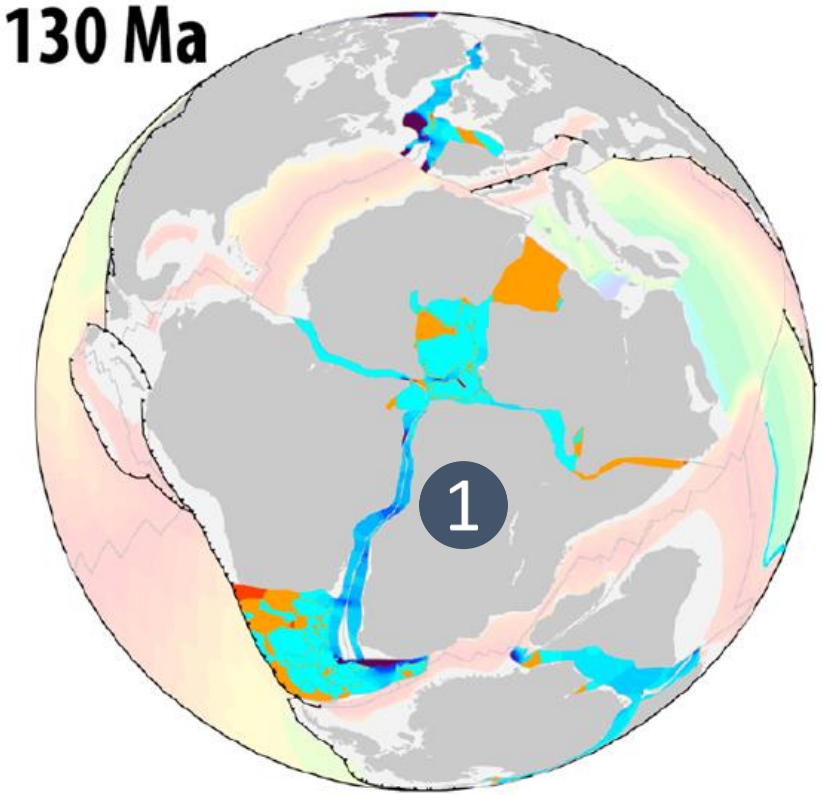
- ✓ Initiation and end of rifting
- ✓ Crustal thickness
- ✓ Stretching factor

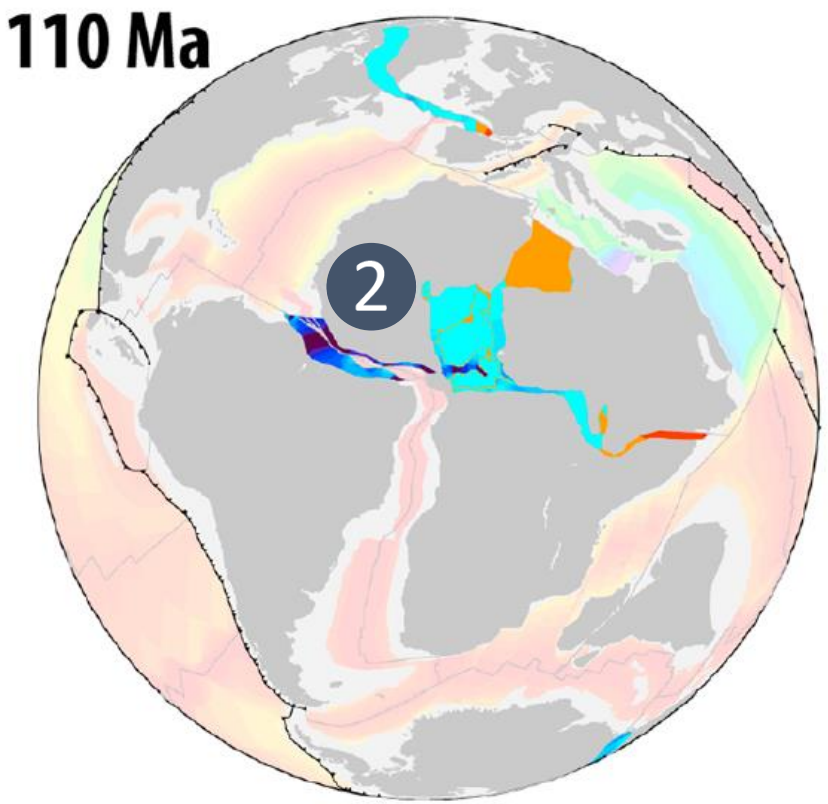
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Initiation and end of rifting in the South Atlantic

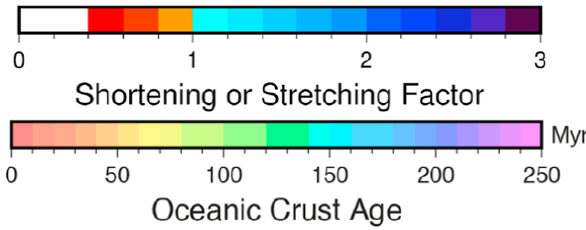




1 *Opening of the southern segment between 141-120 Ma*

2 *Opening of the equatorial segment between 121-107 Ma*

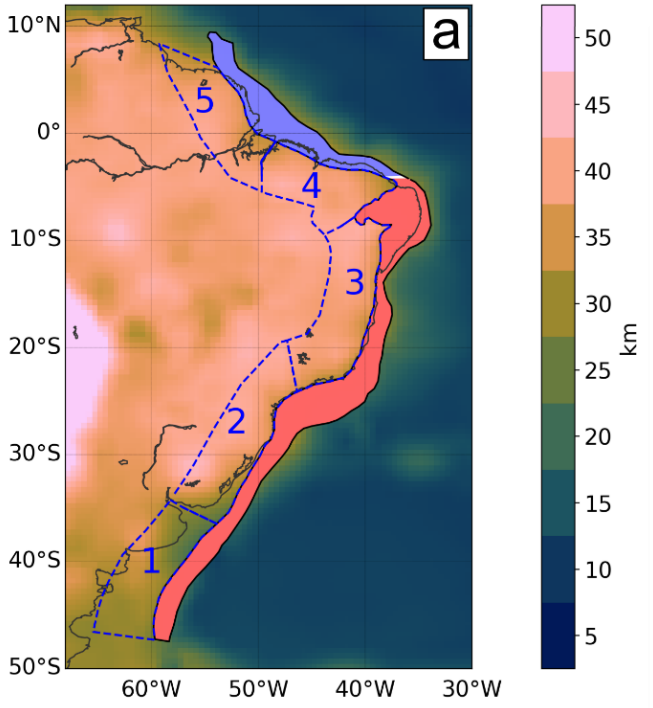
The two rifting stages define start and end time of lithospheric thinnning



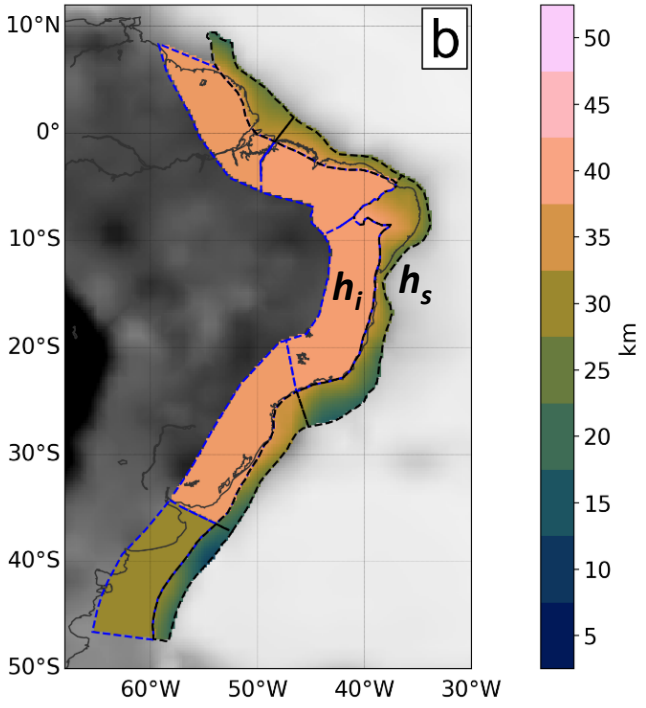
Figures taken from Müller et al 2019

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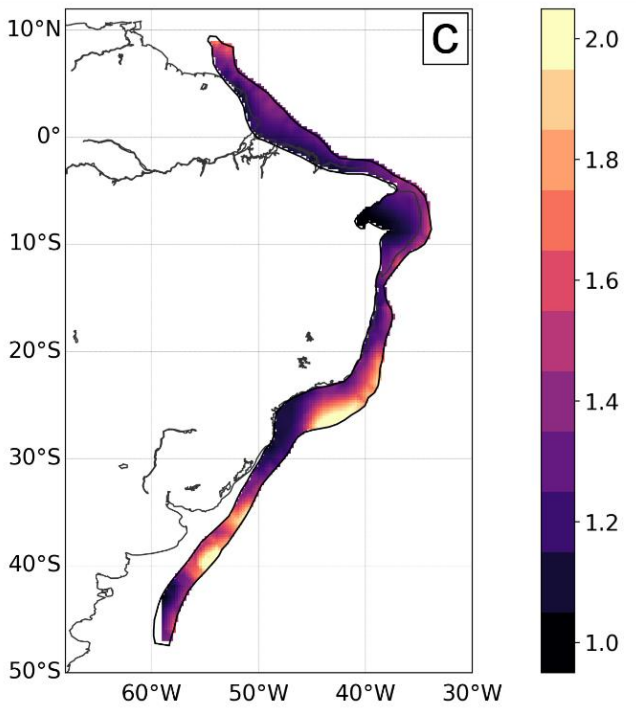
Crustal thickness and stretching factor



Crustal thickness model of Finger et al. 2021. Masked area: Geometry of the South American passive margin. The coral polygon corresponds to the early opening of the South Atlantic, the blue polygon to the later stage.



Crustal thickness values for deformable region h_s and inner extension area h_i. Values for inner area are averaged (see Table)



Stretching factors of deforming region of passive margin ($ß=h_i/h_s$)

Rifting time, crustal thickness and stretching factor are used to calculate $z_{LAB,rifted}$ for each grid point of the passive margin

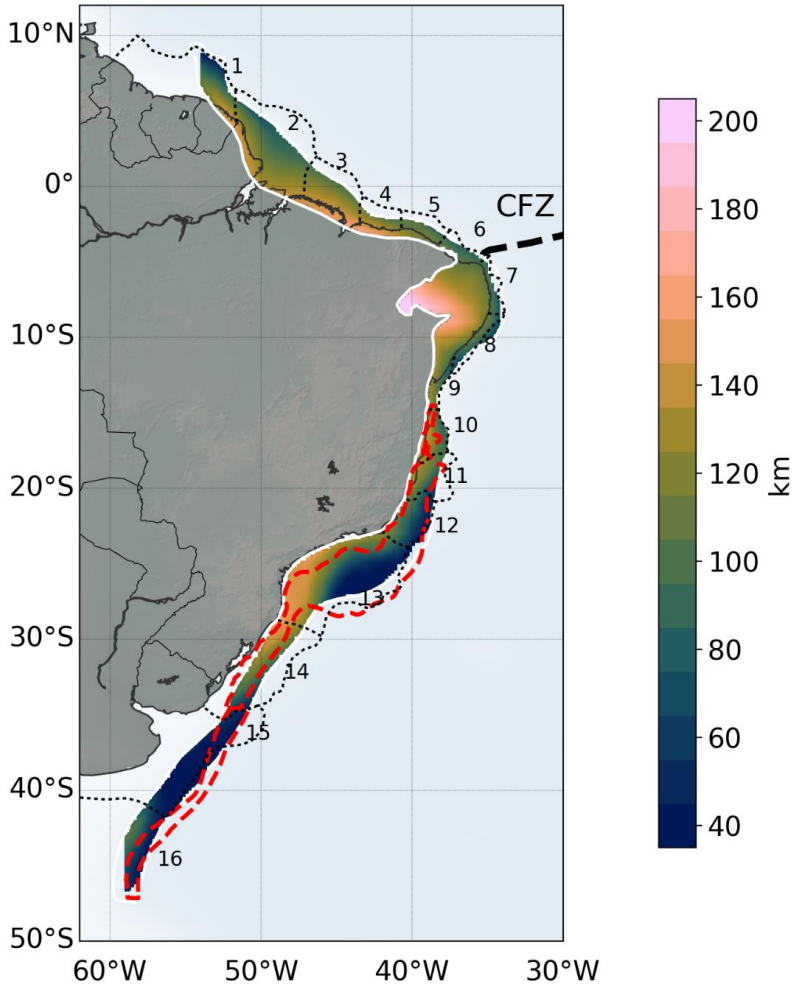
Segment	Geology	Crustal Thickness [km]
1	Colorado Basin (offshore)	29,9
2	Parana Basin	38,2
3	Sao Francisco	38,8
4	Amazonia South	38,6
5	Amazonia North	37,5

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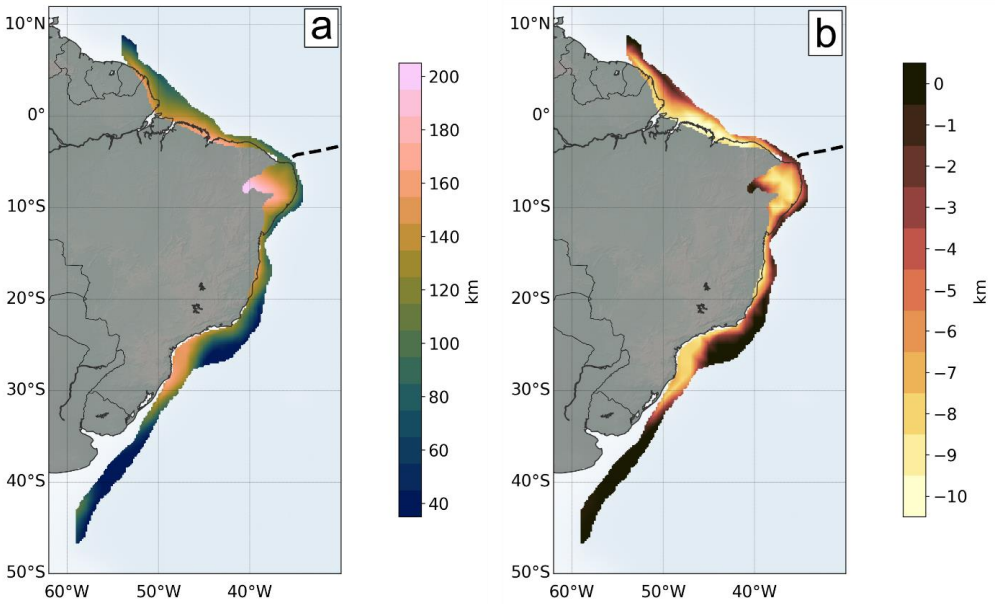
Modelled LAB after rifting for the South American passive margin



Sedimentary Basins:

1: Guyana
2: Foz do Amazonas-Marajo
3: Para-Maranhao
4: Barreirinhas
5: Ceara
6: Potiguar
7: Pernambuco-Parnaiba
8: Sergipe-Alagoas
9: Bahia Norte
10: Bahia Sul
11: Espirito Santo
12: Campos
13: Santos
14: Pelotas
15: Punta del Este
16: Colorado

- $z_{LAB,rifted}$ varies between 50-200 km
- Deeper LAB in equatorial segment than in southern segment
- High across-margin gradients of LAB depth for individual basins



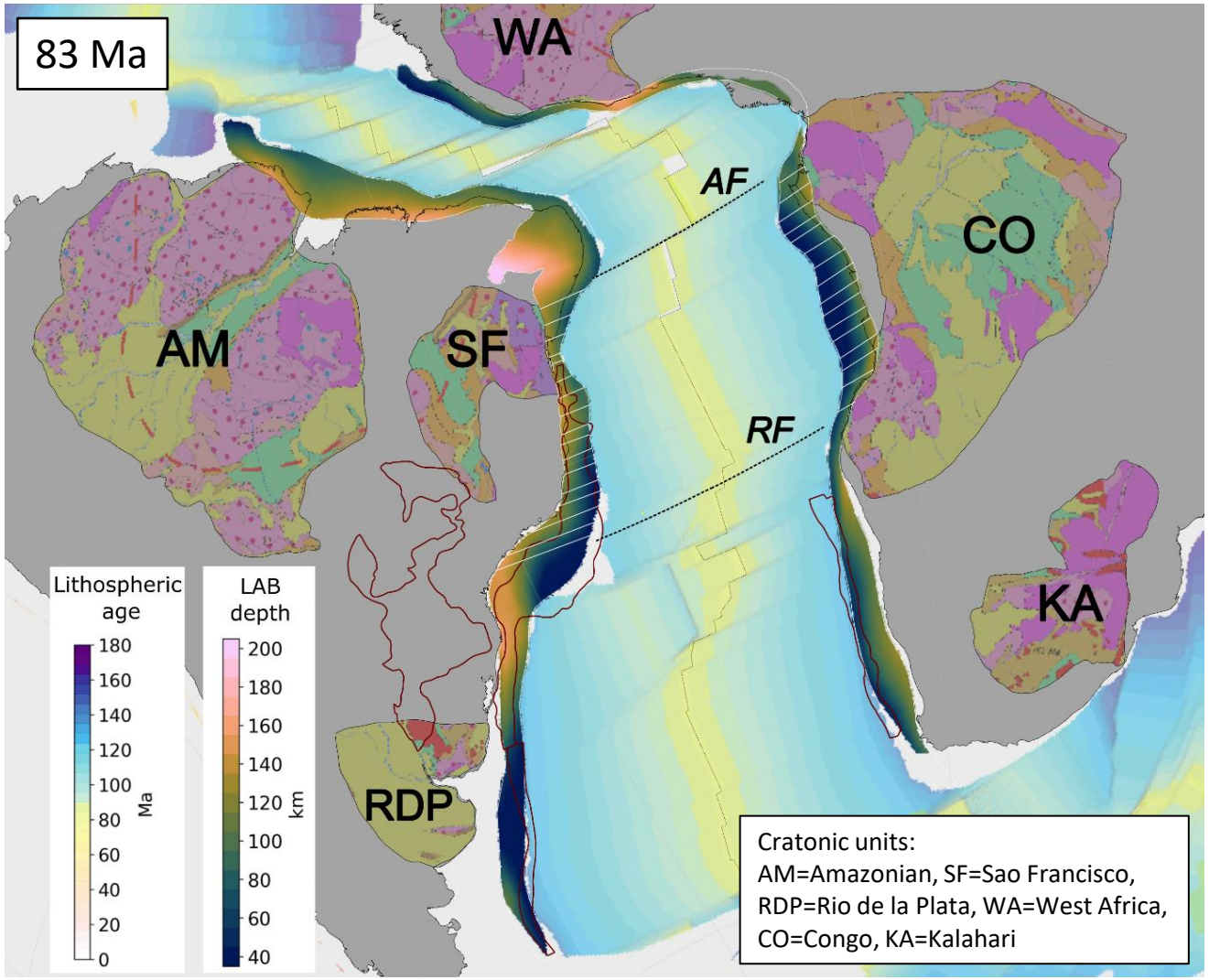
Thick dashed black line indicates Chain Fracture Zone (CFZ). Thick dashed red polygon marks the extension of Large Igneous Provinces (LIPs) offshore South America (Johansson et al. 2018). Numbers indicate offshore sedimentary basin locations (Wen et al. 2019).

a) $z_{LAB,init}$, b) Difference between $z_{LAB,init}$ and $z_{LAB,rifted}$

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Modelled LAB after rifting for conjugate margins



- Same workflow applied to African passive margin
- Deeper LAB in southern segment than in equatorial segment maintained
- LAB depth correlates with margin width

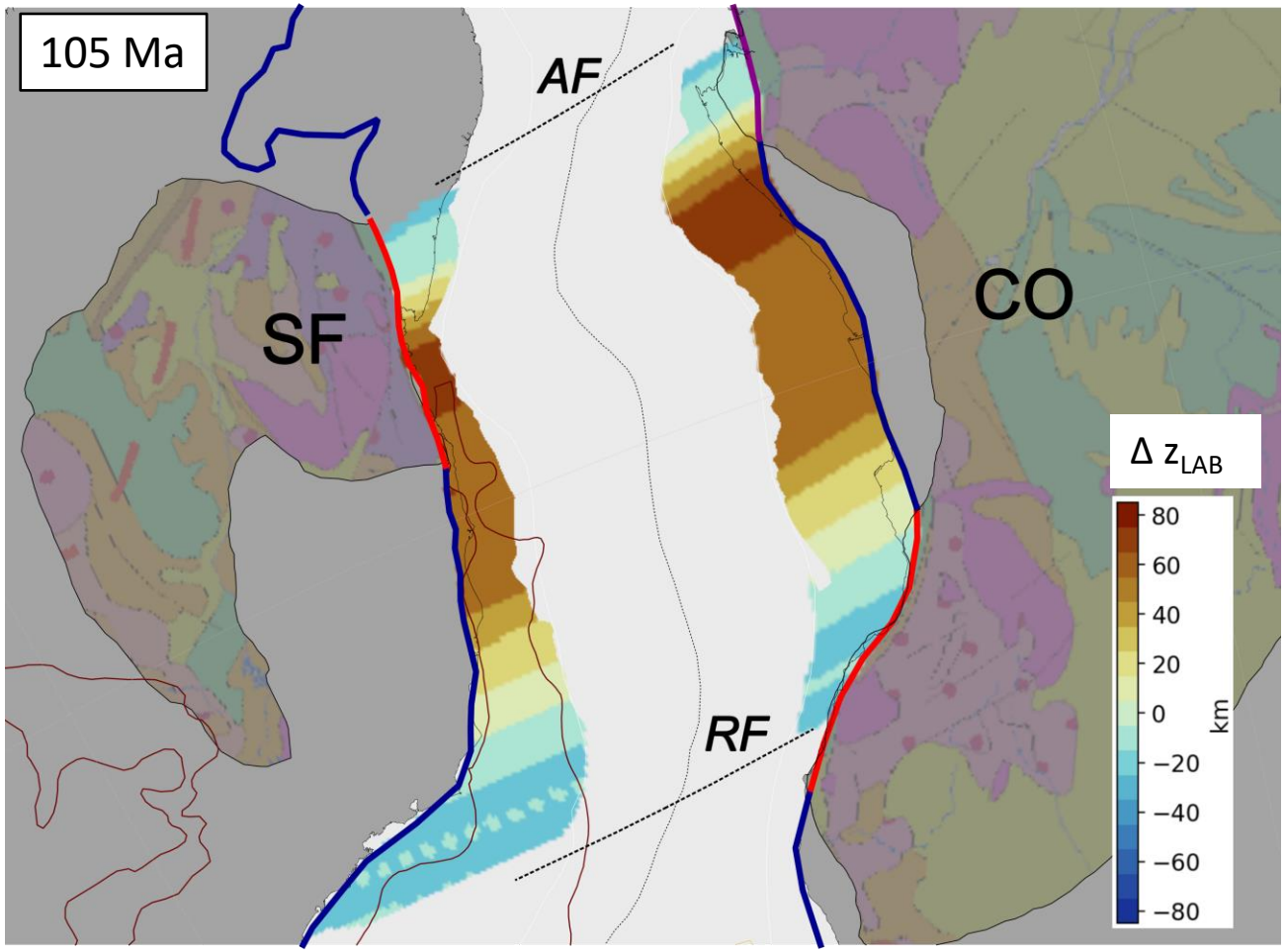
✓ The wider the margin, the shallower LAB

LAB depth for South Atlantic passive margins in Gondwana framework. In between, the age of the oceanic lithosphere is visualized (Seton et al., 2020). Thin dashed line represents the location of the Mid Atlantic Ridge at 83 Ma. AF=Ascension Fracture Zone, RF=Rio de Janeiro Fracture Zone. Grey lines represent flowlines intersecting the passive margins. Dark red polygons show location of LIPs, taken from the Johansson et al. (2018) data base. Reconstruction is done with GPlates (Müller et al. 2018)

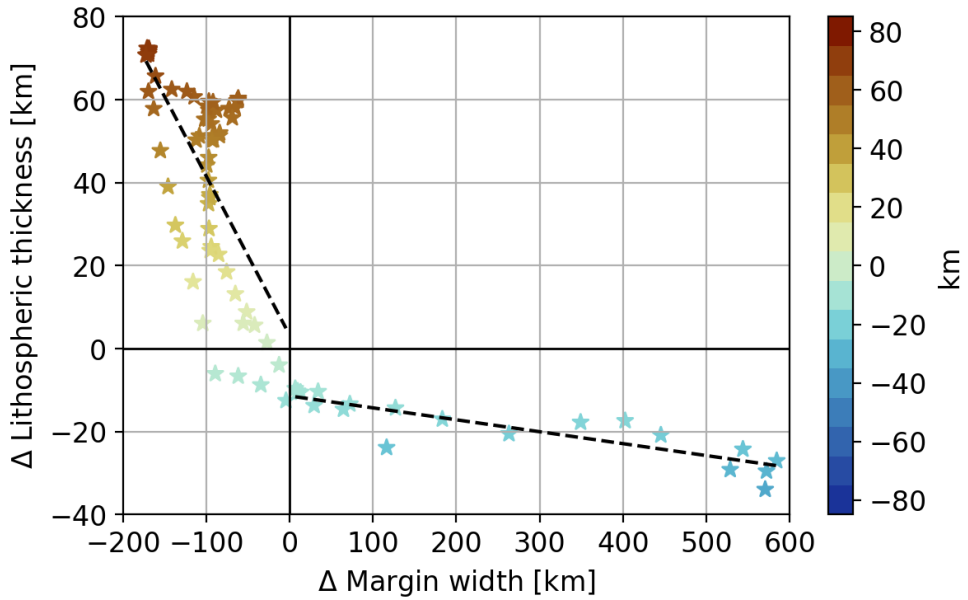
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Correlation of LAB depth and margin width



Difference of LAB depth for selected conjugate South American and African basins. Red colours indicate deeper LAB in South America, blue colours deeper LAB in Africa. Thick lines at the inner COBs indicate directly adjacent cratons (Red: Sao Francisco and northern Congo Craton, purple: southern Congo Craton, Blue: No craton adjacent). Red polygons indicate LIPs.



Difference of margin width of conjugate margin pairs versus difference of LAB depth at the outer COB. Red colours indicate deeper LAB in South America, blue colours deeper LAB in Africa. Dashed lines show the linear fit for the pairs with wider African margin (negative Δ Margin width) and for the pairs with wider South American margin (positive Δ Margin width).

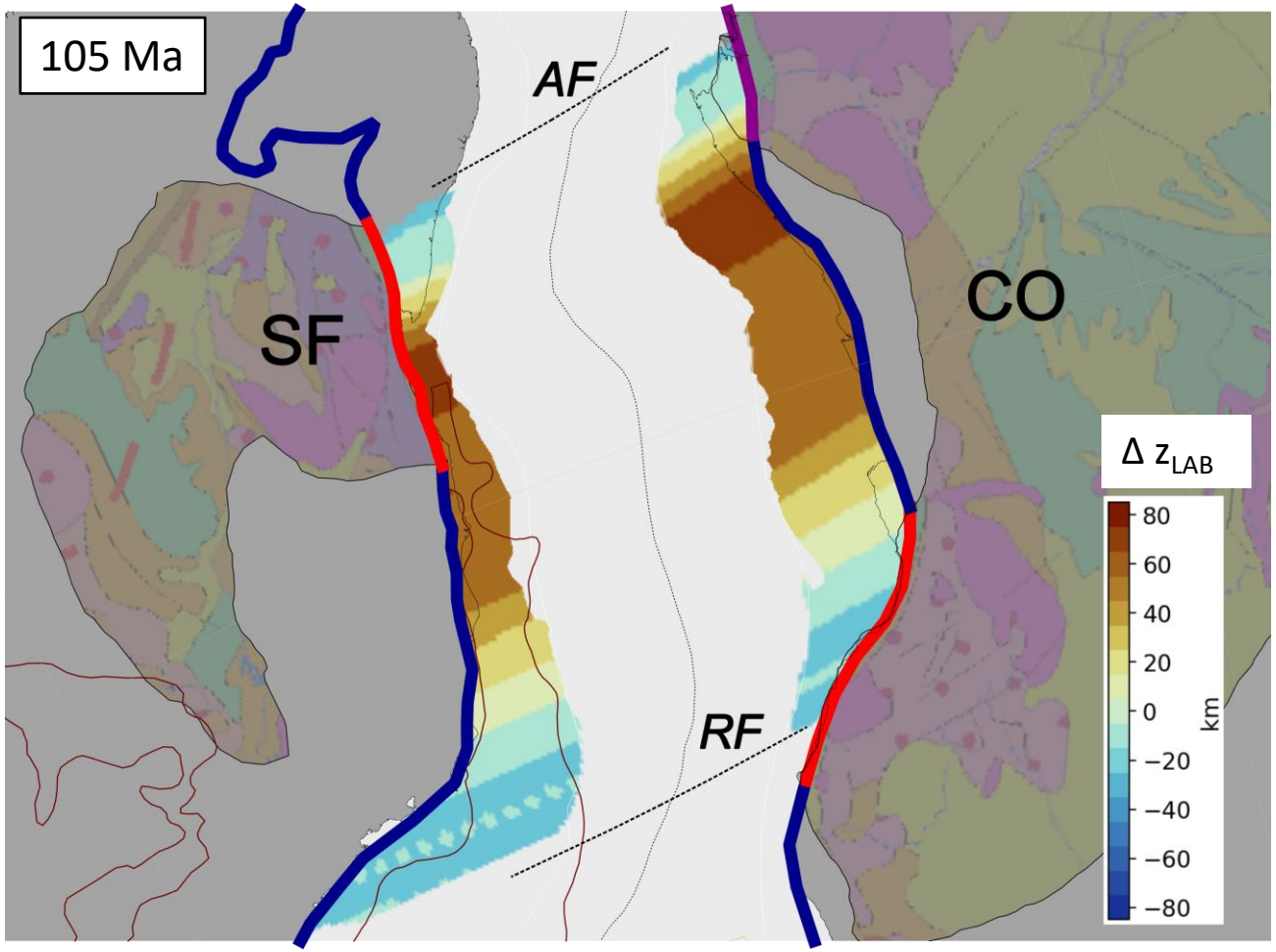
- Strong differences in LAB depth correlate with strong gradients in margin width

✓ Asymmetric melting and lithospheric thinning prior to rifting

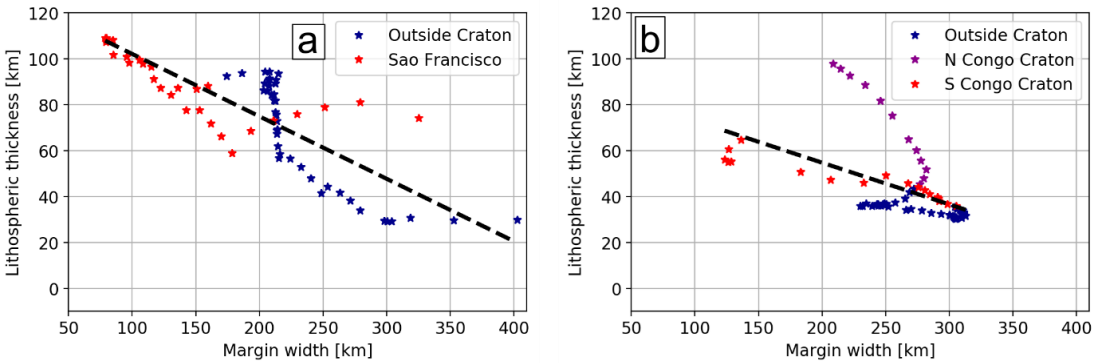
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Margin width of conjugate margin pairs versus lithospheric thickness for the individual passive margins. Linear trend is visualized as black dashed line. a) South America, b) Africa

- South America: Deeper LAB at vicinity of Sao Francisco Craton
- Africa: Deeper LAB at vicinity of Congo Craton, strong deviations for northern part

✓ Thinned crust contains portions of cratonic lithosphere in northern Congo

✓ Location of cratons controls the LAB depth

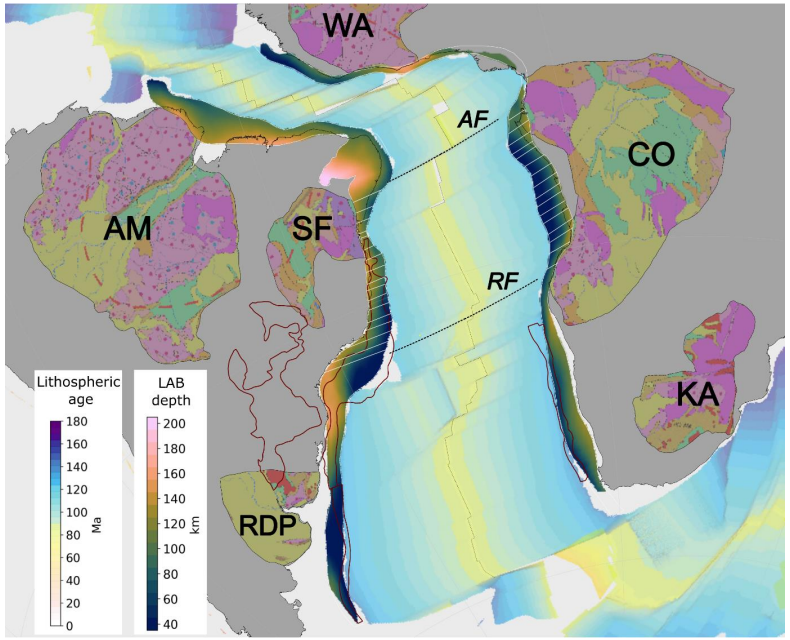
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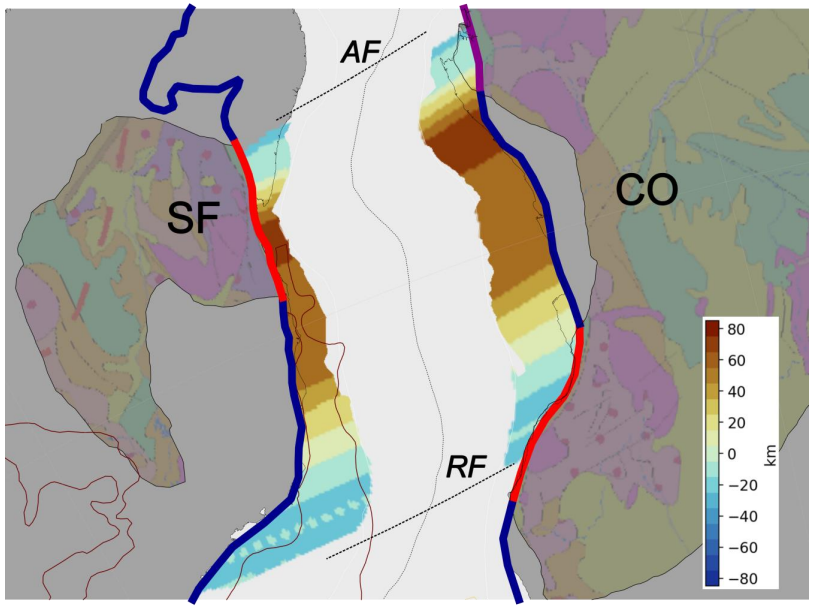
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Take home messages

- ✓ A simple thermal LAB model for the South Atlantic passive margins was developed
- ✓ The LAB model shows highly variable lithospheric thickness that reflects different rifting stages of the South Atlantic
- ✓ The difference of LAB depths for conjugate margin pairs correlates with asymmetry in margin width, implying asymmetric lithospheric thinning





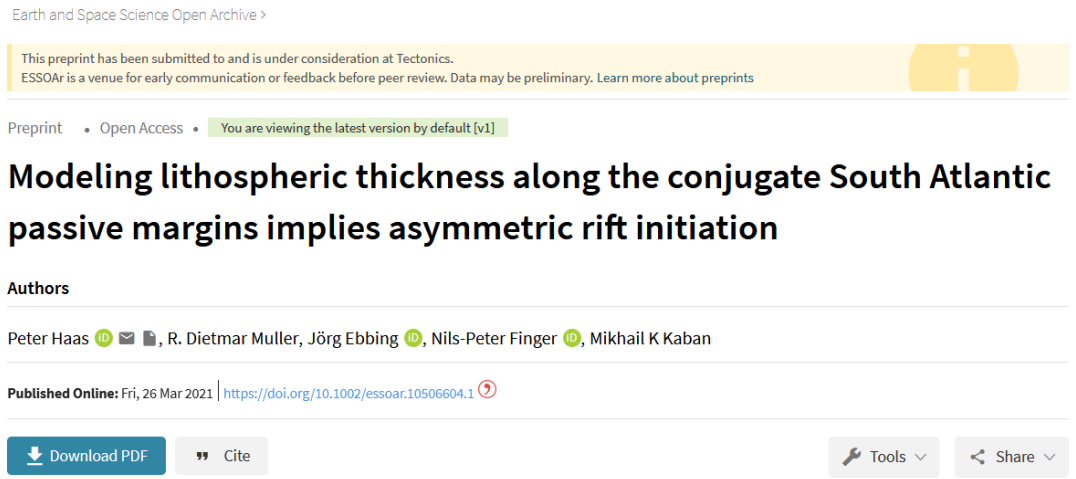
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Further reading & Acknowledgments

We have submitted our work to *Tectonics*. For more detailed information, you are invited to have a look in our manuscript, which is available via *Earth and Space Science Open Archive*:

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