Abstract

Here we use dynamical models of rifting to show how lower crustal rheology affects conjugate margin architecture and the nature of the continent-ocean transition (COT). We explore the behavior of South Atlantic conjugate margins, specifically the Campos/Angola, which developed along the Late Proterozoic Ribeira/Kaoko fold belt, to the Camamu/South Gabon basins, formed on the São Francisco/Congo Craton. Along these conjugate margins the degree of asymmetry increases southwards. Additionally, in Campos the crust tapers smoothly towards break-up; faults show small offsets; and the area of hyper-extended crust (< 10 km thickness) is very wide (~ 200 km). To the North, in the Camamu, faults have much larger offsets; crustal thinning is abrupt; and the margin is much narrower. Our models show that a strong lower crustal rheology, which would be expected for a craton-like setting of the Camamu, effectively couples deformation in upper crust and mantle, leading to rapid crustal break-up and subsidence through crust-cutting faults. These crust-cutting faults allow serpentinisation to start before break-up and produce narrow margins with only slight degrees of asymmetry. Coupling of lithospheric layers leads to quick upwelling of the asthenosphere and melting. For slow extension velocities, such as those prevalent in this area, < 5 mm/yr, melting starts after the onset of serpinetisation. The resulting COT consists of exhumed and serpentinised mantle, underlain by a thin layer of frozen magma. For the same extension velocities, when the lower crust is weak as anticipated for a fold belt
setting, such as in Campos/Angola, rifting starts with a prolonged phase characterized by minor faulting distributed over a wide area and moderate crustal thinning. Continuing extension leads to strain localization, coupling of lithospheric layers, more pronounced crustal thinning and the emergence of an array of sequential, and oceanward-younging faults and produces wide, hyper-extended and asymmetric margins (Brune et al., 2014). In this case, serpentinisation is insignificant because active faults do not reach the mantle. Asthenospheric upwelling is less pronounced, and the onset and amount of melting is delayed with respect to the previous case. When crustal break-up occurs, magma rises to form oceanic crust and a narrow continent-ocean transition. Thus, during rifting, melting and oceanization are not only controlled by extension velocity but also by the rheology of the lower crust.

**Selected References**


Modes of Extension and Oceanization at magma-poor margins: An example from the Brazilian/African margins

Marta Pérez-Gussinyé (1), Mario Araujo (2), M. Romeiro (2), Miguel Andres Martinez (1), Jason Phipps Morgan (1), Elena Ros (1)

(1) Dept. Earth Sciences, Royal Holloway, University of London
(2) CENPES, Petrobras
South Atlantic margins

1- Camamu - South Gabon
2- Campos - Kwanza
3- North Santos - S. Kwanza

From North to South:

- Initial lithospheric configuration changes from craton to mobile belt
- Crustal thicknesses vary from 35-40 km.
- Extension velocity increases, from 2.5 km/Myr- 5km/Myr (half).
Degree of asymmetry & margin width

1- CAMAMU-GABON

2- CAMPOS - KWANZA

3- NORTH SANTOS - SOUTH KWANZA

San Francisco craton

Congo craton

salt basin

continent-ocean transition

4 mm/a

8 mm/a

10 mm/a

-50 -45 40 35 30 -25 -20

-10 -15 -20 -25 -30

-35 -40 -45 -50

-10 -5 0 5 10 15 20 25 30 35 40 45 50

Distance (km)
Questions

• What controls asymmetry formation and its degree?

• What controls on margin width?

• Can we correlate margin architectonical styles with types of oceanization (exhumed mantle/abrupt transition to magmatic crust)?
Magma-poor margins characterized by ultra-slow extension

Rocks cool during very slow extension
Formation of asymmetry:

Emergence of an oceanward dipping fault array that is sequential in time.

Formation of conjugate asymmetric margins.

Progressive cooling leads to:

Progressive coupling of upper, lower crust and mantle.

Emergence of an oceanward dipping fault array that is sequential in time.

Rheology of lower crust controls degree of asymmetry, margin width and oceanization style.

High viscosity lower crust can NOT flow so much $\rightarrow$ effective crustal thinning

Low viscosity lower crust CAN flow very much $\rightarrow$ NO effective crustal thinning
Fully dynamic models of rifting with:

1- STRONG mafic granulite
   - 35 km thick crust
   - 40 km thick crust

2- WEAK wet quartzite
   - 35 km thick crust
   - 40 km thick crust

5 mm/yr half extension velocity
(adequate for southern part of study area)
Effect of crustal thickness on margin width/symmetry

Strong mafic granulite

Initial configuration – vel 5 mm/yr – mafic granulite -35/40 km crust

Local temperature higher by 100 C Close to Moho

Boundary conditions: constant velocity 5mm/yr at box edges
Visco-elasto-plastic rheologies. Viscous and brittle strain softening
Initial weak seed: temperature higher by 100C close to Moho.

Graphs showing temperature and differential stress profiles for different crustal thicknesses.
Effect of crustal thickness on margin width/symmetry

Strong mafic granulite

2nd strain rate invariant, Crustal thickness 35 km, Wet Quartzite lower crust 18.01 ma

Narrow symmetric margins

Viscosities less than $10^{21}$ Pas

Isotherms of 700 and 1300 C

Case 3: Crustal thickness 35/40 km
Weak wet quartzite lower crust.

Boundary conditions: constant velocity 5mm/yr at box edges
Viscous and brittle strain softening
Initial weak seed: temperature higher by 100C close to Moho.
Effect of crustal thickness on margin width/symmetry

Weak wet quartzite

- 35 km: Wide slightly asymmetric margins
- 40 km: Ultra-wide asymmetric margins

Wet quartzite

Viscosities less than $10^{21}$ Pas

Isotherms of 700 and 1300°C
Can we relate architectural types of margins with oceanization styles?

During rifting, onset and amount of melting strongly depends on extension velocity.

Perez-Gussinye et al., EPSL, 2006.
Effect of crustal rheology on serpentinisation/melting.

**Strong mafic granulite**
Effect of crustal rheology on serpentinisation/melting.

Strong mafic granulite

Accumulated serpentinization 20.01 Ma

Area of melt production 20.01 Ma

Magmatic crustal thickness 20.01 Ma
Effect of crustal rheology on serpentinisation/melting.

Accumulated serpentinization 29.51 Ma

Accumulated serpentinization 49.01 Ma

Area of melt production 29.51 Ma

Area of melt production 49.01 Ma

Magmatic crustal thickness 29.51 Ma

Magmatic crustal thickness 49.01 Ma
Melt production & lower crustal rheology

![Graph showing magmatic crustal thickness over time for different crustal thicknesses.](image)

- MG 35 km
- MG 40 km
- WG 35 km
- WG 40 km
Modes of extension and oceanization along the Brazilian/African margins
Modes of extension and oceanization along the Brazilian/African margins
Presenter’s notes: In the 1970’s and 1980’s two very different models were put forward which attempted to explain architecture and symmetry of conjugate margins and basins. However, it was soon clear that these models were oversimplifications of reality and that they could not explain the richness in extensional styles observed in Nature. Roger Buck (1991) did a very important step by describing and classifying extensional styles into narrow, wide and core-complex modes and showing that the transition of one to the other would occur with increasing lower crustal viscosity. (Presenter’s notes continued on next slide)
By looking at the richness of extensional styles along the South American margin, we have come to the conclusion that there is a fourth extensional mode, the sequential faulting mode, which when combined with the previous modes can well explain the wide variety of margin architectures that we see. We have also found that the predominance of one or the other modes during extension is intimately related to the width and nature of the continent-ocean transition zone.
Conclusions

• **Formation of asymmetry.**
  Occurs when sequential faulting kicks in lower crust is strong enough to couple lithospheric deformation but weak enough to avoid crustal break-up by faulting.

• **Degree of asymmetry and margin width.**
  Depends on the prevalent mode during extension.
  Very weak lower crust tends to promote wide margins and sequential faulting only kicks in at the very last stages of extension (if).
  Margins will tend to be more symmetrical during a longer time.

• **Oceanization style.**
  Depends on strength of lower crust & velocity. Strong lower crust leads to faster ascent of mantle and early onset of serpentinisation.
  Weak lower crust inhibits both melting and serpentinisation.
Conclusions

- **Formation of asymmetry.**
  Occurs when sequential faulting kicks in if lower crust is strong enough to couple lithospheric deformation but weak enough to avoid crustal break-up by faulting.

- **Degree of asymmetry and margin width.**
  Depends on the prevalent mode during extension.
  Very weak lower crust tends to promote wide margins and sequential faulting only kicks in at the very last stages of extension (if).
  Margins will tend to be more symmetrical during a longer time.

- **Fault geometry.**
  Sequential faulting will listrify faults turning them detachment like.
  Strong lower crust promotes large faults & long offsets and vice versa. The orientation of faults will depend on which mode prevails.

- **Oceanization style.**
  Depends on strength of lower crust & velocity. Strong lower crust leads to faster ascent of mantle and early onset of serpentnisation. Weak lower crust inhibits both.

[Part 2]