A modeling perspective on rifting

Luc Lavier, UTIG/DGS
Jackson School of Geosciences
S. Jammes, G. Mohn.
Magma-"poor" margins versus "volcanic" margins

What do we really know about volcanic margins?
Are they really so different from “magma” poor rifted margins?
What is the origin of the volcanism? – what are the dynamic processes involved?
What are the mechanisms leading to breakup?

LCB: « Lower Crustal Body »
SDRS: »Seaward Dipping Reflectors »
COT: Continent-Ocean Transition

Origin of the magmatism
Laurent Geoffroy
WEAKENING OF THE LITHOSPHERE

**General Framework: Weakening of the Lithosphere**

- Detachment faults are present.
- Weakening of the lithosphere by fluids.
- Late serpen/niza/on of the mantle (fluids).
- Storage of melt in the mantle.

**Tectonic Stretching**

Needs a gradual evolution of the rheology.

**Magmatic Extension**

- Needs multiple dikes.
- Normal faulting with dikes.
- A plume head is often present.
- Needs 2-3 km of dikes to continue rifting without magma.
Some Questions addressed?

• Extreme crustal thinning.
• Mantle exhumation at the Ocean Continent Transition (OCT).
• Detachment fault/low angle normal fault.
• Melt migration or stagnation during rifting.
• Dike (Giant) propagation during rifting and at the transition from continent to ocean.
• The effect of sedimentation and erosion on rifting.
• The subsidence history during rifting.
Extreme Crustal Thinning

O’Reilly et al., 2006

Untherner et al., 2010
Detachment fault/low angle normal fault/Brittle-Ductile weakening/Boudinage.

Peron-Pinvidic & Manatschal, subm.
Mantle exhumation at the Ocean Continent Transition (OCT).

Sibuet et al., 2007

Manatschal et al., 2004
Detachment systems associated with lithospheric extension

oceanic core complexes

Few examples of detachment systems associated with continental breakup have been described

metamorphic core complexes

Mid-Atlantic Ridge

Death Valley

From Barbara John
Field Geology (Alps/Pyrenees-Bay of Biscay)
Detachment faults and brittle-ductile weakening associated with necking and crustal thinning.

Mohn et al., 2010
Melt infiltration and thermal evolution during final rifting

**Observation**
Infiltrated sub-continental mantle

**Processes**
melt trapping, leading to thermal erosion of the deep mantle lithosphere during final rifting

**Consequences**
- change of the mantle rheology (*weakening*)
- thermal structure (*hotter than expected*)
- subsidence history (*retardation of subsidence*)

WHY DOESN’T IT FORM A DIKE?

10% infiltration in 10 km thick mantle
no seismically ‘visible’ Moho

‘non-volcanic’ ?
‘volcanic’

1 km ‘true’ oceanic crust
seismically ‘visible’ Moho

9 km depleted mantle

Muentener et al., 2009
Observed magmatic processes in magma-poor rifted margins

(1) **pre-breakup**
- melt infiltration in sub-continental mantle

(2) **syn-exhumation**
- MOR-gabbro in serpentinized mantle

(3) **Breakup and post-breakup**
- Alkaline sills in post-rift sediments

Cannat et al. 2009

ODP Site 1070 9R-1
ODP Site 1276-87R-6

Cannat et al. 2009
Numerical technique

• Same conservation of momentum and energy.

• Differ in their constitutive updates
  – Viscoplastic
  – Elastoplastic
  – Elastoviscoplastic.
  – Different approaches for localization in the brittle and ductile media.
  – It is very difficult to account for melt production and migration in a large deformation code.
  – Diking can be modeled by boundary elements.
WEAKENING OF THE LITHOSPHERE

• Needs multiple dikes.
• Normal faulting with dikes.
• A plume head is often present
• Needs 2-3 km of dikes to continue rifting with magma.
Cordillera Darwin (Patagonia)
Rocas Verde rift basin (Jurassic)

Klepeis et al., 2010
From Bialas et al., 2010.
Kinematic, Dynamic Velocity Boundary Condition

- **New Dike**
  - **Crust**
  - **Mantle**

- Velocity applied at sides of model
- No applied velocity

**Frozen Dikes**

---

Bialas, Buck and Qin, 2010
Magma Injection Weakens Lithosphere

Weak Lithosphere Extends Tectonically

Sometimes a Pulse of Extrusion Makes a Volcanic Margin

From Roger Buck
Intrusion of giant dikes explains:

1. Opening of rifts in normal continental areas

2. No opening of rifts where mantle lithosphere is thick: Cratons or old oceanic crust

3. Only a few kilometers of magmatic rifting may weaken lithosphere enough for extension to continue at moderate stress levels

4. Magma does not have to reach the surface to weaken lithosphere. Need seismics to ‘see’ magma

From Roger Buck
NEEDS A GRADUAL EVOLUTION OF THE RHEOLOGY

- Detachment faults are present.
- Weakening of the middle-lower crust by fluids.
- Late serpentinization of the mantle (fluids).

Diagram:

- Crust
- Mantle
- Lithosphere
- Asthenosphere

Graph:

- Temperature (°C)
- Pressure (MPa)
- Depth (km)
Viscous strain softening

Strong Crust, Sensitivity to Velocity
(a) High Velocity, $V = 10 \text{ cm/a}$
$t = 12 \text{ Ma}, \Delta x = 120 \text{ km}$
(b) Moderate Velocity, $V = 0.3 \text{ cm/a}$
$t = 40 \text{ Ma}, \Delta x = 120 \text{ km}$
(c) Very Low Velocity, $V = 0.06 \text{ cm/a}$
$t = 370 \text{ Ma}, \Delta x = 222 \text{ km}$

Effect Strength Lower Crust
(a) Weak Lower Crust, $V = 0.3 \text{ cm/a}$
$t = 40 \text{ Ma}, \Delta x = 120 \text{ km}$
(b) Strong Lower Crust, $V = 0.3 \text{ cm/a}$

Huismans and Beaumont, 2007
Physical Model: Both brittle and ductile deformation. Triggered by fluids/metamorphic reaction.

Logan, L

Lavier and Bennett, 2010
Semibrittle media

Increasing ratio of incompetent/competent material

Discontinuities dominant
- Seismic slip at kilometer-scale possible in interacting clusters of competent bodies
- High interaction through stress bridges
- Localized peaks in shear strain rate

Mixed continuous-discontinuous
- < meter scale seismic slip possible
- Moderate interaction between competent bodies
- Fluctuating shear strain rates

Continuous deformation dominant
- Microseismically active, flowing zone, large ruptures do not nucleate but may propagate through
- Low interaction between competent bodies
- Fairly uniform shear strain rates

Chrystalls Beach Complex, California.

Fagereng and Sibson, 2010
Partitioning between pure and simple shear.

66% of brittle material

33% of brittle material (Macroductile)
Failure envelope in the models: Middle crust is weakened.

Competent: Anorthosite
Incompetent: Quartz.

Competent: Olivine
Incompetent: Serpentine.

We can use similar mechanism for the mantle to decrease the strength in the mantle with serpentinization.

Jammes, Lavier. Manatschal, 2010
Wet vs. dry and not so wet rifts: Relation to subsidence.

**DRY RIFT/ NORMAL FAULTS**
- Very strong subsidence
- Rift flanks
- Normal fault (60-30°)

**WET RIFT/ NO NORMAL FAULTS**
- Little subsidence
- Weak ductile shear zones
- Flow of the lower crust

![Graphs showing subsidence at different time periods](image)
Rheological evolution (progressive weakening of the lithosphere)

**STRETCHING**
- Normal fault/Mohr-Coulomb
- Diffuse stretching

**THINNING**
- Detachment faults/Semi brittle.
- Granite weakened by fluids.
- Localized thinning.

**EXHUMATION**
*Detachment faults/semi brittle.
- Serpentinized mantle.
- Localized exhumation.
Typical structural and heat flow evolution
Untherner et al., 2010.
**Melt focusing mechanisms on top of shear zone.**

Holtzman and Kohlstedt 2007

Lanzo (ask Mary, or see Kaczmarek and Müntener J. Petrol 2008, in press)

Shearing with time:

Melt enhanced shearing and focussing: strain localization in presence of melt
High permeability
- 'melt conductor'

After cooling and crystallization:
mylonite and ultramylonite:
extreme localization, Low permeability
The common processes between each questions (fluid-rock interactions).

- The evolution of crustal and mantle rheology during rifting.
- The weakening effect of fluids in the crust and during mantle exhumation.
- The weakening/strengthening effect of melt and diking in both non-volcanic and volcanic environments.
- The evolution of topography (free surface), sedimentation, erosion and geological structures.