Effect of Lithospheric Stratification on Extensional Styles and Rift Basin Geometry

Ritske Huismans, Chris Beaumont
Geodynamics Group, Dalhousie University, Halifax

RCL Working Group:
Roger Buck, John Hopper, Rob Bialas, Audrey Huerta
Wide Rift Mode

Wide Crustal Extension-Narrow Mantle Lithosphere Extension

Crust
Mantle
Asthenosphere

Crustal Thinning

Narrow Rift Mode

Slow/Cold Rifting
Asymmetric ‘Simple Shear’ Rift Mode

Crust
Mantle
Asthenosphere

Fast/Hot Rifting
Symmetric ‘Pure Shear’ Rift Mode

Crust
Mantle
Asthenosphere
Overview

• Examples of Narrow and Wide, Symmetric and Asymmetric Rifts

• Magmatic Rifting

• Role of Heat Production / Thermal Structure on Rift Mode

• Volcanic Margins and Small Scale Convection

• Control of Strength of Lower Crust on Rift Mode

• Control of Thickness Crust on Rift Mode
Central Atlantic Passive Margins
Northern Nova Scotia - Morocco Conjugate Margins

Fig. 9. 2D-Model of the conjugate margins of Morocco and Nova Scotia at a pre-rupture stage (see location Fig. 2). The margin structure is build from seismic reflection and refraction data of Sismar and Smart cruises. Note the asymmetry of the margins at the COB. Black squares are homologous points along the large detachment fault, whose latest active part was the LDR.

Maillard et al. EPSL 2005 in press
South Atlantic Salt Basin: Angola Margin

Conrucci et al. GJI, 2005
Magmatic Rifting: Buck; Kendall, Stuart, Ebinger et al.
Magmatic Rifting II

Magmatic Rifting Model

SKS and Magmatism Ethiopian Rift

Buck, Pontresina 2004

Kendall et al. Nature 2005
Crustal Heat Production and Rift Geometry

Increasing Heat Production

$A = 0.0 \mu W/m^3$

$t = 0$ m.y.

$t = 10$ m.y.

$t = 13$ m.y. $\beta = 5$

$A = 0.75 \mu W/m^3$

$t = 0$ m.y.

$t = 10$ m.y.

$t = 13$ m.y. $\beta = 5$

$A = 1.25 \mu W/m^3$

$t = 0$ m.y.

$t = 10$ m.y.

$t = 20$ m.y. $\beta = 5$

$A = 1.5 \mu W/m^3$

$t = 0$ m.y.

$t = 10$ m.y.

$t = 20$ m.y. $\beta = 5$

Increasing Crustal Heat Production => Wider Rift

A.D. Huerta, in preparation
Bialas, Buck and Qin: Core Complex to Narrow Rifting. $V = 2\text{cm/yr}$

**Initial Conditions:**

<table>
<thead>
<tr>
<th>Strain Rate</th>
<th>Crustal Thickness</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Ma</td>
<td>Crustal Thickness</td>
<td></td>
</tr>
<tr>
<td>10 Ma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 Ma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 Ma</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Volcanic Margins I

Nielsen and Hopper 2004; Boutelier and Keen, 1999
Volcanic Margins II

Either no-SSC and stable crust production or SSC and unstable oceanic crust production

Inclusion of hot ‘plume’ sheet below lithosphere produces transient peak in oceanic crust production

Oceanic Crustal Thickness

Oceanic Crustal Thickness

Nielsen and Hopper 2004; Boutilier and Keen, 1999
Depth Dependent Rheology

- Crust: Wet Quartz
- Upper Mantle Lithosphere: Dry Olivine
- Lower Mantle Lithosphere: Dry Olivine

Temperature:
- $T_m = 550 \degree C$
- $T_a = 1330 \degree C$

Stress vs. Depth (km):
- Wet Quartz
- Dry Olivine

Stress (MPa):
- 0 to 150
Causes of Weakening in Frictional (Brittle) Rocks

a) Cohesion loss

\[ C = 20 \text{ MPa} \]

\[ C = 0 \quad \phi = 30^\circ \]

Brittle-ductile transition

b) Mineral transformations

\[ \phi_{\text{dry}} = 30^\circ \]

\[ \phi = 2-12^\circ \]

c) Pore fluid pressure weakening

\[ \phi_{\text{eff(dry)}} = 30^\circ \]

\[ \phi_{\text{eff(hydro.)}} = 18^\circ \]

\[ \phi_{\text{eff(-lithostatic)}} = 1^\circ \]

Huismans and Beaumont, Submitted
Thermo-Mechanical Model Setup

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

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

Moho:
- Temperature: \( T_{Moho} = 550 \text{ °C} \)

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

Isothermal mantle, Temperature:
- \( T_a = 1330 \text{ °C} \)

Depth:
- \( z = 600 \text{ km} \)
- \( x = 1200 \text{ km} \)
Sensitivity of Rift Mode to Strength Lower Crust

Strong Lower Crust

Asymmetric Mode of Extension

Weak Lower Crust

More Symmetric Mode of Extension

Very Weak Lower Crust

Wide Crustal Rifting / Narrow Mantle Lithosphere Rifting

Huismans and Beaumont, Submitted
Core Complex Extension

Brun et al., 1999
Extension of Orogenic Thickened Crust

A  \( \text{Time, } t = 4 \text{ Ma, } \Delta x = 12.5 \text{ km} \)  \( \text{Vext} = 0.3 \text{ cm/yr} \)

Core Complex Extension

B  \( \text{Time, } t = 24 \text{ Ma, } \Delta x = 75 \text{ km} \)  \( 0.3 \text{ cm/yr} \)

Wide Rift Extension

C  \( \text{Time, } t = 48 \text{ Ma, } \Delta x = 150 \text{ km} \)  \( 0.3 \text{ cm/yr} \)

Huismans and Beaumont, 2000
Conclusions I

• Strong Sensitivity of Rift Mode to Strength Lower Crust
  
  • Strong Lower Crust:
    – Narrow Asymmetric Upper and Lower Lithosphere Extension
  
  • Weak Lower Crust:
    – Narrow Asymmetric Upper Lithosphere
    – Narrow Symmetric Lower Lithosphere
  
  • Very Weak Lower Crust, Strong Mantle Lithosphere:
    – Wide Symmetric Upper Lithosphere
    – Narrow Symmetric Lower Lithosphere
  
  • Extension of Thickened Crust:
    – Initial Core Complex Extension
    – Later Wide Rift Extension
Questions

- 3D Aspects of Deformation?
- Transpressional / Transtensional Effects?
- Role of Magmatism?
- Coupling of Fluids and Deformation?
- Feedback between Surface Processes and Deformation?
Questions Salton Through

• 3D Aspects of Deformation and Role of Transtension?

• Is the Rift Style Variation in the South, Wide/Narrow a Consequence of Short Segments and Transform Resistance to Deformation?

• Is Deformation in the North Really Core Complex or is this an Older Part of the History?

• How do Surface Processes and Deformation relate in the Northern Part of the System?