Forward Modeling of Rift and Passive Margin Formation

Implications for South, North, and Central Atlantic Margins

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Overview

• Styles of rifted margin formation: Variability in natural systems

• First order controls on extension mode

• Type I: Narrow non volcanic rifted margins

• Type II: Wide rifted margins and depth dependent extension
First order rift modes

- Natural systems appear to exhibit a range of styles including:
  1. Core complex extension
  2. Wide rift and passive margin
  3. Narrow rift and passive margin
  4. Symmetric rift and passive margin
  5. Asymmetric rift and passive margin
Narrow Rift Mode

Symmetric ‘Pure Shear’ Rift Mode

Asymmetric ‘Simple Shear’ Rift Mode

Wide Rift Mode

Wide Crustal Extension-Narrow Mantle Lithosphere Extension

Huismans and Beaumont, 2008
Symmetric Continental Breakup?

Figure 1.2: Diagram illustrating the evolution of a continental rift to an extensional basin and eventually a rifted continental margin (modified after Salvestron, 1978).
Asymmetric continental breakup?

- Synrift volcanism
- Initial break-away
- Plateau basalts
- Lower plate shoulder
- Final break-away
- Upper plate shoulder
- Dike complex
- Asthenospheric upwelling
- Mid ocean ridge

$T_0 =$ Transtensive phase

$T_0 + 10 \text{ Ma} =$ Lithospheric break-up dominated by simple shear

$T_0 + 15 \text{ Ma} =$ Asthenospheric diapir and thermal uplift, dominated by pure shear

$T_0 + 25 \text{ Ma} =$ Sea floor spreading

Extension may carry on within the upper plate

- Stampfli
Narrow asymmetric rifting
Yinchuan graben

He et al., GRL 2003
Red Sea / Gulf of Suez

Extension is localized in a Narrow rift system with a width ~ 100 - 150 km

Symmetric or Asymmetric?
Narrow Rifting

Upper Rhine Graben Section

- Brun et al.
Central Atlantic Passive Margins

Huismans and Beaumont, 2008
Core Complex to Wide Rift Extension

- Brun et al., 1999
Core Complex Style Extension

- Extension with a high grade metamorphic core exhumed to the surface
- Juxtaposition of low and high grade materials
- Single detachment faults with large offset
• Basin and Range
• wide rift (800 km)
• Multiple horst and grabens
• Distributed Extension
Wide (Non)-Volcanic Rifting

South Atlantic Salt Basin

- Brazilian Espirito Santo Margin
- West African north Angolan Margin

Stratigraphy:
- Salt

Deposition Rate:
- Post Rift
- Late Syn-Rift
- Un-Faulted

Depth (km):
- 0
- 10
- 20
- 30

Distance (km):
- 0
- 100
- 200

Layer Descriptions:
- Shallow Water Salt
- Late Syn-Rift Sag
- Early Syn-Rift Fault Bounded

Pre Salt Sag Basin
- 2
- 3

Crust
Wide Volcanic Rifting in the North Atlantic
First order control on modes of extension

Buck, 1991
Dynamic Extension Models
Contrasting Styles

Braun and Beaumont, 1989
Plastic strain weakening allows efficient localisation
Plastic Strain weakening allows efficient localisation

Lavier et al., Geology 1999
Narrow Non Volcanic Margin Formation

Lavier and Manatschal, Nature 2006
Thermo-Mechanical Model Setup

Crust:
- Wet Quartz
- Frictional plastic
  \[ \rho_0 = 2800 \text{ kg/m}^3 \]

Weak Seed:
- 12 x 10 km
- von Mises plastic
  \[ \rho_0 = 3300 \text{ kg/m}^3 \]
  \[ \sigma_y = 10^7 \text{ Pa} \]

Lithosphere and Sublithospheric Mantle
- Dry Olivine
- Frictional plastic (see right)
  \[ \rho_0 = 3300 \text{ kg/m}^3 \]

Isothermal mantle, \textit{Temperature} \[ T_a = 1330 ^\circ \text{C} \]

\[ V \]

\[ x, z = 0 \text{ km} \]

\[ x = 1200 \text{ km} \]

\[ z = 600 \text{ km} \]

\[ V_b \]
Model Crust Strength Variation

Model 1
Strong Crust

- Wet Quartz x 100
- $\phi_{eff} = 2^\circ$
- $\phi_{eff} = 15^\circ$
- Dry Olivine
- $\dot{\varepsilon} = 1 \times 10^{-15} / \text{s}$

Model 2
Weak Crust

- Wet Quartz
- Moho
- Dry Olivine

Model 3
Very Weak Crust

- Wet Quartz / 10
- Upper Crust
- Lower Crust
- Upper Mantle Lithosphere
- Lower Mantle Lithosphere

Strength Lower Crust

Huismans and Beaumont, 2005
Sensitivity of Rift Mode to Strength Lower Crust

Strong Lower Crust

Asymmetric Mode of Extension

U Crust
L Crust
Upper ML
Lower ML
Sub Lithosphere Mantle

Weak Lower Crust

More Symmetric Mode of Extension

Very Weak Lower Crust

Wide Crustal Rifting / Narrow Mantle Lithosphere Rifting

Effect of Weak Mantle Lithosphere

Model 4. Strong Crust, Weak Mantle Lithosphere

A) $t = 16.5$ My, $\Delta x = 50$ km

B) $t = 33$ My, $\Delta x = 100$ km

C) $t = 50$ My, $\Delta x = 150$ km

Model 6. Very Weak Lower Crust, Weak Mantle Lithosphere

A) $t = 16.5$ My, $\Delta x = 50$ km

B) $t = 33$ My, $\Delta x = 100$ km

C) $t = 50$ My, $\Delta x = 150$ km

Huismans and Beaumont, 2005
Effect of Brittle Ductile Coupling: Prediction of mode transition

• Ratio of Brittle / Ductile Stress
  – Mode boundary not defined

• Compare Integrated Force for different modes, e.g. mode transition when:
  – \( F_{\text{mode1}} = F_{\text{mode2}} \) and \( F_{\text{mode2}} = F_{\text{mode3}} \)

  – Well defined mode transition, but does resolve not higher order features, e.g. difference between symmetric – pure shear mode

• Compare Rate of Work for different modes, e.g. mode transition when:
  – \( W_{\text{mode1}} = W_{\text{mode2}} \) and \( W_{\text{mode2}} = W_{\text{mode3}} \)

  Huismans et al., JGR, 2005
Modes for Dissipation Analysis

a) Pure Shear Mode (PS)

PS

b) Symmetric Plug Mode (SP)

SP

c) Asymmetric Plug Mode (AP)

AP

Huisman et al., JGR, 2005
RATE OF DISSIPATION ANALYSIS

Mode 1 \[ \dot{W}_p^A + \dot{W}_v^A \]

Mode 2 \[ \dot{W}_p^S + \dot{W}_v^S \]

At the mode transition

\[ \dot{W}_T = \int_A \varepsilon \cdot \sigma \, dA \]

Huisman et al., JGR, 2005
Symmetric versus Asymmetric Mode
Von Mises Plastic Layer, Cohesion C

Transition viscosity

\[ \eta_t = 3 \frac{h_b \ h_p \ (C_S - C_A)}{L_A \ V} \]

\[ \eta_t \ L_A \ \frac{V}{h_b} = 3 \ h_p \ (C_S - C_A) \]

\[ L_A \ \eta_t \ \dot{\varepsilon}_A = 3 \ h_p \ (C_S - C_A) \]

\[ \Delta F_v = \Delta F_p \]

Differential viscous penalty force  Differential plastic gain force
MS2: Two Layer Model, Frictional-Plastic Strain Softening

40 km extension at 1 cm/yr

1. \( \phi = 15-2^\circ \)
   \( \eta = 10^{21} \text{ Pa s} \)

2. \( \phi = 15-2^\circ \)
   \( \eta = 10^{22} \text{ Pa s} \)

3. \( \phi = 15-2^\circ \)
   \( \eta = 10^{23} \text{ Pa s} \)

Huismans et al., JGR, 2005
Cold Non Volcanic Margins
Iberia - Newfoundland

- Magma starved rifting
- Exhumation of Mantle Lithosphere to seafloor
- Final rift stage very narrow with very narrow crustal necks <100km
- Mantle lithosphere exhumation decreases with increasing crustal neck width
- Progressive deeper levels of ML in distal positions

Iberia-Newfoundland, Models & Interpretations

**Stretching Cold Lithosphere**
- \( t = 22 \text{ My}, \Delta x = 67 \text{ km} \)
- \( t = 38 \text{ My}, \Delta x = 120 \text{ km} \)

**Cold and Slow Stretching**


Peron-Pinvidic et al, Tectonics 2007

Peron-Pinvidic and Manatschal, Int J Earth Sci, in press
Iberia Type I margin

Huismans and Beaumont, Nature 2011
Iberia Type I margin

Type-I, $t = 0.0$ My, $\Delta x = 0$ km

Animation, see: http://folk.uib.no/rhu002/huismans_beaumont_nature2011.html

Huismans and Beaumont, Nature 2011
Type I Margins

- During last phase of rifting the crust breaks before the mantle lithosphere
- Largely a-magmatic
- Type I margin:
  - Crust breaks first, mantle lithosphere necks later
  - Exhume mantle lithosphere
  - Favored by stronger crust
Wide Hot Rifted Margins with Anomalous Vertical Motions, Depth Dependent Stretching (and Magmatism ?)

**South Atlantic Salt Basin**

- **Brazilian Espirito Santo Margin**
- **West African north Angolan Margin**

Late shallow water salt on thin crust indicates depth dependent thinning between crust and mantle

- **Stratigraphy**
- **Deposition Rate**

- **Time (Myr)**
- **Distance (km)**

- **Shallow Water Salt**
- **Late Syn-Rift Sag Un-Faulted**
- **Early Syn-Rift Fault Bounded**

- **COB**
- **7.2-7.4 km/s**

-Moulin et al., 2005; Huismans and Beaumont, Geology 2008; Huismans and Beaumont, Nature
Weak Lower Crust, Seed in Mantle

- Narrow rifting of mantle lithosphere
- Distributed extension in crust
- Lower crustal flow to thinning area

- Narrow rifting of mantle lithosphere
- Lower crustal flow to thinning area
- Regional ‘sag’ subsidence

- Very wide upper crustal sections
- Lower crustal flow to distal margin
- Regional ‘sag’ subsidence
- Little deformed upper crustal section

• Huismans and Beaumont, Nature 2011
Very Weak Lower Crust

- Lower crustal flow to distal margin
- Diachronous ‘sag’ subsidence

• Huismans and Beaumont, Nature 2011
Type II-A

$\text{Type-II-A, } t = 0.0 \text{ My, } \Delta x = 0 \text{ km}$

Animation, see: [http://folk.uib.no/rhu002/huismans_beaumont_nature2011.html](http://folk.uib.no/rhu002/huismans_beaumont_nature2011.html)

Tomography

Begg et al, Geosphere 2009
Lithospheric layering in the North American craton

Huaiyu Yuan\textsuperscript{1} & Barbara Romanowicz\textsuperscript{1}

How cratons—extremely stable continental areas of the Earth’s crust—formed and remained largely unchanged for more than 2,500 million years is much debated. Recent studies of seismic-wave receiver function data have detected a structural boundary under continental cratons at depths too shallow to be consistent with the lithosphere–asthenosphere boundary, as inferred from seismic tomography and other geophysical studies. Here we show that changes in the direction of azimuthal anisotropy with depth reveal the presence of two distinct lithospheric layers throughout the stable part of the North American continent. The top layer is thick (~150 km) under the Archaean core and tapers out on the surrounding Palaeozoic borders. Its thickness variations follow those of a highly depleted layer inferred from thermo-barometric analysis of xenoliths. The lithosphere–asthenosphere boundary is relatively flat (ranging from 180 to 240 km in depth), in agreement with the presence of a thermal conductive root that subsequently formed around the depleted chemical layer. Our findings tie together seismological, geochemical and geodynamical studies of the cratonic lithosphere in North America. They also suggest that the horizon detected in receiver function studies probably corresponds to the sharp mid-lithospheric boundary rather than to the more gradual lithosphere–asthenosphere boundary.
Lower Lithospheric Mantle Layer

Yuan and Romanovich, Nature 2010
Type-II Craton

Lithospheric Mantle
Wet Olivine, $f = 5$
\[ \rho_0 = 3,300 \text{ kg/m}^3 \]

Upper Cratonic Lithosphere
Wet Olivine, $f = 5$
\[ \rho_0 = 3,285 \text{ kg/m}^3 \]

Lower Cratonic Lithosphere
is Wet Olivine, $f = 3$
\[ \rho_0 = 3,283 \text{ kg/m}^3 \]

1,380 °C
250 km

1,520 °C

\[ x = 1,200 \text{ km} \]

• Huismans and Beaumont, Nature 2011
Type II-Cratonic inflow

c) $t = 8 \text{ Ma, } \Delta x = 120 \text{ km}$

d) $t = 14 \text{ Ma, } \Delta x = 210 \text{ km}$

f) $t = 36 \text{ Ma, } \Delta x = 540 \text{ km}$

Type II-C

Type II-C, t = 0.0 My, Δx = 0 km

Animation, see: http://folk.uib.no/rhu002/huismans_beaumont_nature2011.html

• Huismans and Beaumont, Nature 2011
Type II-Cratonic Inflow

Type I & II Contrasting Styles

Type I: Strong Crust

Type II-A: Weak Crust

Lower Lithosphere breakup before Upper Lithosphere

Cratonic Underplate?

Huismans and Beaumont, Nature 2011
Conclusions

- **Type I margins:**
  - Crust breaks first, mantle lithosphere necks later
  - Exhume mantle lithosphere
  - Favored by stronger crust

- **Type II-A margins:**
  - Mantle lithosphere necks first, crust breaks later
  - No mantle lithosphere exhumation
  - Favored by weak crust

- **Type II-C margins:**
  - Cratonic lower mantle lithosphere flows into necking area
  - Low density owing to depletion promotes shallow water depth
  - Depleted nature inhibits magmatism

- Lower mantle lithosphere inflow may explain large tracts of exhumed mantle in narrow Type I margins