Coupling Basin Modeling and Lithospheric Modeling for Exploring Rift Basins*

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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.

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AAPG 2020 - BAHRAIN

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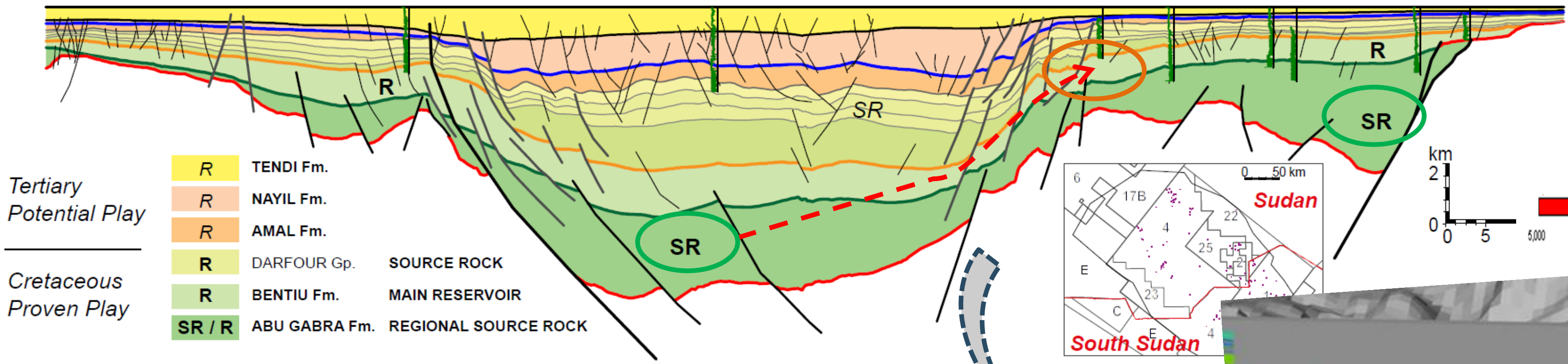
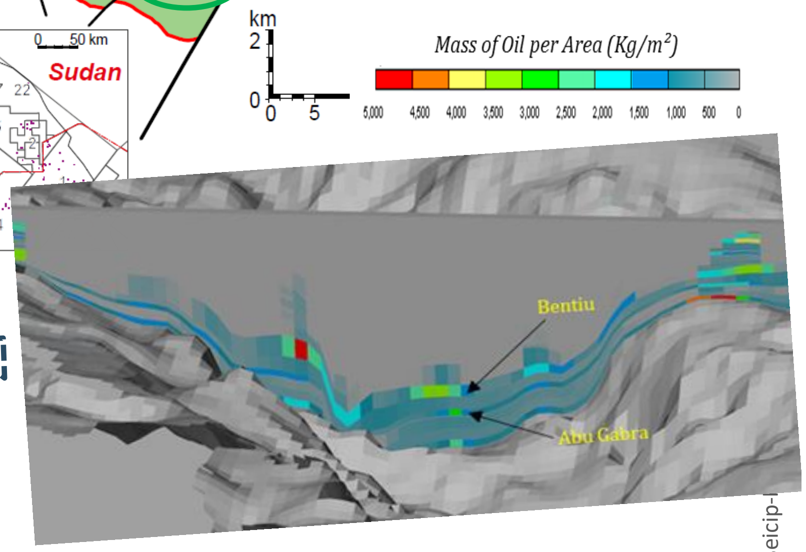
Rift basins & petroleum system

- 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 ?

?

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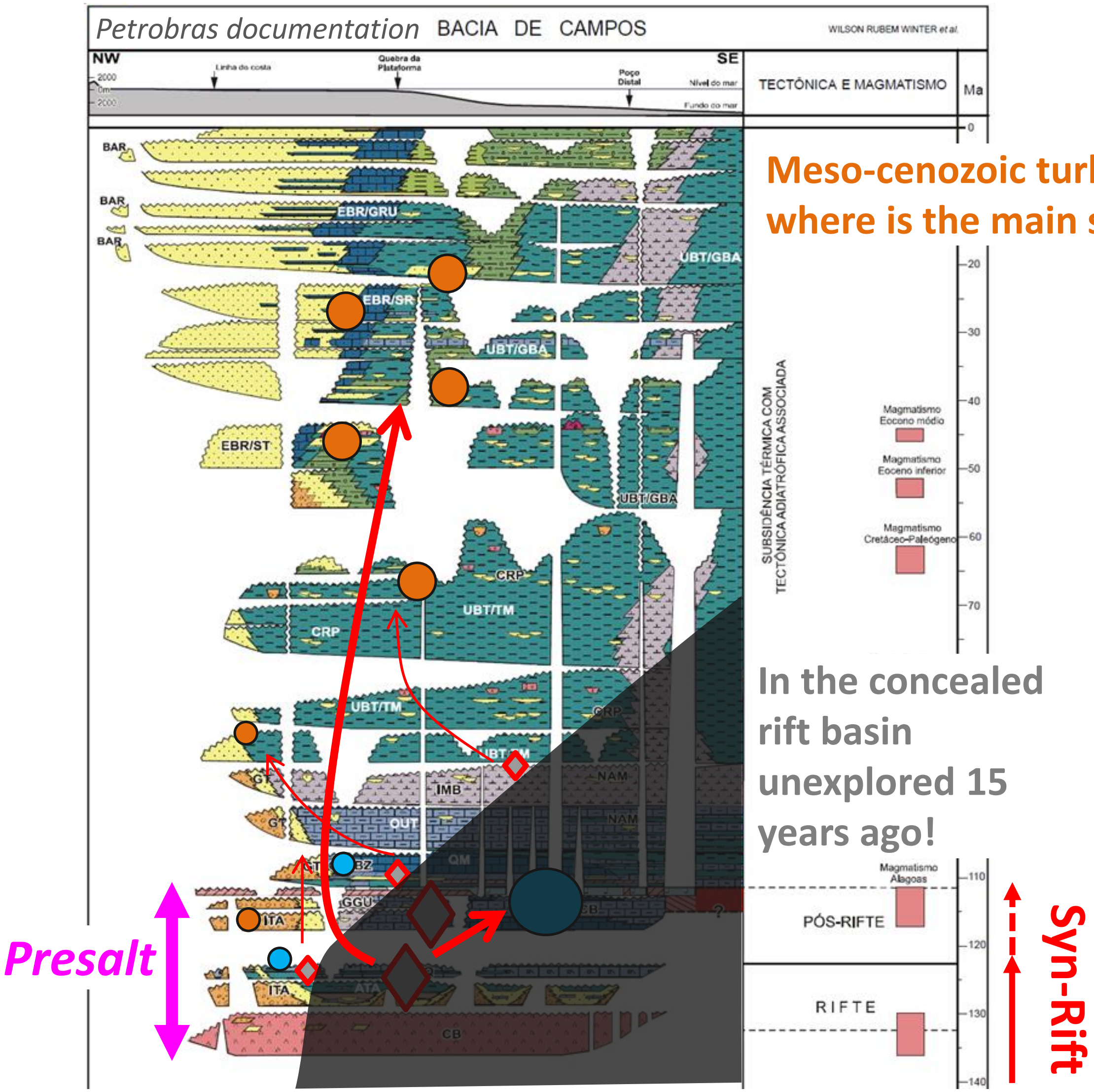
Rift basins… and pre/post-rift history

Many sedimentary basins throughout the word hide a rift basin!

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



There are **concealed rift basins** in many other petroleum provinces:

- Beneath L. Jurassic salt in **Gulf of Mexico**?
- Beneath Hormuz salt in the **Gulf** & in **Oman**?
- Beneath Miocene salt in the **Red Sea**?
- …

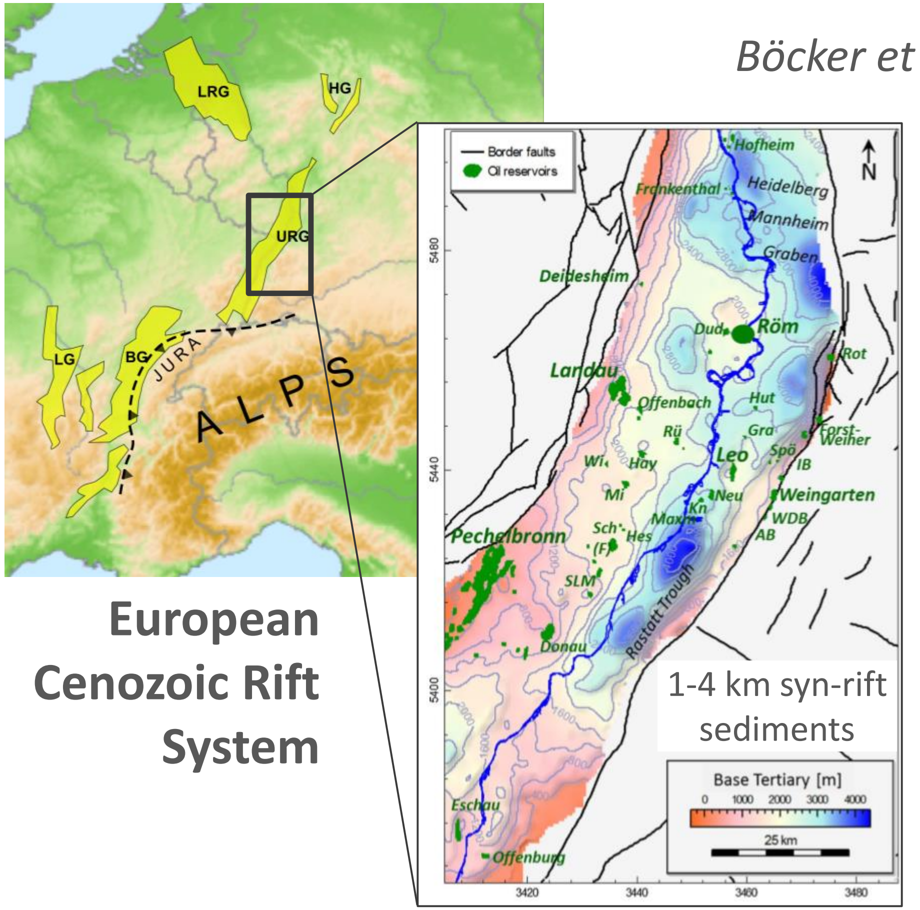
Deep rift basins may be new targets… and may be associated to already known shallower petroleum systems.

Understanding & predicting such systems requires a knowledge of the thermal evolution <u>during</u> and <u>after</u> the rifting

Rift basins… and pre/post-rift history

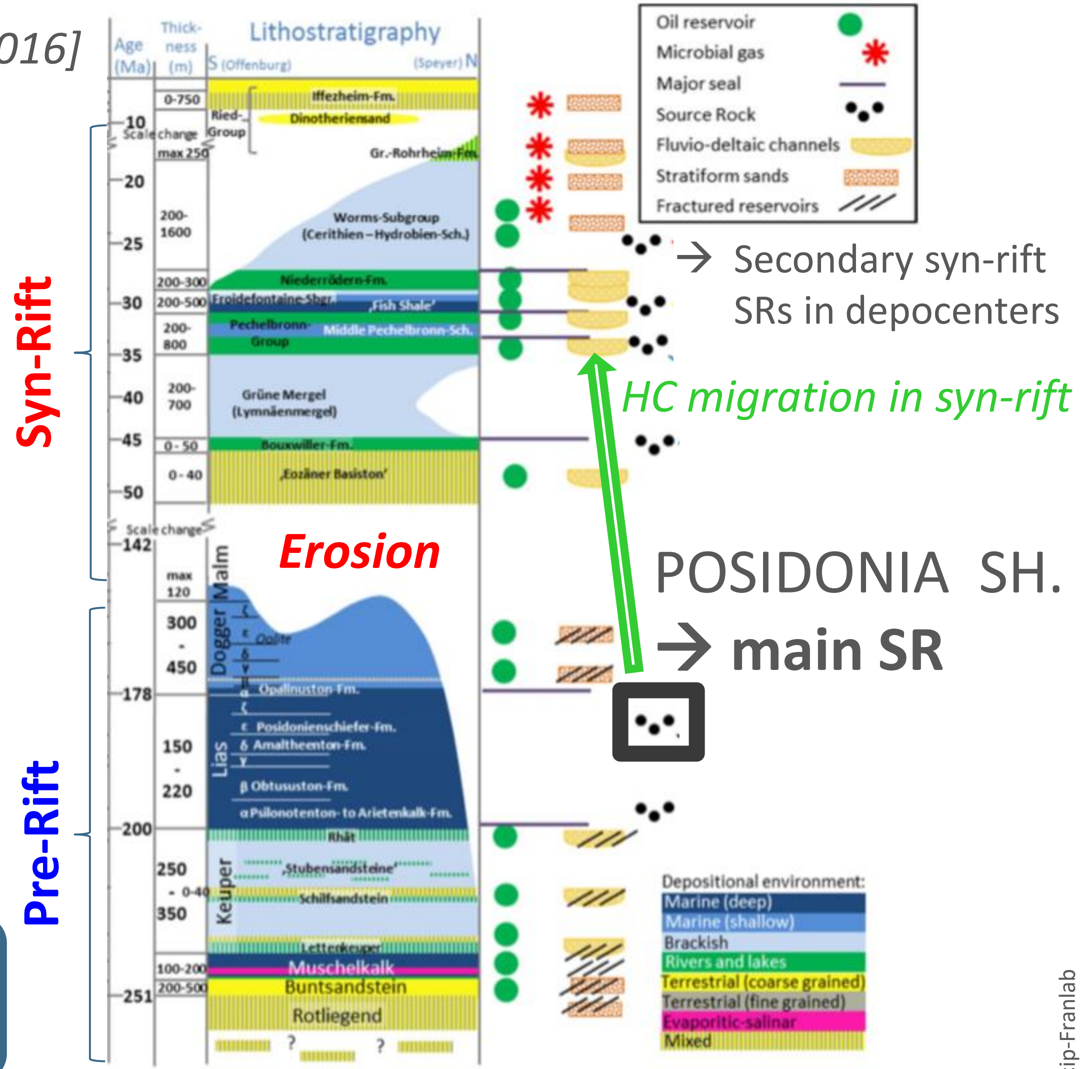
Many sedimentary basins throughout the word hide a rift basin!

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



European Cenozoic Rift System

Böcker et al. [2016]

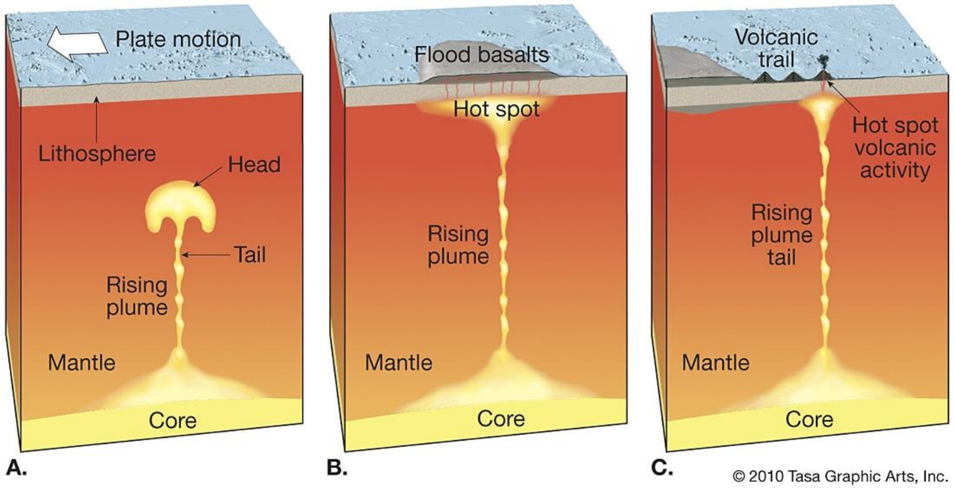


Is there a remaining efficient petroleum system in the pre-rift after rifting thermal event?

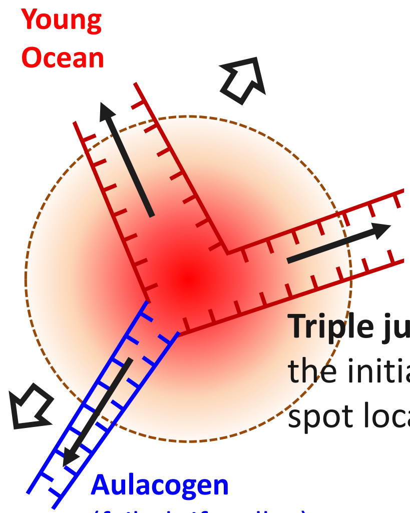
Heating rift basins – Initiation

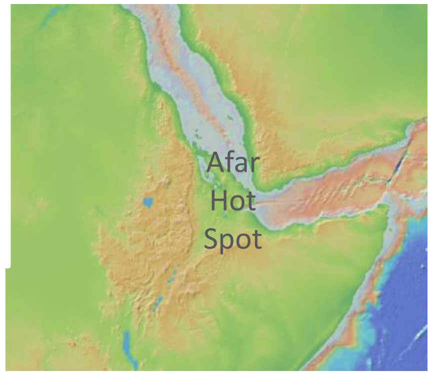
- Typical rift systems are associated to **intense heating** of the crust and of the sediments …

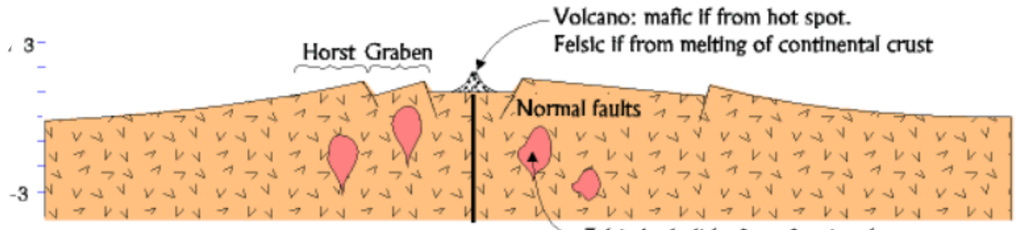
… but the heating is not always and everywhere “intense”



Volcanism + heating & weakening the continental lithosphere







Hot Spot / Thermal Doming

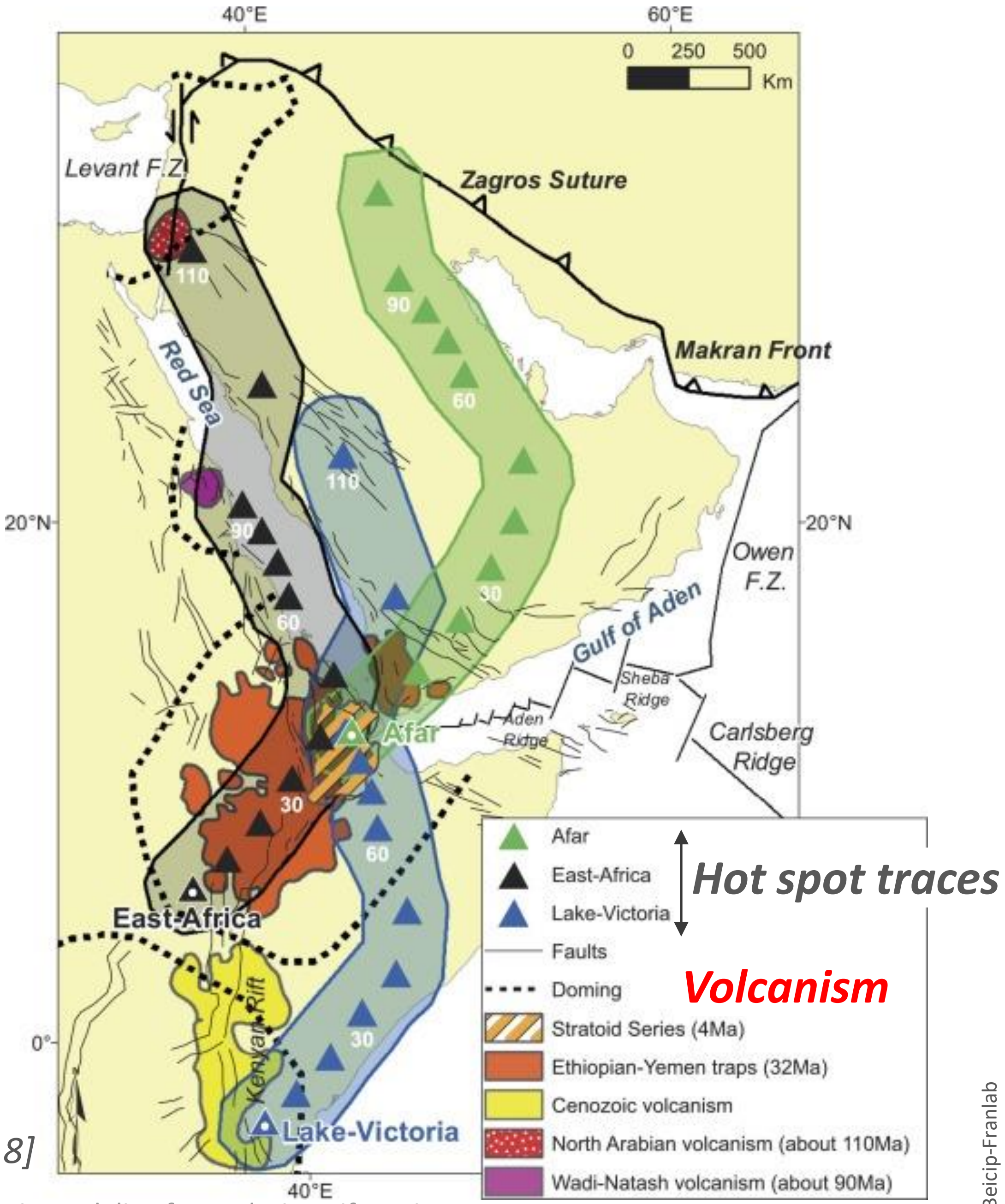
http://csmgeo.csm.jmu.edu/geollab/vageol/vahist/riftmodel.html

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…

Heating rift basins – Initiation

- 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]

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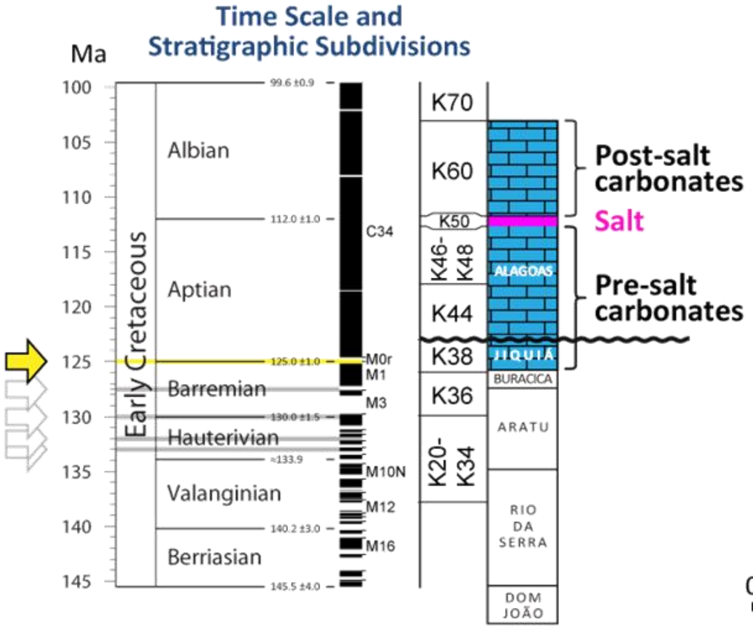
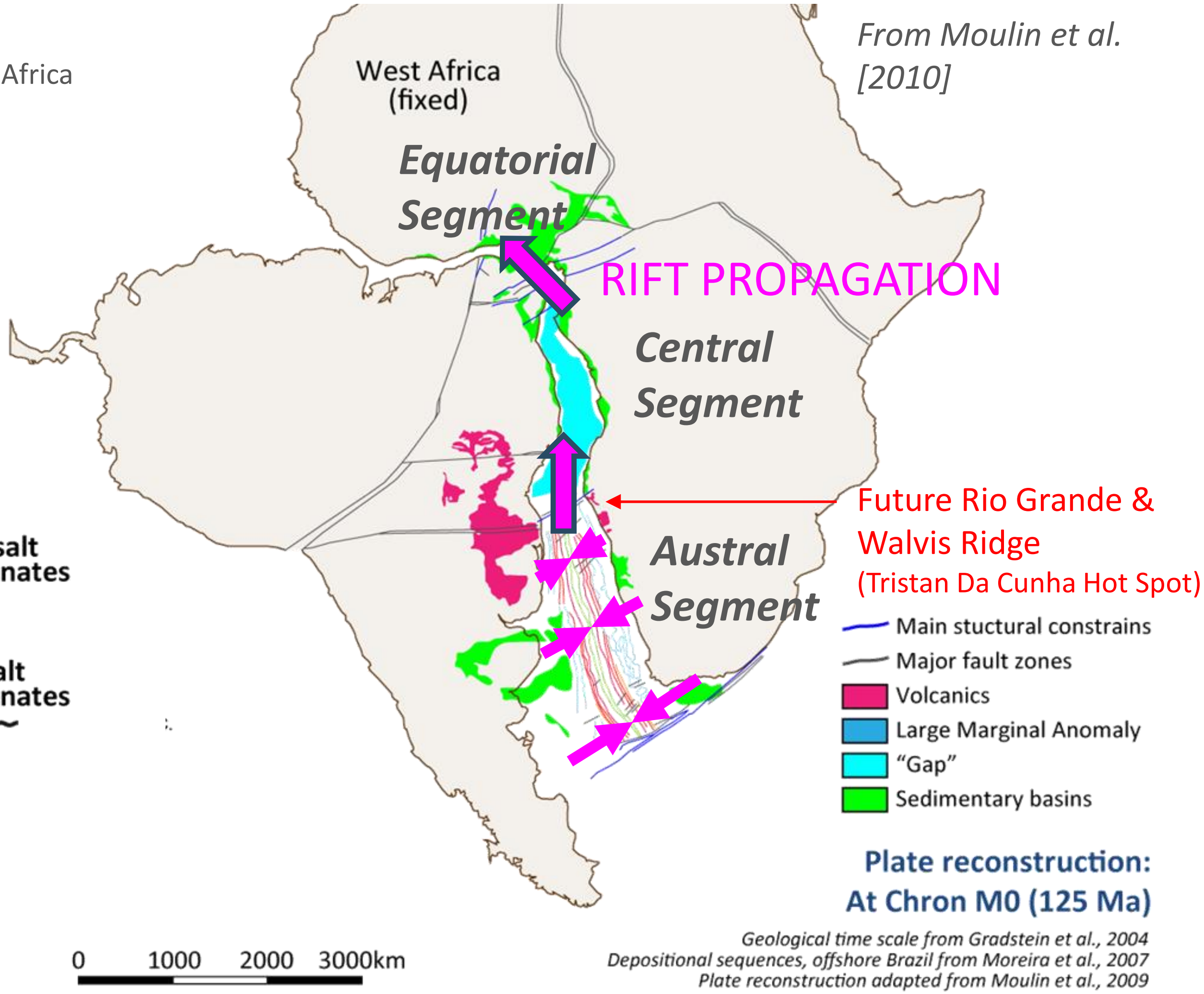
Heating rift basins – Propagation

- 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 ?





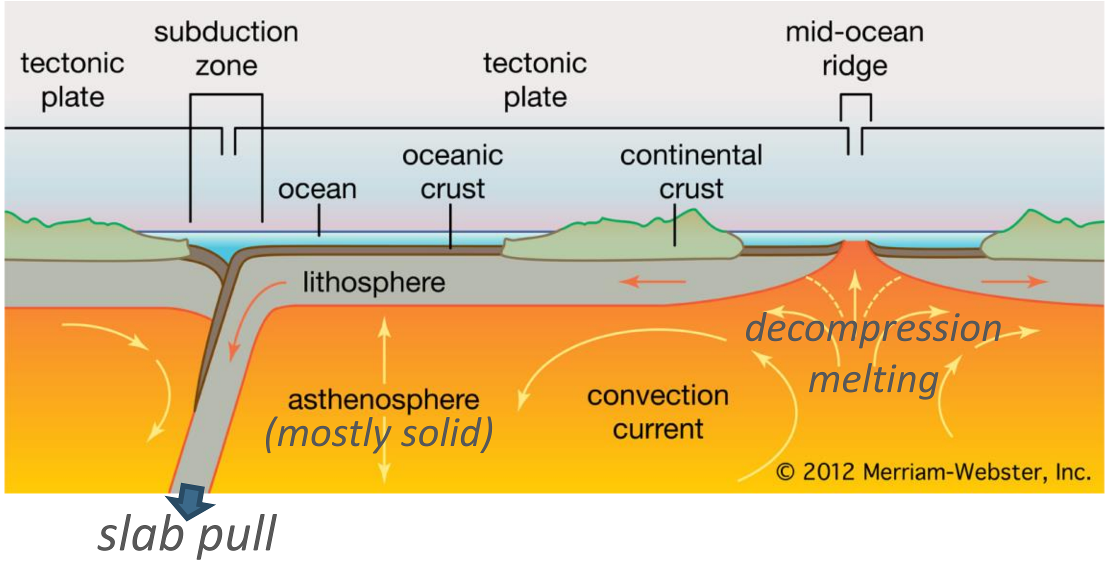
Geological time scale from Gradstein et al., 2004
Depositional sequences, offshore Brazil from Moreira et al., 2007
Plate reconstruction adapted from Moulin et al., 2009

Thermal effect of the rifting is spatially diachronous in large basins,
both transversally and longitudinally.

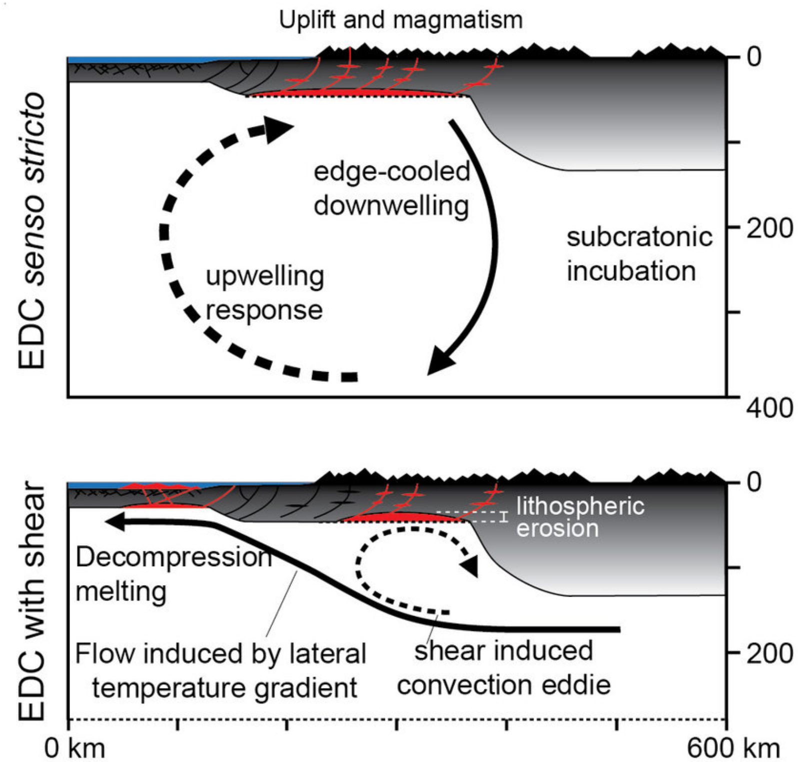
Heating rift basins – Perpetuation

- During and after the breakup, extension is associated with more or less powerfull « plastic » **convection cells** in the asthenosphere, below the lithosphere… the main driving force being the « slab pull ».

Rifting center after the breakup



Of course things can be more complex…



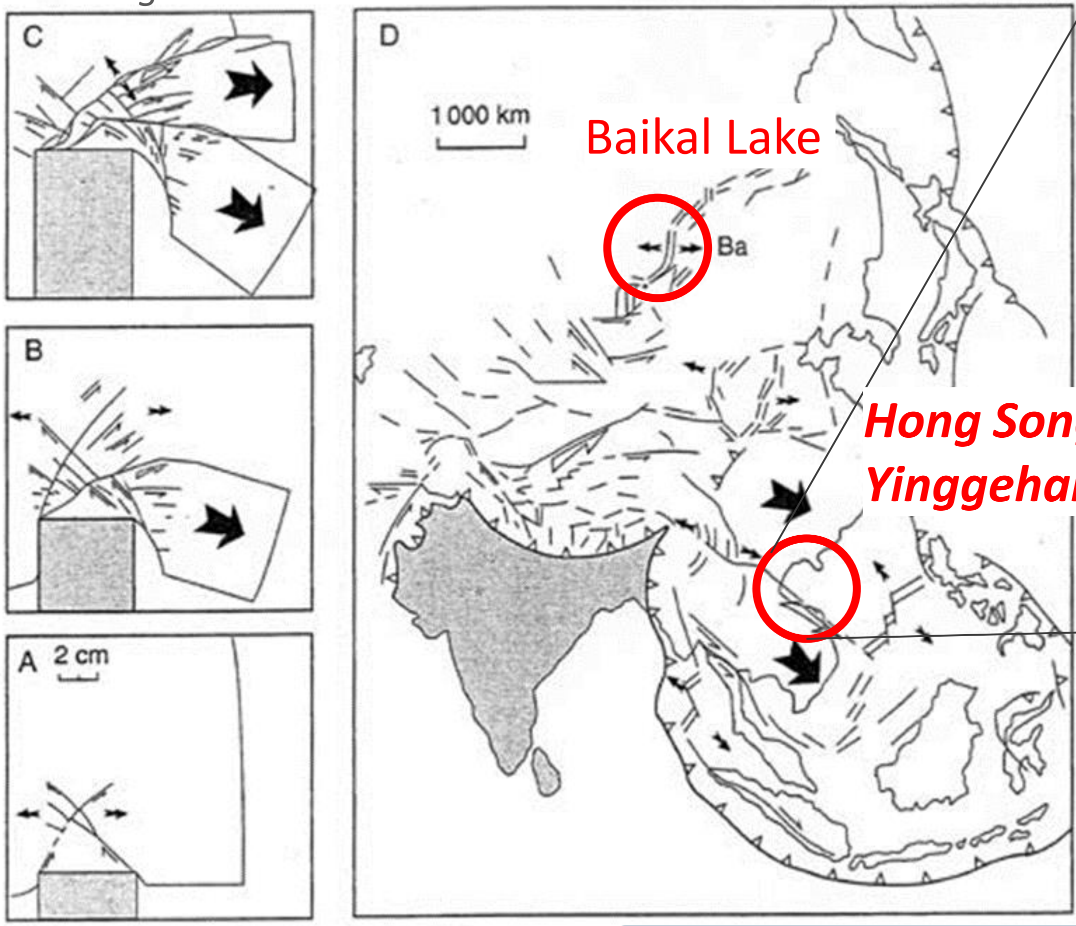
"Edge Driven Convection" (EDC)
in Dockman from Kaislaniemi and van Hunen [2014]

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

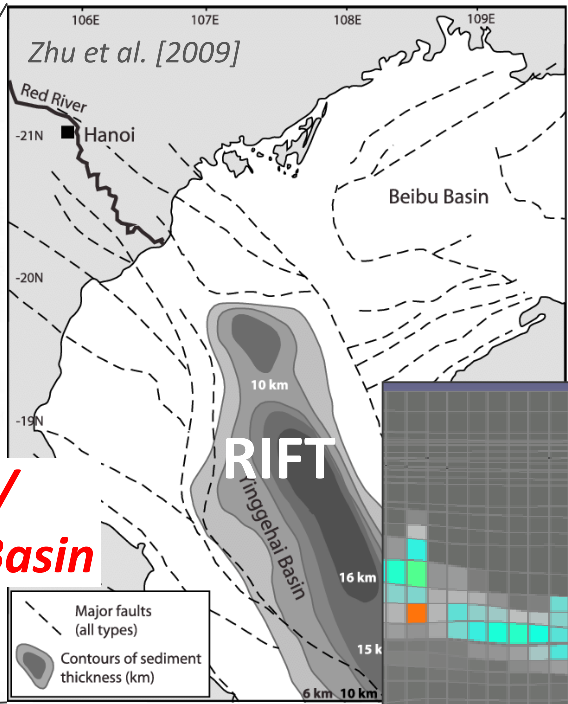
Heating rift basins – « less hot » cases

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

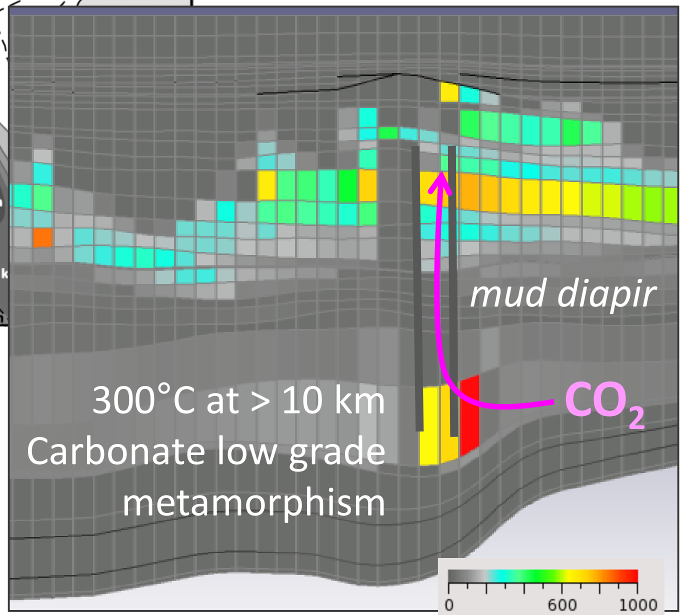
Analogic model



From Tapponier et al. [1982]



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



GAS kg/m^2

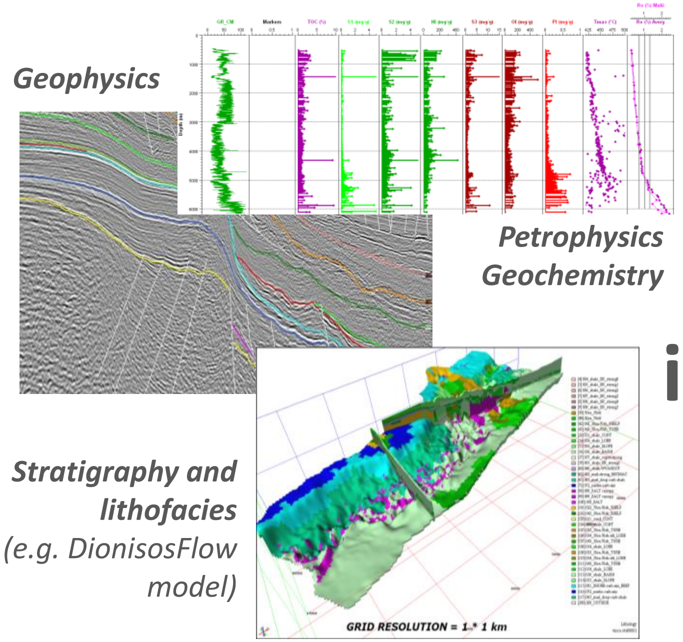
Such rift systems including large scale pull apart basins are not as hot as the other rift systems… but still hot.

Now, let's go back to the basin modeling…

- Geological model that integrate all G&G data in a single coherent framework
- Solution for analyzing the evolution of sedimentary basin and more particularly petroleum systems through geological times

INPUTS

Geophysics



Petrophysics Geochemistry

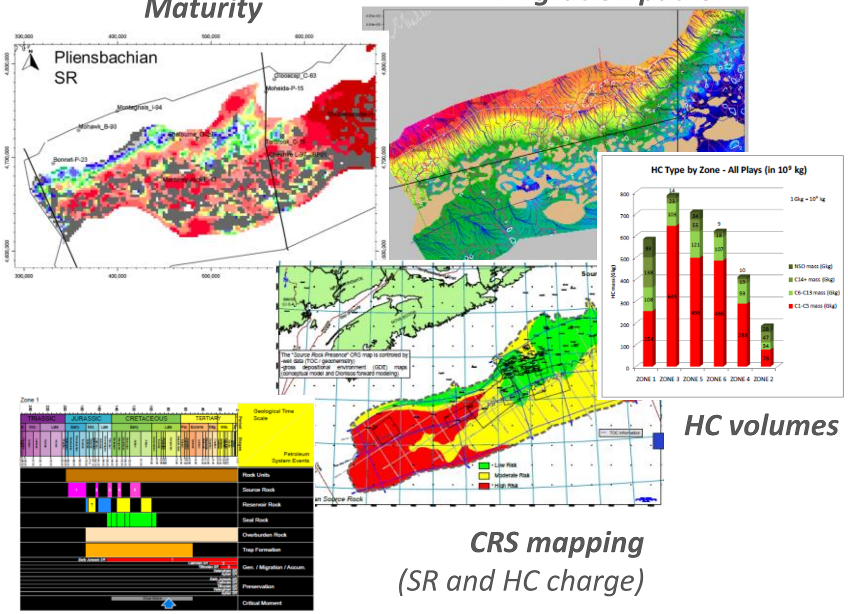
Stratigraphy and lithofacies (e.g. DionisosFlow model)

in TemisFlow™ =

OUTPUTS

Maturity

Drainage areas & migration paths



HC volumes

CRS mapping (SR and HC charge)

Petroleum system chart

Better assessment of exploration risks

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

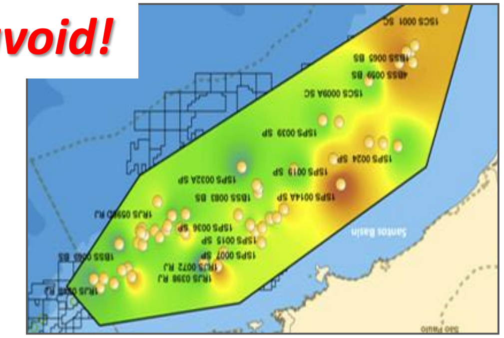
The core is the **thermal model** which computes the maturity of the source rock.
It depends on thermal boundary conditions at the top and <u>at the base of the sediments</u>.

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

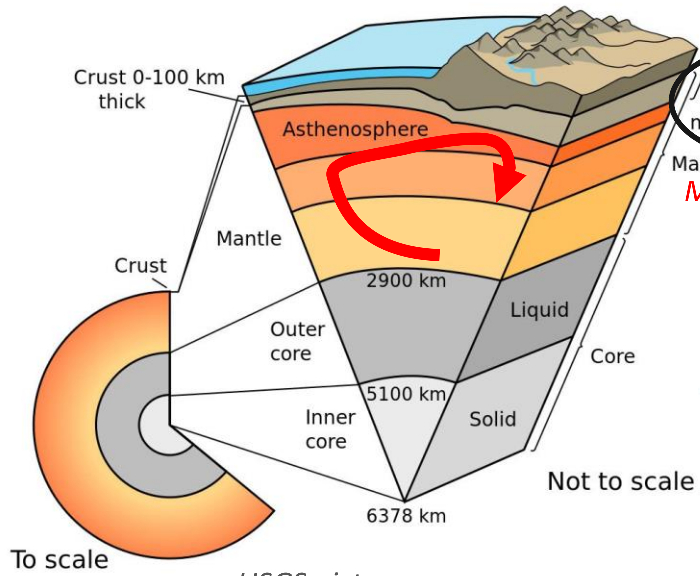
Thermal model of the "crust + the lithospheric mantle" **fully coupled** to the sedimentary "basin model".

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

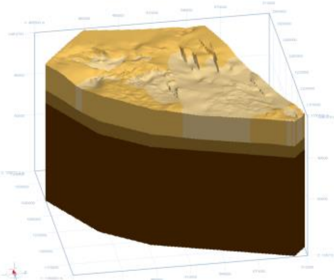
LAB often associated to the isotherm **~1300°C**

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.



USGS picture



3D lithospheric model in TemisFlow

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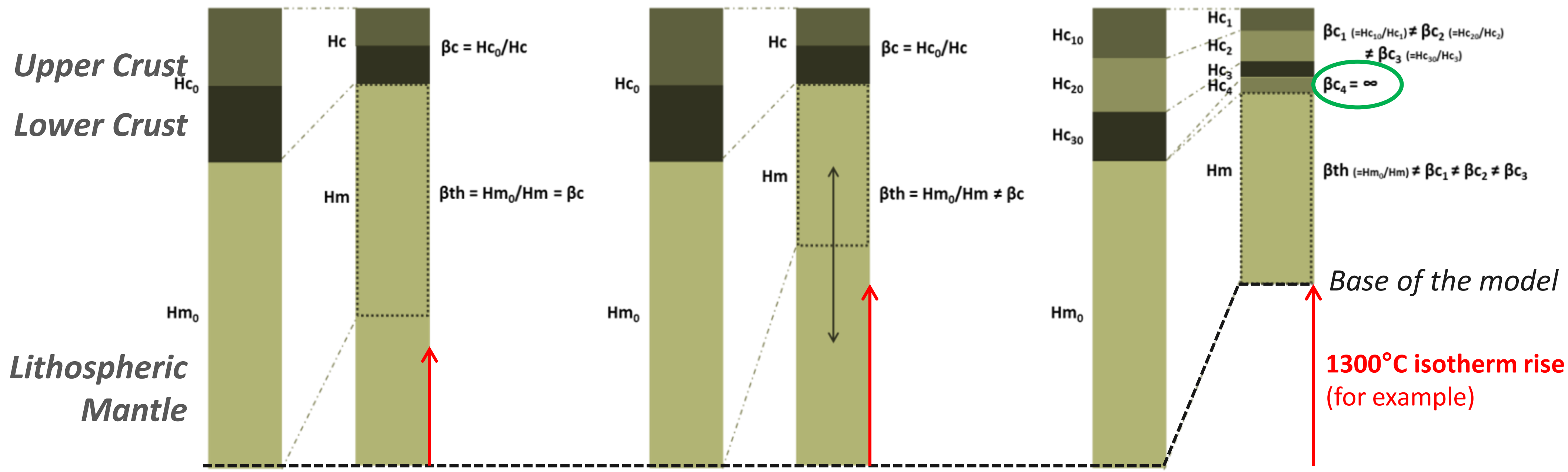
Options for thermal modeling of rifting

- The rifting modeling is based on the Beta Factor (β) concept $\beta = \frac{Crust\ Thickness_{initial}}{Crust\ Thickness_{final}}$

« Pure » MacKenzie Model | **« Improved » MacKenzie Model** | **New « Flexible » Model**



« Pure » MacKenzie Model
- 3 units (UC, LC, LM)
- Homogeneous β

« Improved » MacKenzie Model
- 3 units (UC, LC, LM)
- Heterogeneous β (UC vs. LC)
- Specific « thermal » βth characterizing the potential uplift of the basal isotherm
- Possible lithology change
- Variable bottom condition (HF or temperature)

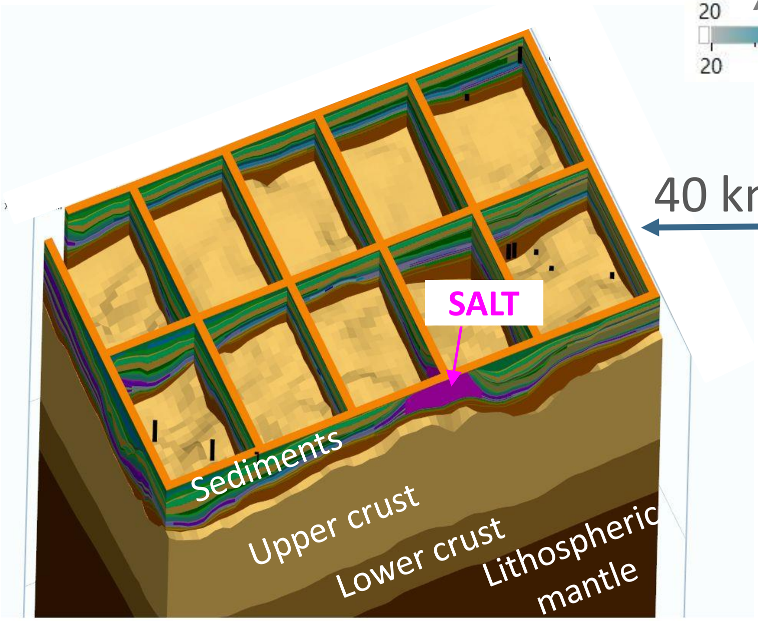
New « Flexible » Model
- n units (unlimited)
- Same as « improved » model + base of the model manually adjustable at every timestep + possible subdivisions

The 3 options are implemented in **OpenFlow.**

Why coupling sediment and crustal model?

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

AT PRESENT

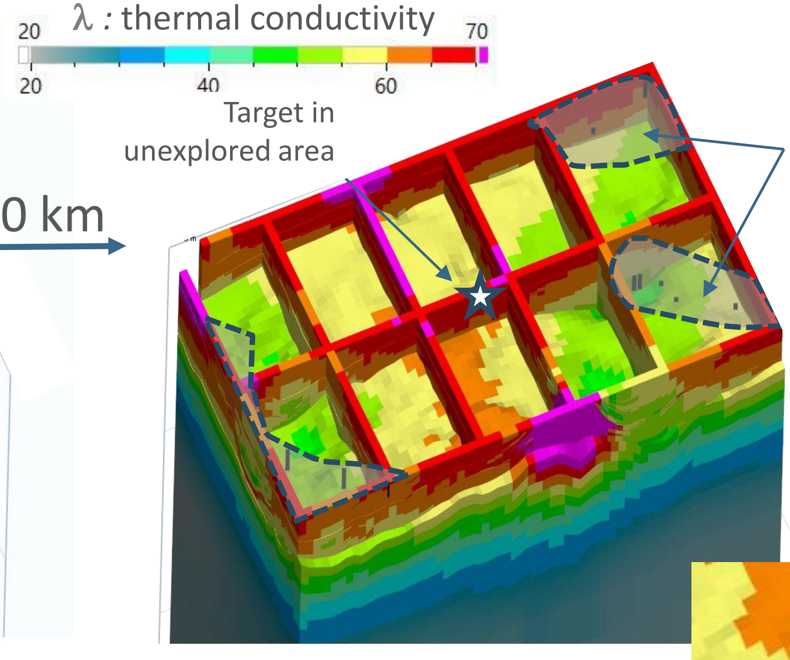


40 km

Heat Flow (HF) mW/m²

HF = λ . grad T

λ : thermal conductivity

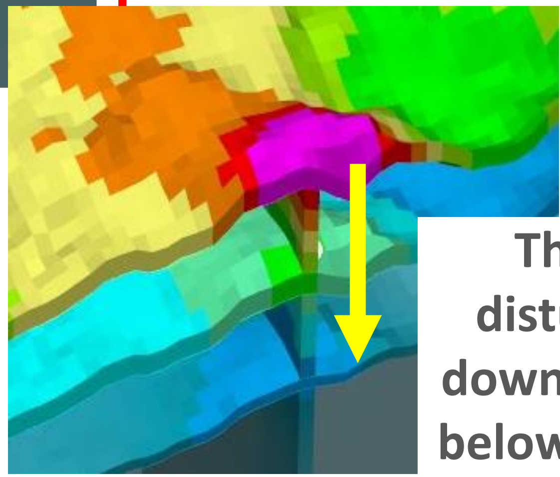


Highly variable HF at base sediment (45-65 mW/m²)…

Sedimentary Model

Lithospheric Model

Continuous heat transfer during the simulations ***COUPLING***



Thermal disturbance down to 18 km below the base sediment!

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

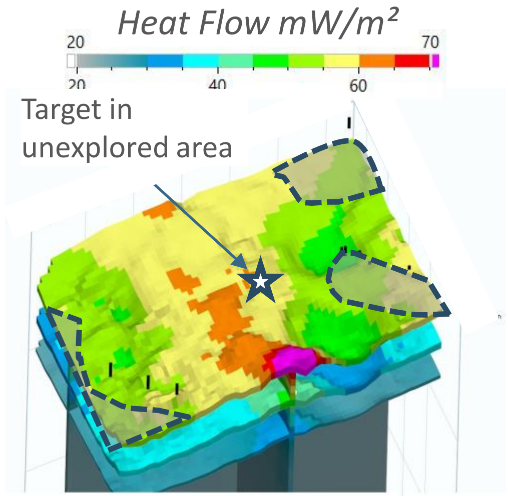
Possibility to assess the HF far from calibration points.

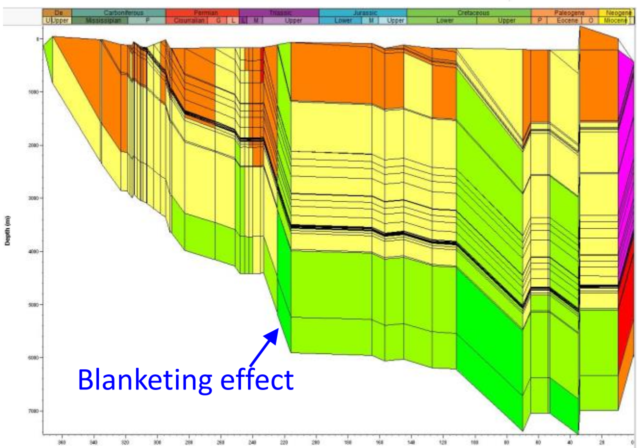
WARNING, many other models are not fully coupled!

Coupling sedimentary and crustal model

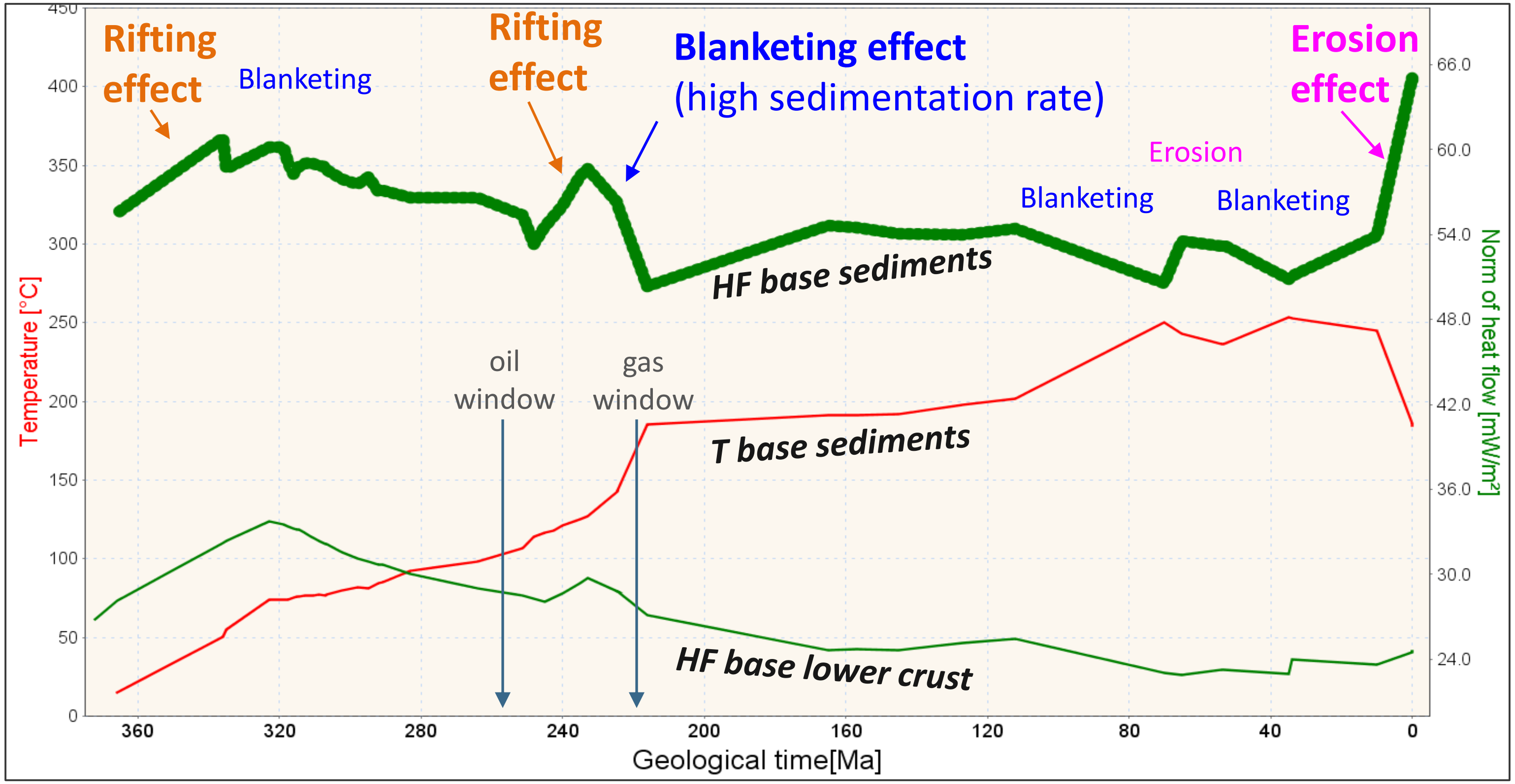
- 3D Example from ***Offshore Europe*** (4 rifting events, blanketing effect, erosion effect,…)

THROUGH TIME





Burial curve

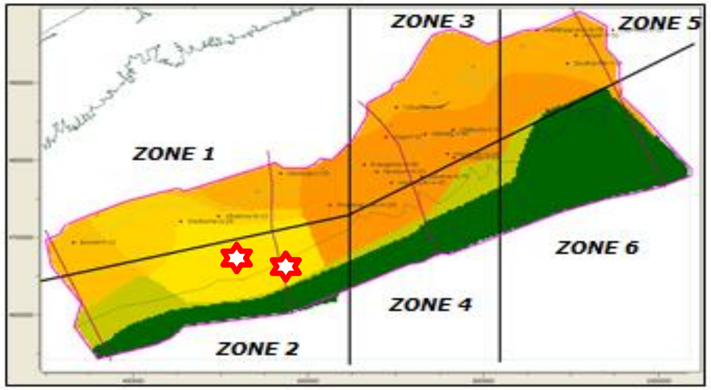


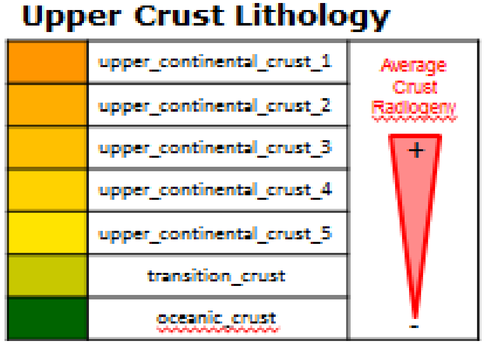
Early carboniferous rifting (main)	***Early Triassic*** rifting	**Early Cretaceous** rifting	**North Norwegian Sea breakup** (distal lithospheric effect)
β = 1,4	**β = 1-1,3**	**β = 1-1,2**	**β = 0**
(pure MacKenzie)	**(pure MacKenzie)**	**(pure MacKenzie)**	**βth = 1-1,3** **(Improved MacKenzie)**

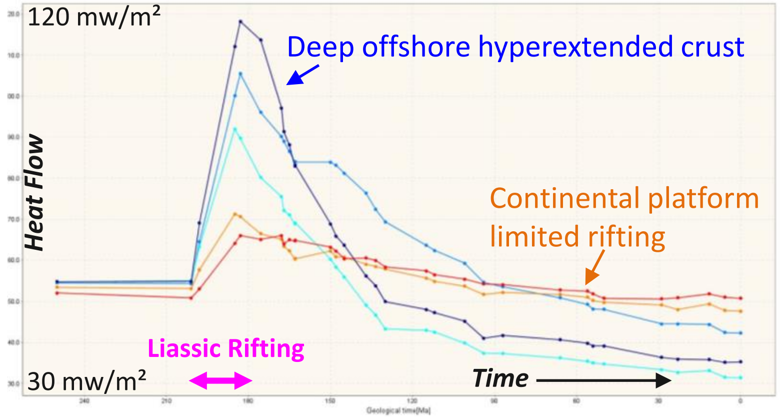
HF evolution through time influenced both by **sedimentary processes & riftings.**

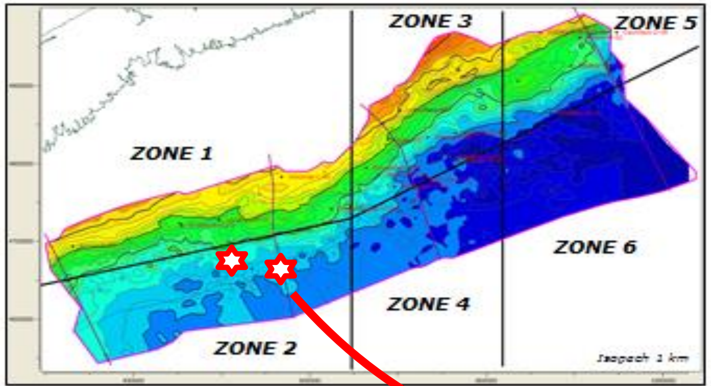
Model **predictivity** – e.g. Nova Scotia

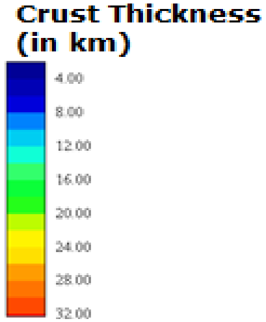
- Let's have a look to another example ***Offshore Canada*** with more intense rifting & magmatism

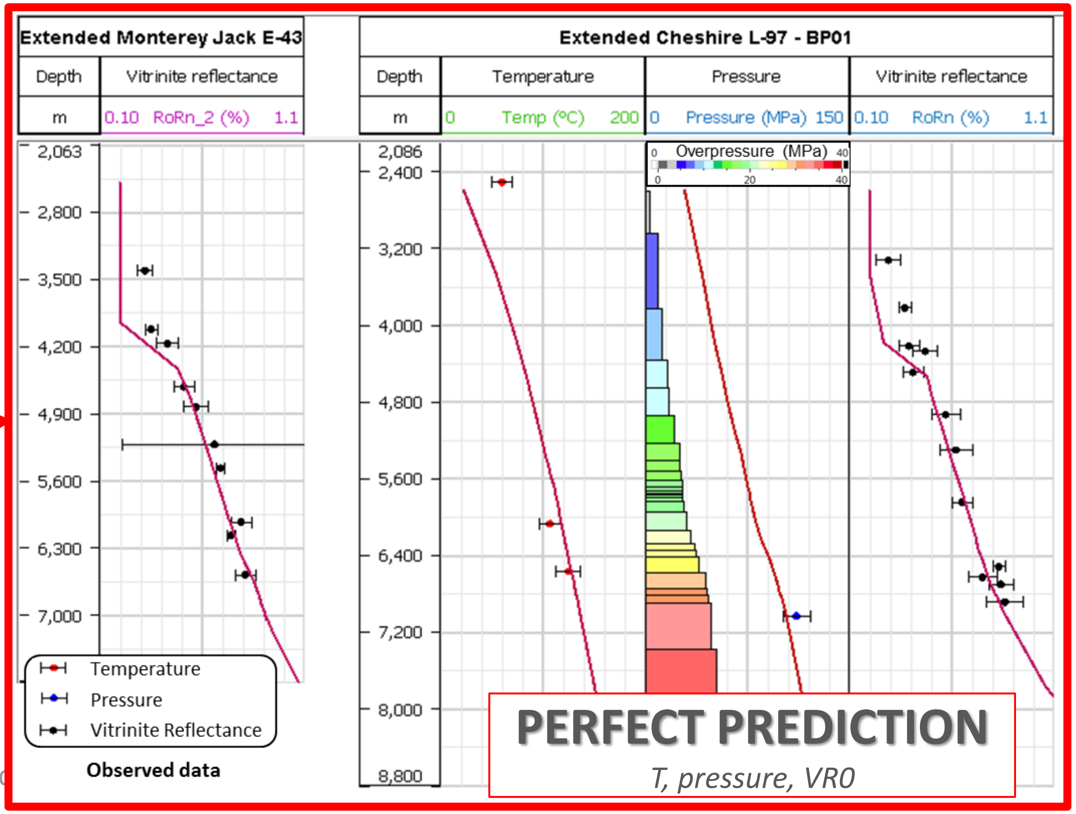










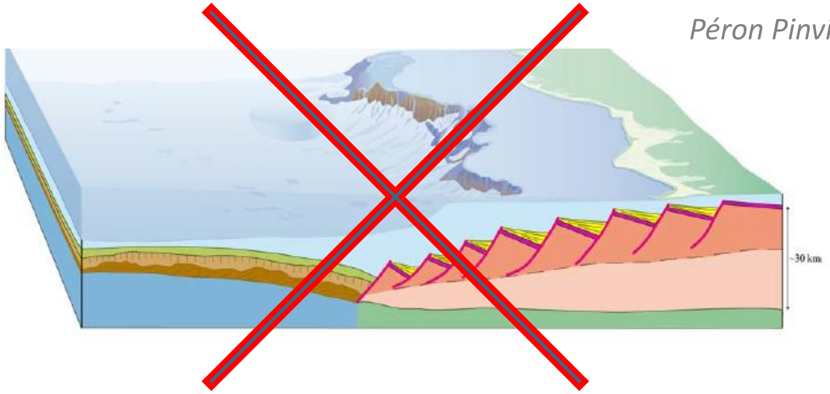


First deep offshore wells drilled <u>after the study</u>
(hyperextended crust domain), more than 50 km from the closest calibration well on the shelf…

Lithospheric and basin models are predictive.

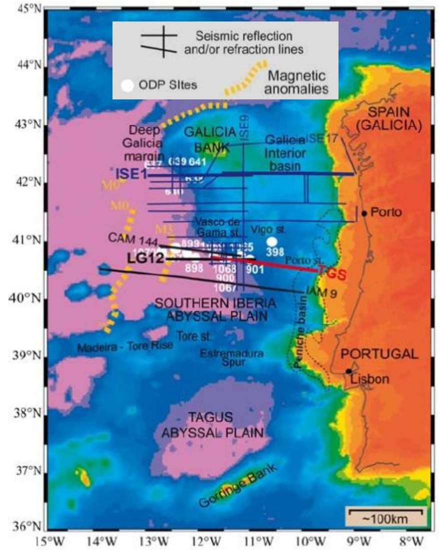
More **flexibility** in rifting modeling

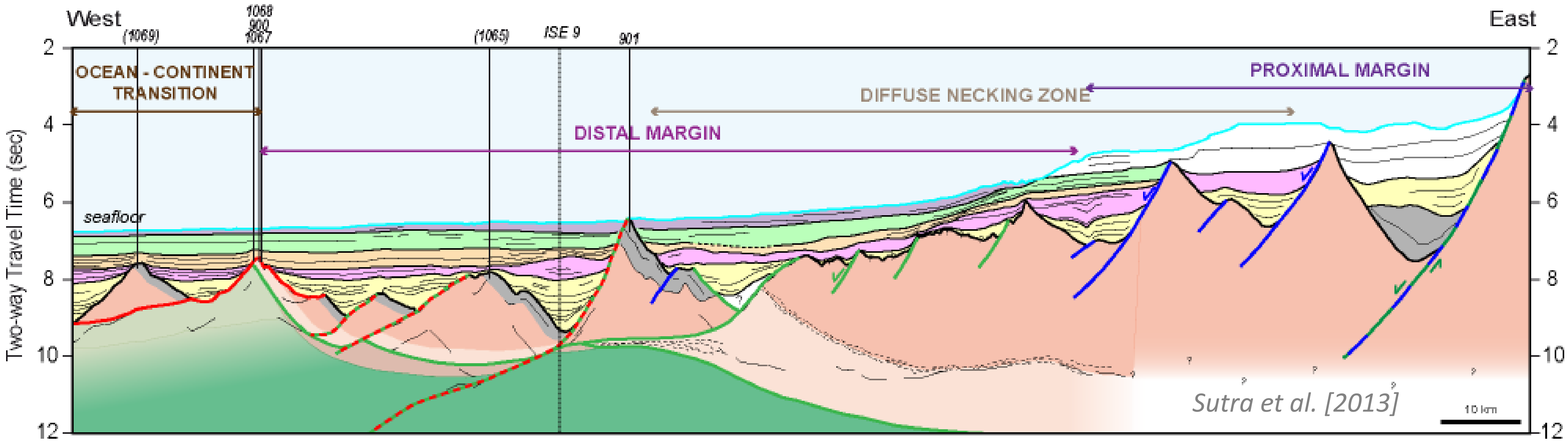
- Now, how far can we go in a more complex / more detailed study case?



Péron Pinvidic et al.[2008]

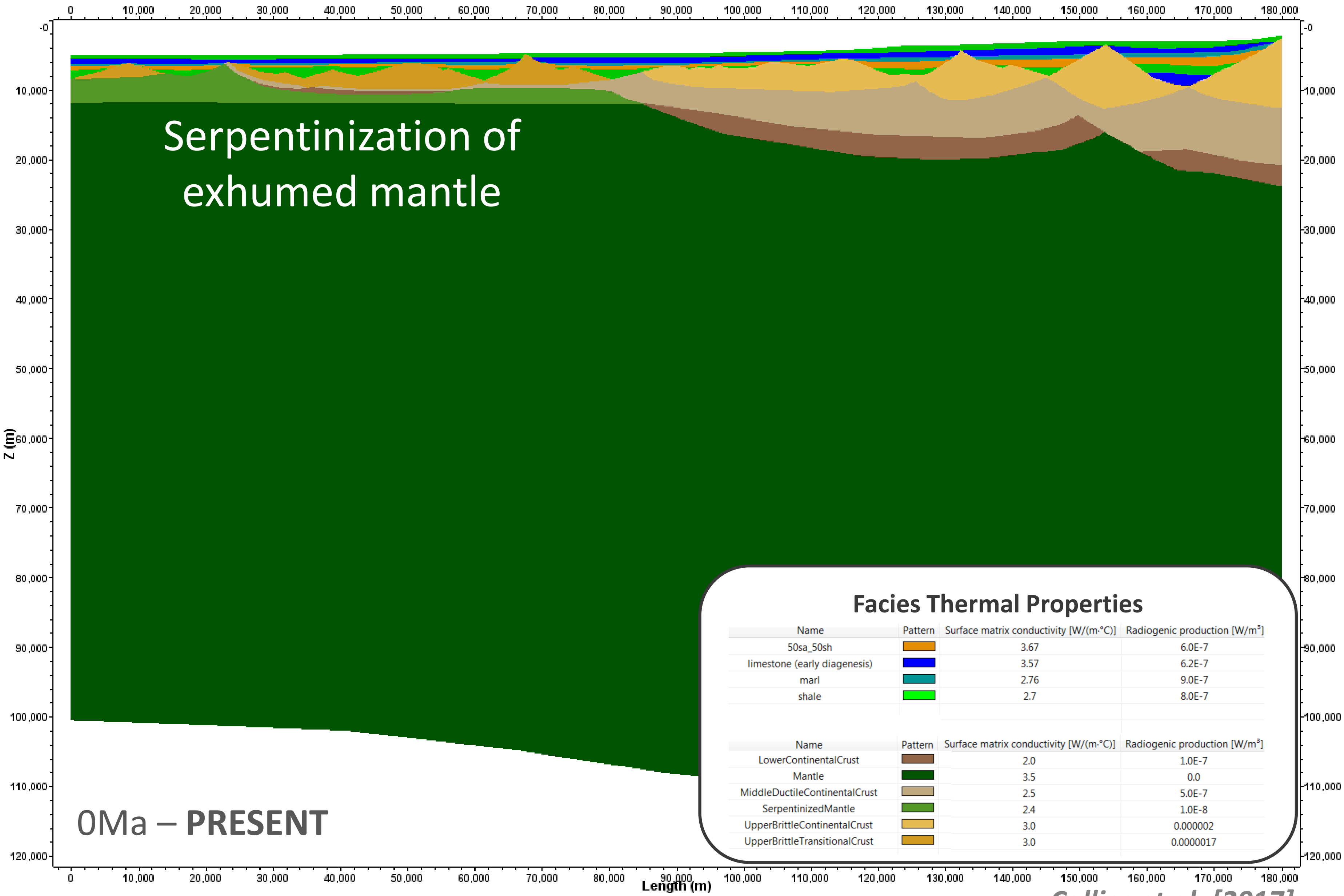
Iberia margin
Offshore Portugal





MacKenzie model not sufficient → use of the new "flexible" model in TemisFlow.

Reconstruction



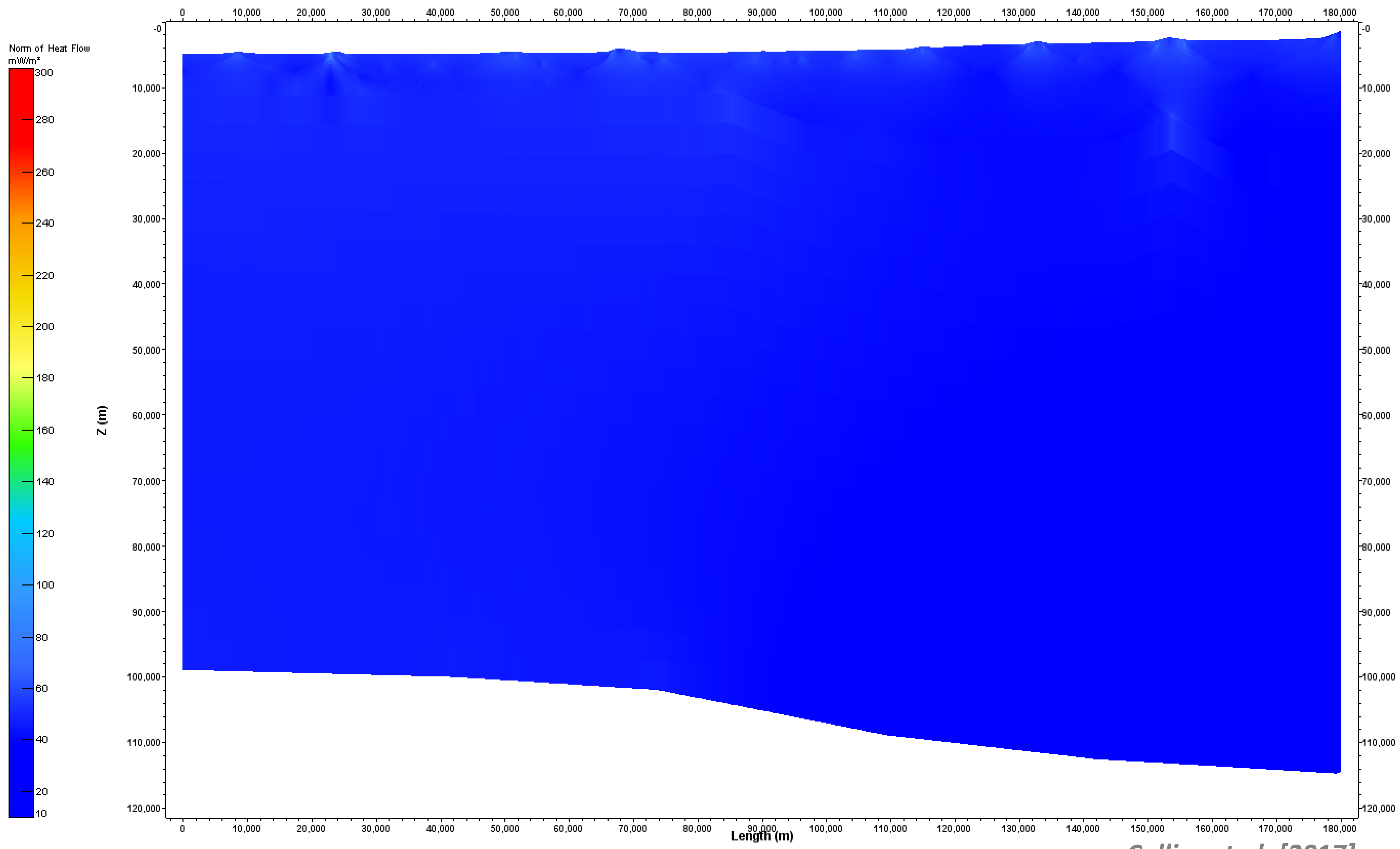
Facies Thermal Properties

Name	Pattern	Surface matrix conductivity [W/(m·°C)]	Radiogenic production [W/m³]
50sa_50sh		3.67	6.0E-7
limestone (early diagenesis)		3.57	6.2E-7
marl		2.76	9.0E-7
shale		2.7	8.0E-7

Name	Pattern	Surface matrix conductivity [W/(m·°C)]	Radiogenic production [W/m³]
LowerContinentalCrust		2.0	1.0E-7
Mantle		3.5	0.0
MiddleDuctileContinentalCrust		2.5	5.0E-7
SerpentinizedMantle		2.4	1.0E-8
UpperBrittleContinentalCrust		3.0	0.000002
UpperBrittleTransitionalCrust		3.0	0.0000017

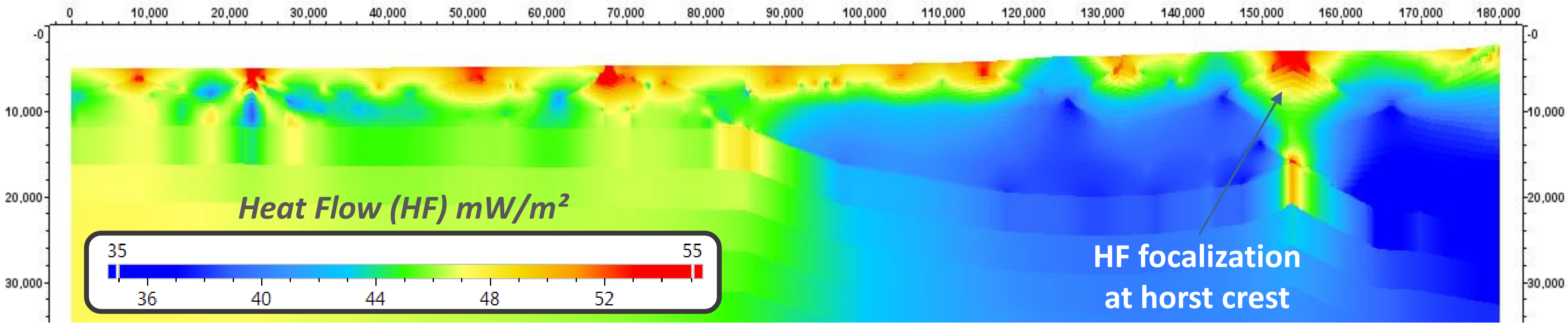
Callies et al. [2017]

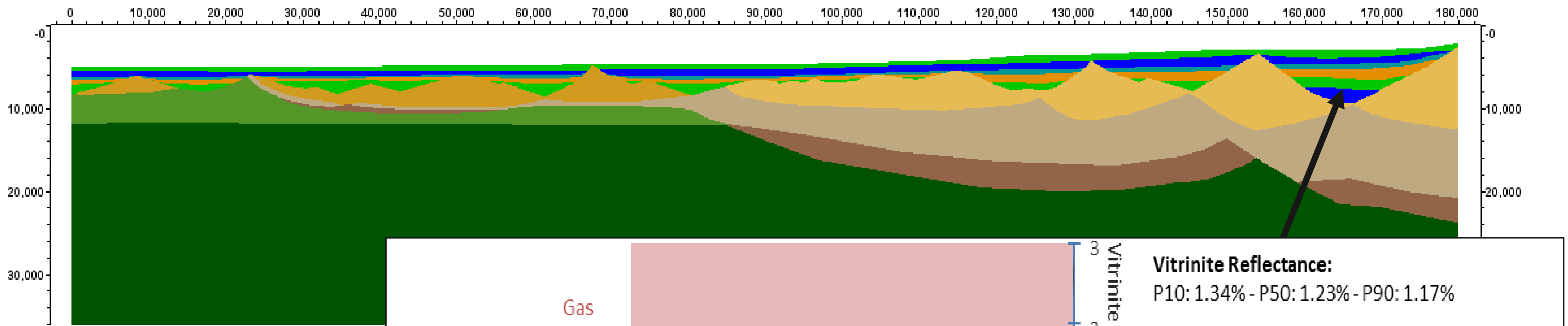
Heat Flow through time



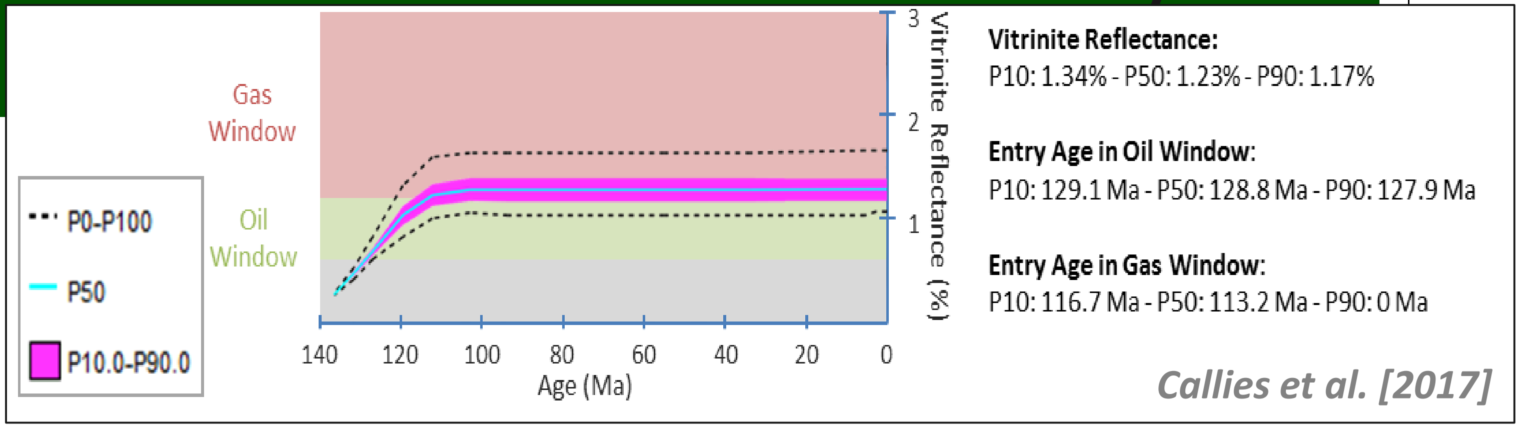
Callies et al. [2017]

Resulting maturity analysis





Uncertainty analysis
on the maturity level of potential petroleum systems



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

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

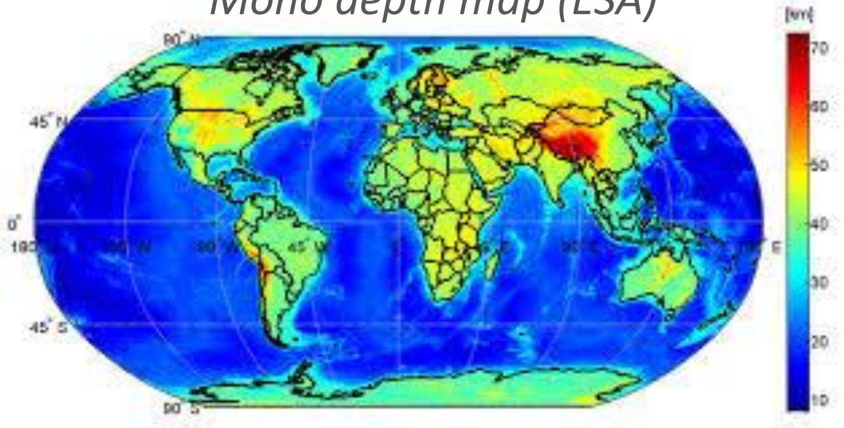
Thou shalt use a model with sediments and lithosphere fully coupled.

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**

Moho depth map (ESA)



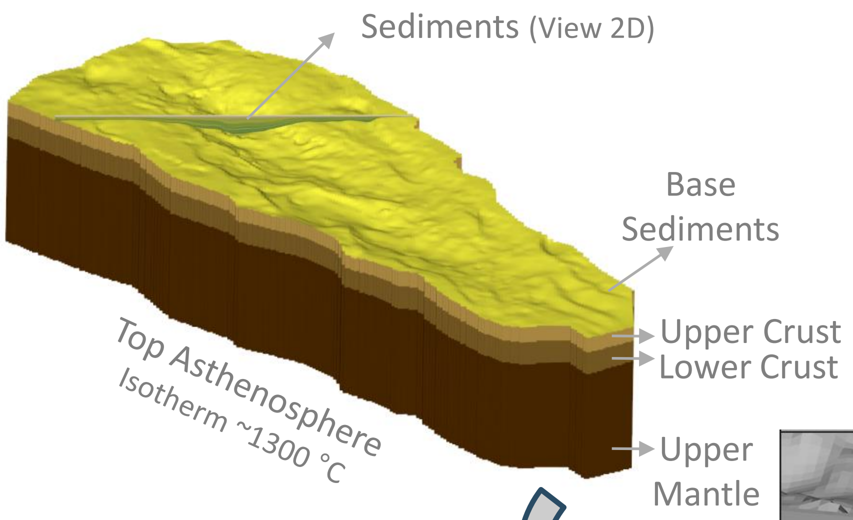
With a few calibration points (HF maps, T, VR0, etc.),
coupling a simple lithospheric model with a basin model always give <u>better results</u>

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

Several lithospheric modeling options available, **there are flexible approaches for modeling all kinds of rifting**

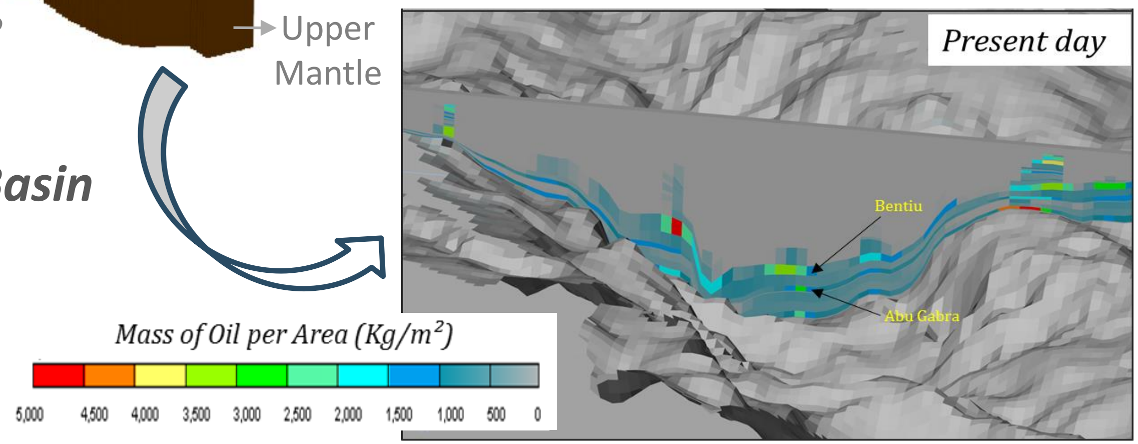


Only way to fully predict the thermal history even if there are plenty of well data

Thermal disturbances propagate deep into the crust: **use a buffer!**

Muglad Rift Basin

Sudan(s)



Thank You!

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