Abstract

Hydrocarbon-rich rift basins present a wide variety of structures and histories. Some are very young such as the Red Sea, others are very old and still productive such as the Barents Sea. Some have experienced a passive margin history after the rifting phase such as the Brazilian Pre-Salt basins, others have remained intra-continental rift basins with sometimes a complex polyphasic rifting history such as the Sudanese rift systems. Common points between all these rift basins are the high heat flow during the rifting phase(s) and the high sedimentation rates first related to focalized tectonic activity and then to widespread thermal subsidence. Although sedimentary patterns are extremely variable in rift basins, thick and localized lacustrine source rock as well as evaporite units sealing the system are widely found. In this context, petroleum system analysis requires a sophisticated modeling of the thermal history as well as a detailed prognosis of the sedimentary compaction and of the pressure field. This presentation will show different modeling examples of such basins throughout the world. For instance, coupling lithospheric evolution with sedimentation and integrated petroleum system modeling has proven to add value compared with user-defined heat flows applied at the base of sediments. It will be shown that the blanketing effect due to high sedimentation rate or salt diapir formation has a transient impact on the heat flow history in the lithosphere deep below the basement/sediment interface. Classic approaches based on uniform stretching factors will also be discussed as they are limited in the case of hyperextended margins where more complex models are required. In this regard, an improved lithospheric model allowing a precise description of the lithosphere shape and properties through time will be introduced. These modeling examples demonstrate the strength of the approach to build reliable geological reconstruction of the heat flow and of the pressure field through time, even from a minimum of data and in a limited time, which eventually leaves room for sensitivity and risk analysis.

References Cited


Website Cited

Coupling Basin Modeling and Lithospheric Modeling for Exploring Rift Basins

Matthieu Dubille, Marie Callies, Matthieu Gravito*
Rift basins & petroleum system

A rift is a zone where the **lithosphere** (crust + lithospheric mantle) is being pulled apart

Rift basins are often prolific petroleum provinces

- Often favorable restricted environment for **source rock** deposition
- Relatively **high maturity level** for HC generation and migration
- Various sedimentary settings, **clastic/carbonate reservoirs** and often **powerful seals** at the top
- Possibility to find various kinds small and occasionally large **traps** in deformed areas

Still questions on the **heating intensity** during the rifting and the **petroleum system timing**

**e.g. Muglad Rift Basin**

What is the migration timing for feeding shallow traps on the rift shoulder?

Is it possible to define a reliable thermal history?
Many sedimentary basins throughout the world hide a rift basin!

There is very often a basin history **AFTER** the rift(s): e.g. *Campos and Santos basins* (Brazil)

<table>
<thead>
<tr>
<th>Petrobras documentation</th>
<th>BACIA DE CAMPOS</th>
</tr>
</thead>
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Meso-cenozoic turbidites... where is the main source rock?

Deep rift basins may be new targets... and may be associated to already known shallower petroleum systems.

**Understanding & predicting such systems requires a knowledge of the thermal evolution during and after the rifting**
Rift basins... and pre/post-rift history

Many sedimentary basins throughout the world hide a rift basin!

There is even sometimes a basin history BEFORE the rift(s) = e.g. Upper Rhine Graben (URG)

Is there a remaining efficient petroleum system in the pre-rift after rifting thermal event?

European Cenozoic Rift System

Böcker et al. [2016]

Coupling Basin Modeling and Lithospheric Modeling for Exploring Rift Basins
Heating rift basins – Initiation

Typical rift systems are associated to **intense heating** of the crust and of the sediments ...

... but the heating is not always and everywhere “intense”

Volcanism + heating & weakening the continental lithosphere

Some rifts are supposed to be initiated by large hot spots.
The rift propagate far from the hot spot where the heat flow is certainly lower...

http://csmgeo.csm.jmu.edu/geollab/vageol/vahist/riftmodel.html
In fact rifting events are often **polyphasic**.

There are **sometimes successive hot spots** heating the same region... The activity of each hot spot varying through geological times.

The **volcanism** itself is occasionally a factor which must be implicitly considered in thermal modeling as it locally “brings” heat within the sediments.

**The Heat Flow history may be complex**, successive events affecting the rift basin through geologic times

*Vicente de Gouveia at al. [2018]*

Coupling Basin Modeling and Lithospheric Modeling for Exploring Rift Basins
Heating rift basins – Propagation

The rifting and oceanic breakup propagation is progressive...

- 200-220 Ma – Rifting initiation at the southern tip of Africa
- 170 Ma – Rifting along the Argentinian margin
- 140 Ma – Rifting propagation in Southern Brazil
- 132 Ma – Austral Segment breakup?
- 130-125 – Central segment rifting (Santos-Campos)
- 113 Ma – Central Segment breakup?

The rifting and oceanic breakup propagation is progressive...
During and after the breakup, extension is associated with more or less powerful « plastic » convection cells in the asthenosphere, below the lithosphere... the main driving force being the « slab pull ».

Far from hot spots the heat flow is certainly related to the extension rate: high extension rate = rapid isotherm uplift not fully compensated by heat diffusion = higher heat flow
Heating rift basins – « less hot » cases

Sometimes the rifting is initiated by large scale lithospheric movements without mantle plumes and convection cells...

Such rift systems including large scale pull apart basins are not as hot as the other rift systems... but still hot.

CO2 generation & migration modeling in ultra-deep Cenozoic basins (>16km)

From Tapponnier et al. [1982]
Now, let’s go back to the basin modeling...

Geological model that integrates all G&G data in a single coherent framework

**INPUTS**
- Geophysics
- Petrophysics
- Geochemistry
- Stratigraphy and lithofacies (e.g. DionisosFlow model)

**OUTPUTS**
- Solution for analyzing the evolution of sedimentary basin and more particularly petroleum systems through geological times
- Better assessment of exploration risks
- Drainage areas & migration paths
- Maturity
- HC volumes
- Petroleum system chart
- CRS mapping (SR and HC charge)

It works everywhere even far from the wells and with poor seismic data

The core is the **thermal model** which computes the maturity of the source rock. It depends on thermal boundary conditions at the top and at the base of the sediments.
Options for thermal boundary conditions

1. **Base sediment heat flow**
   Extrapolated from calibration points (well data)...

   **To avoid!**

   “Smallpox mapping”
   Nothing to see with geology.
   Not even good for computing the HF at present day far from the wells.

2. **Lithospheric model**
   Thermal model of the “crust + the lithospheric mantle” **fully coupled** to the sedimentary “basin model”.

   The base of this model is a deep layer, which can be (but which is not necessarily) the **lithosphere/asthenosphere boundary** (LAB, LVZ).

   LAB often associated to the isotherm $\sim 1300^\circ$C

   The lithospheric model reproduces main lithospheric process including rifting events.

   **Its objective is to compute a geologically and physically consistent heat flow at the base of the sediments through geological times.**
Options for thermal modeling of rifting

The rifting modeling is based on the Beta Factor (\(\beta\)) concept

\[ \beta = \frac{\text{Crust Thickness initial}}{\text{Crust Thickness final}} \]

- **« Pure » MacKenzie Model**
  - Upper Crust: \(H_C\)
  - Lower Crust: \(H_m\)
  - Lithospheric Mantle: \(H_m\)
  - 3 units (UC, LC, LM)
  - Homogeneous \(\beta\)

- **« Improved » MacKenzie Model**
  - \(\beta_C = \frac{H_C}{H_c}\)
  - \(\beta_{th} = \frac{H_m}{H_m} = \beta_C\)
  - 3 units (UC, LC, LM)
  - Heterogeneous \(\beta\) (UC vs. LC)
  - Specific « thermal » \(\beta_{th}\) characterizing the potential uplift of the basal isotherm
  - Possible lithology change
  - Variable bottom condition (HF or temperature)

- **New « Flexible » Model**
  - Base of the model
  - \(1300^\circ C\) isotherm rise (for example)
  - \(n\) units (unlimited)
  - Same as « improved » model
  - + base of the model manually adjustable at every timestep
  - + possible subdivisions

The 3 options are implemented in OpenFlow.
**Why coupling sediment and crustal model?**

**AT PRESENT**

3D Example from **Offshore Europe**: thermal effect of a salt diapir (high thermal cond.)

**Heat Flow (HF) mW/m²**

\[ HF = \lambda \cdot \text{grad} \ T \]

- \( \lambda \): thermal conductivity

**Highly variable HF at base sediment (45-65 mW/m²)...**

The model considers lithology effects, high sedimentation rates, overpressures, boundary conditions changes, etc.

**Possibility to assess the HF far from calibration points.**

**WARNING**, many other models are not fully coupled!

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**Coupling Basin Modeling and Lithospheric Modeling for Exploring Rift Basins**
Coupling sedimentary and crustal model

3D Example from **Offshore Europe** (4 rifting events, blanketing effect, erosion effect,...)

**THROUGH TIME**

- Heat Flow mW/m²
- Target in unexplored area

**Through Time**

- **Rifting effect**
- **Blanketing effect**
- **Rifting effect**
- **Blanketing effect** (high sedimentation rate)
- **Erosion effect**

**HF evolution through time influenced both by sedimentary processes & riftings.**

- **Early Carboniferous rift (main)**
  - β = 1.4
  - (pure MacKenzie)

- **Early Triassic rift**
  - β = 1.1-1.3
  - (pure MacKenzie)

- **Early Cretaceous rift**
  - β = 1-1.2
  - (pure MacKenzie)

- **North Norwegian Sea breakup**
  - β = 0
  - βth = 1-1.3
  - (Improved MacKenzie)

**Heat Flow** mW/m²

**Target in unexplored area**

**Burial curve**

**Blanketing effect**

**Erosion effect**

**Temperature [°C]**

**Heat Flow [mW/m²]**

**Geological time [Ma]**

**3D Example from Offshore Europe** (4 rifting events, blanketing effect, erosion effect,...)
Let’s have a look to another example **Offshore Canada** with more intense rifting & magmatism.

Lithospheric and basin models are **predictive**.

First deep offshore wells drilled after the study (hyperextended crust domain), more than 50 km from the closest calibration well on the shelf...
More flexibility in rifting modeling

Now, how far can we go in a more complex / more detailed study case?

Reconstruction

Serpentinization of exhumed mantle

0Ma – PRESENT

Facies Thermal Properties

Callies et al. [2017]

Coupling Basin Modeling and Lithospheric Modeling for Exploring Rift Basins
Heat Flow through time

Callies et al. [2017]

Coupling Basin Modeling and Lithospheric Modeling for Exploring Rift Basins
Resulting maturity analysis

**Uncertainty analysis on the maturity level of potential petroleum systems**

**Heat Flow (HF) mW/m²**

HF focalization at horst crest

*Results presented in AAPG Bulletin 102(04):563-585 · April 2018*

*Callies et al. [2017]*

Coupling Basin Modeling and Lithospheric Modeling for Exploring Rift Basins
Modeling rift basin – The commandments

Thou shalt define a deep base for the model within the lithosphere.
- « Buffer » for thermal anomalies in sedimentary basins evolution
- Direct modeling of rifting processes and much more.
- LAB at ~1300°C can be the model base, it may be a convenient & relatively stable reference

Thou shalt use a model with sediments and lithosphere fully coupled.

Thou shalt not be shy in building thy lithospheric model.

Collecting information is not as difficult as it seems!

- Quite easy to find or compute Moho depth
- More ambiguous LAB definition, use analog
- Consider bibliography and analogs for distributing crustal lithologies
- Check the presence of hot spots, mantle plumes, intense magmatism, etc.
- Start simple, add complexity if needed

With a few calibration points (HF maps, T, VR0, etc.), coupling a simple lithospheric model with a basin model always give better results
Coupling Basin Modeling and Lithospheric Modeling for Exploring Rift Basins

**Modeling rift basin – Key notes**

- **Very quick thermal calibration** with a well-prepared model.
- **Geologically and physically valid results** through geological times obtained with a minimum of data.
- **Only way to fully predict the thermal history** even if there are plenty of well data.

**Key points**:

- Several lithospheric modeling options available, there are flexible approaches for modeling all kinds of rifting.
- Thermal disturbances propagate deep into the crust: use a buffer!

**Example**: Muglad Rift Basin, Sudan(s)

**Map**: Present day

**Legend**:

- Mass of Oil per Area (Kg/m²)
- Scale:
  - 0
  - 500
  - 1,000
  - 1,500
  - 2,000
  - 2,500
  - 3,000
  - 4,000
  - 5,000

Thank You!
Some references


