Modelling Petroleum Systems of Hyperextended Margins: Angola Case Study*

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Abstract

The Kwanza Basin of Angola is a South Atlantic basin which evolved from Early Cretaceous rifting to passive margin basin. It is interpreted by several authors as lying over a Hyperextended Margin (e.g. Unternehr, 2010). In such a setting, thinning of the lithosphere is not linear from undeformed continental to oceanic domain like in the pure shear model (Mc Kenzie, 1978) but present “hyperextended” portions where crust or mantle lithosphere has been preferentially removed (Huismans and Beaumont, 2011).

The Kwanza Basin infill is characterized by a thick Aptian salt layer that separates different petroleum plays. The post-salt plays were the first explored in the offshore, targeting Albian carbonates and Upper Cretaceous - Tertiary clastics. The pre-salt play that was already tested in the onshore and shallow offshore generated great interest in deep and ultra-deep offshore during the last decade in search of analogs to the prolific mirror Campos and Santos basins of Brazil.

Massive inversion and an intense drilling campaign of 23 exploration wells (2011 to 2016) were realized but gave contrasting results from the pre-salt play, including giant oil and condensate discoveries, dry gas and CO_2 rich accumulations, but also a number of dry wells. This revealed a complex petroleum system that might only be understood at a regional scale, taking into account deep geodynamics and related thermal and geochemical processes. That was the objective of a regional petroleum system analysis that will be presented here.

The applied workflow included basin-scale structural and facies mapping, well database construction, review and interpretation of organic geochemical data, integration of petrographic and non-organic geochemical data, and finally building and simulation of a 3D basin model to be used as an integration and visualization tool testing different hypotheses.

3D basin modelling of such a hyperextended margin was a challenging novelty and required the implementation of a specific workflow to face an unusual crustal structure and thermal history, both of them further complicated by a thick salt layer. After a detail trial and error process a good calibration of the model was achieved.

Modelling results show that the thermal impact is higher than in a classical pure shear model and the difficulty consists in estimating the limits of the different crustal domains, the timing of rifting and the extent of the rise of the asthenosphere and its consequences on thermicity. This case study also highlighted new processes to decipher and take into account, and software limitations inherent to this specific margin type when assessing petroleum systems.

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Modelling Hyperextended Margins: the Angola Kwanza Basin Case Study

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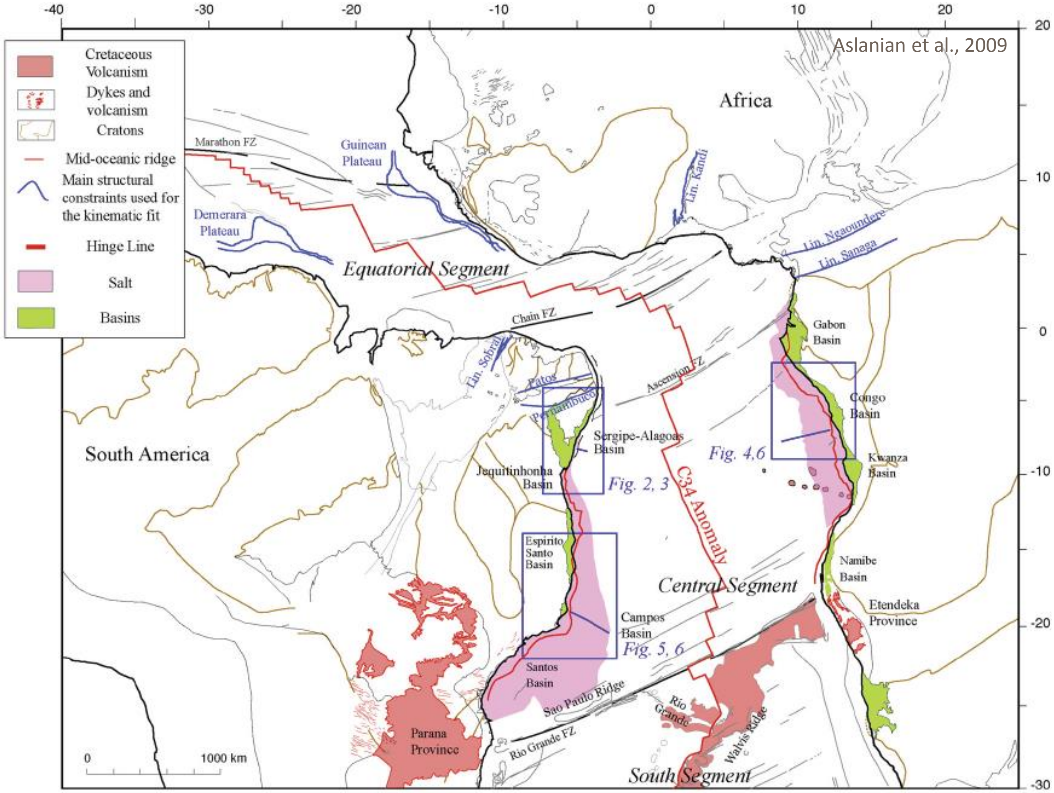
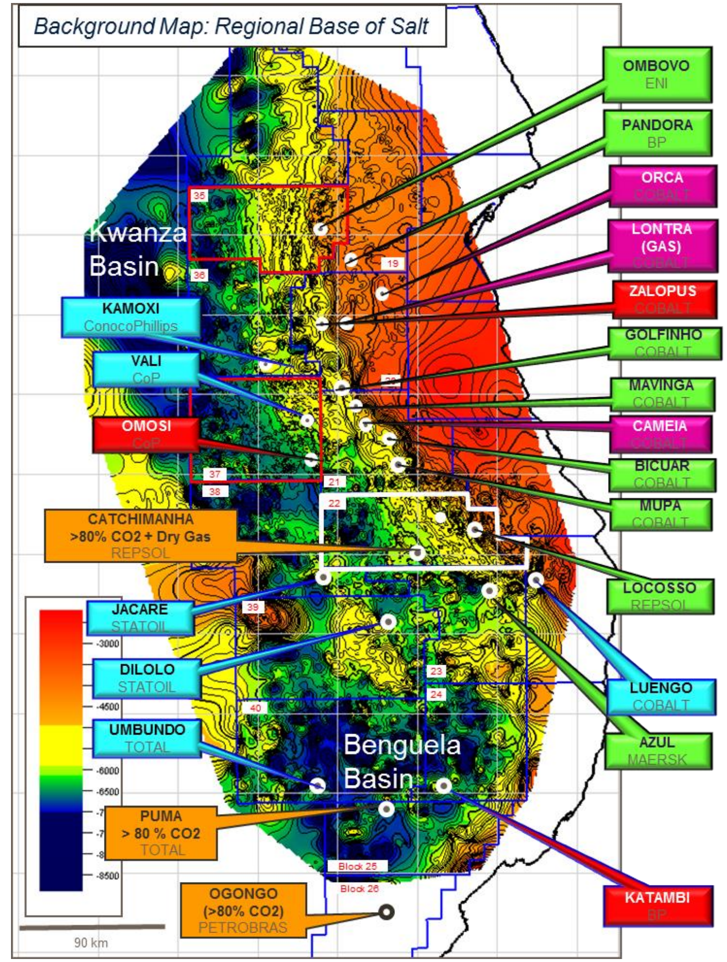
1- Introduction and Regional Setting





The Kwanza Basin is a South Atlantic basin that evolved from an Early Cretaceous rifting to a passive margin. A thick Aptian salt layer separates two petroleum plays .

- Commercial (Appraisal campaign ongoing)
- OIL No-Commercial Discovery
- GAS Discovery
- High CO2 plus Hydrocarbons
- Dry Wells

The pre-salt generated great interest in deep and ultra-deep offshore in search of analogs to the prolific mirror basins of Brazil. Massive inversion and an intense drilling campaign of 23 exploration wells (2011 to 2016) gave contrasting results .

This situation reveals a complex petroleum system that might only be understood at a regional scale, considering deep geodynamics and related thermal and geochemical processes.

2- Workflow

A regional petroleum system study that included the following tasks was performed:

1- regional mapping (structure and facies, including source rocks and basement definition);

2- well database construction, including all data that can be used to calibrate a basin model (stratigraphy, temperature, maturity, poro-perm, lithology, facies, etc…);

3- review and interpretation of all geochemical data on a regional basis, perform additional analyses if possible;

4- integrate existing petrographic and non-organic geochemical data, eventually realize additional studies (fluid inclusions and bitumen analyses, absolute dating, etc…);

5- building and simulating a basin model calibrated by the previous data and try to reproduce the known pre-salt hydrocarbon accumulations in their location, volume and nature;

6- performing sensitivity tests (on parameters such as source rock characteristics, location and depth, thermal history, structural evolution, etc…) to determine if several *scenarii* can work.

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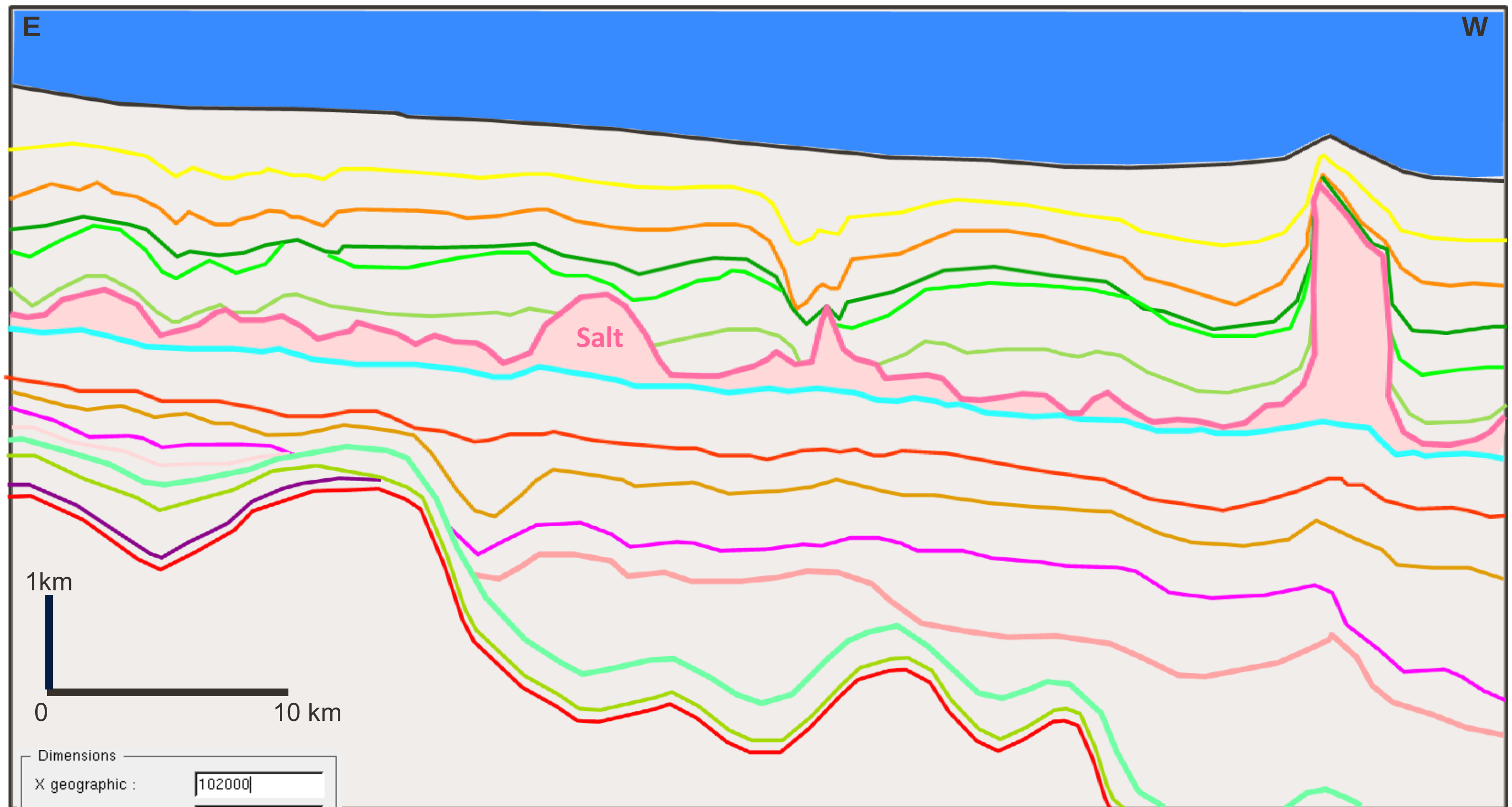
3.1- Model Construction: Structural Mapping and Stratigraphy



Dimensions

X geographic :	102000
Y geographic :	8.6039e+06
X length :	248807
Y length :	525920
Alpha angle :	0

Meshes

Cells number in x :	206
Cells number in y :	438
DX Cell	1207.8
DY Cell	1200.73

- 17 horizons interpreted regionally and tied to well markers;

- 3 of the previous (Miocene, Top Cretaceous and Intra-Albian) were interpolated since they mark a limit between different lithologies easily visible in the seismic. An Albian Source and Etendeka volcanics were defined;

- Initial gridding was 206 x 438 cells of 1200 x 1200 m length (1 263 192 cells).

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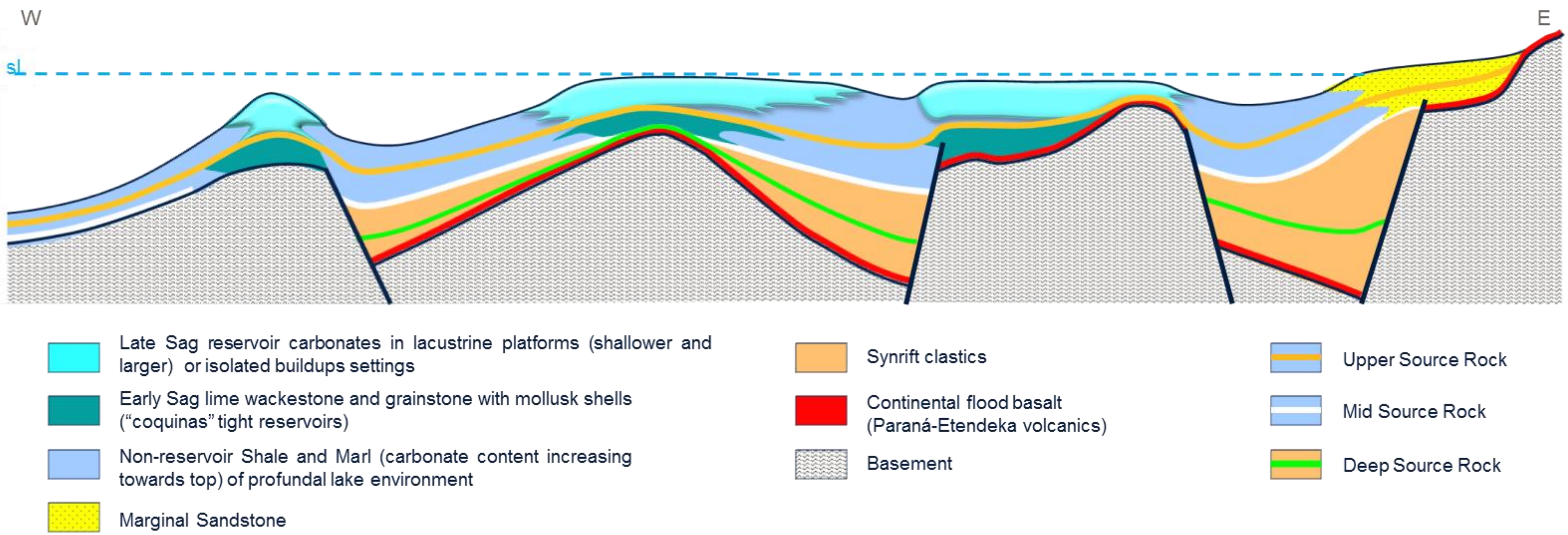
3.2- Lithology Mapping: Pre-salt sequence depositional model

Post –salt sequence lithology mapping is based on well data.

The pre-salt sequence lithology maps are a synthesis of the extensive work performed by in-house specialists and based on 3D seismic interpretation over blocks where Repsol has interests.

Given the scale of this study, the objective was to distinguish the reservoir vs. non-reservoir units and keep a reliable vertical division of the pre-salt sequence ("Rift" and "Sag"), including the source intervals and main lithology.



W-E schematic lithostratigraphic section of the offshore Kwanza Basin at the end of the Late Sag unit deposition (main reservoir). It illustrates how the pre-salt sequence was set in the model in terms of lithological units and source rocks layers.

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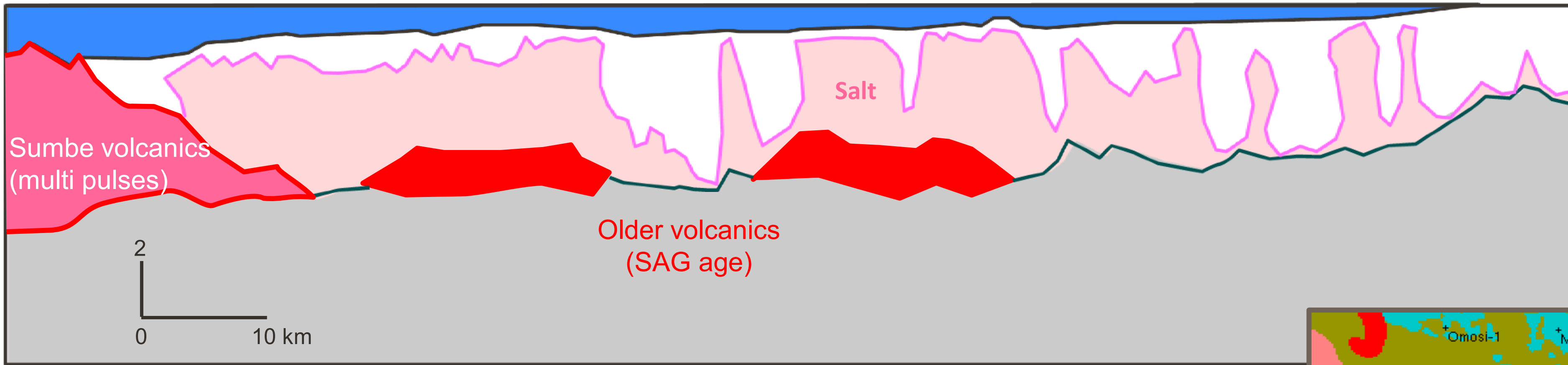
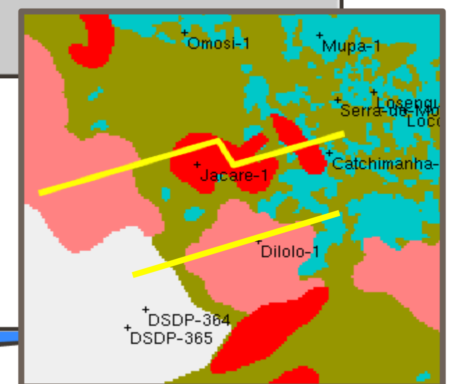
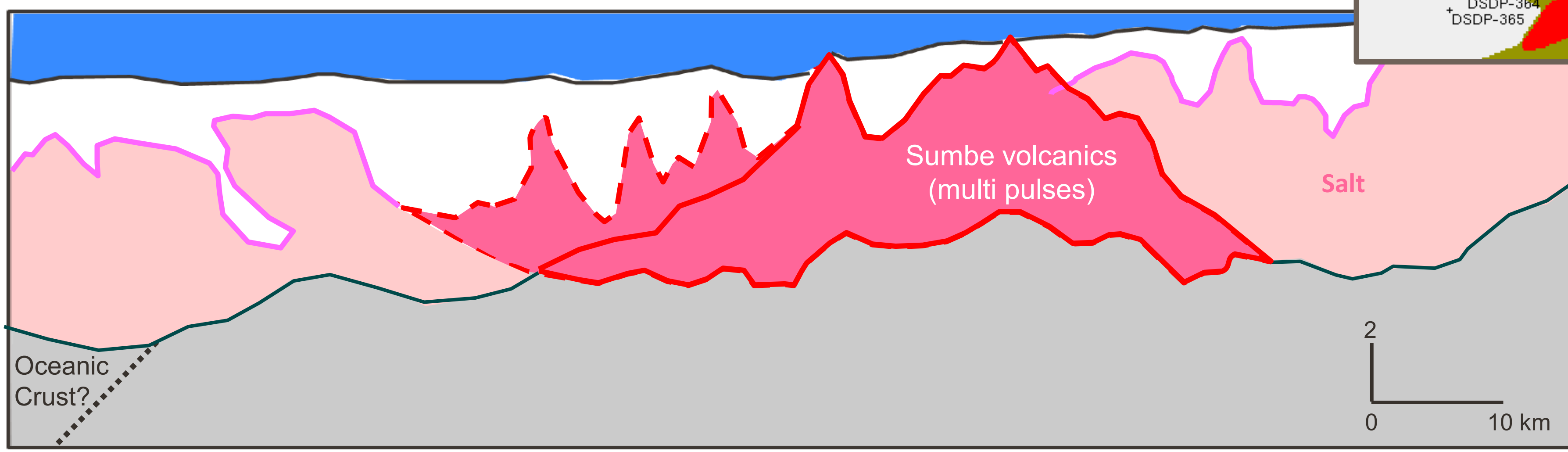
3.2- Lithology Mapping: Volcanics Mapping





Two types of volcanics were identified: 1-the Sumbe volcanics, associated to a hot-spot by most authors, showing huge edifices of pyramidal shape with young sharp expression at sea bottom; 2- older volcanics, SAG to early salt age, showing flat shape smaller and more elongated edifices.



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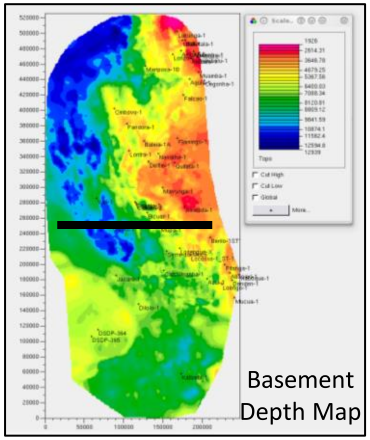
3.2- Basin Evolution In Time: Forward Modelling (1)



Snapshots at different ages of the above W-E cross section illustrate our reconstruction in time resulting from the previous structural and lithology mapping .

Parana-Etendeka volcanics flood above continental crust;

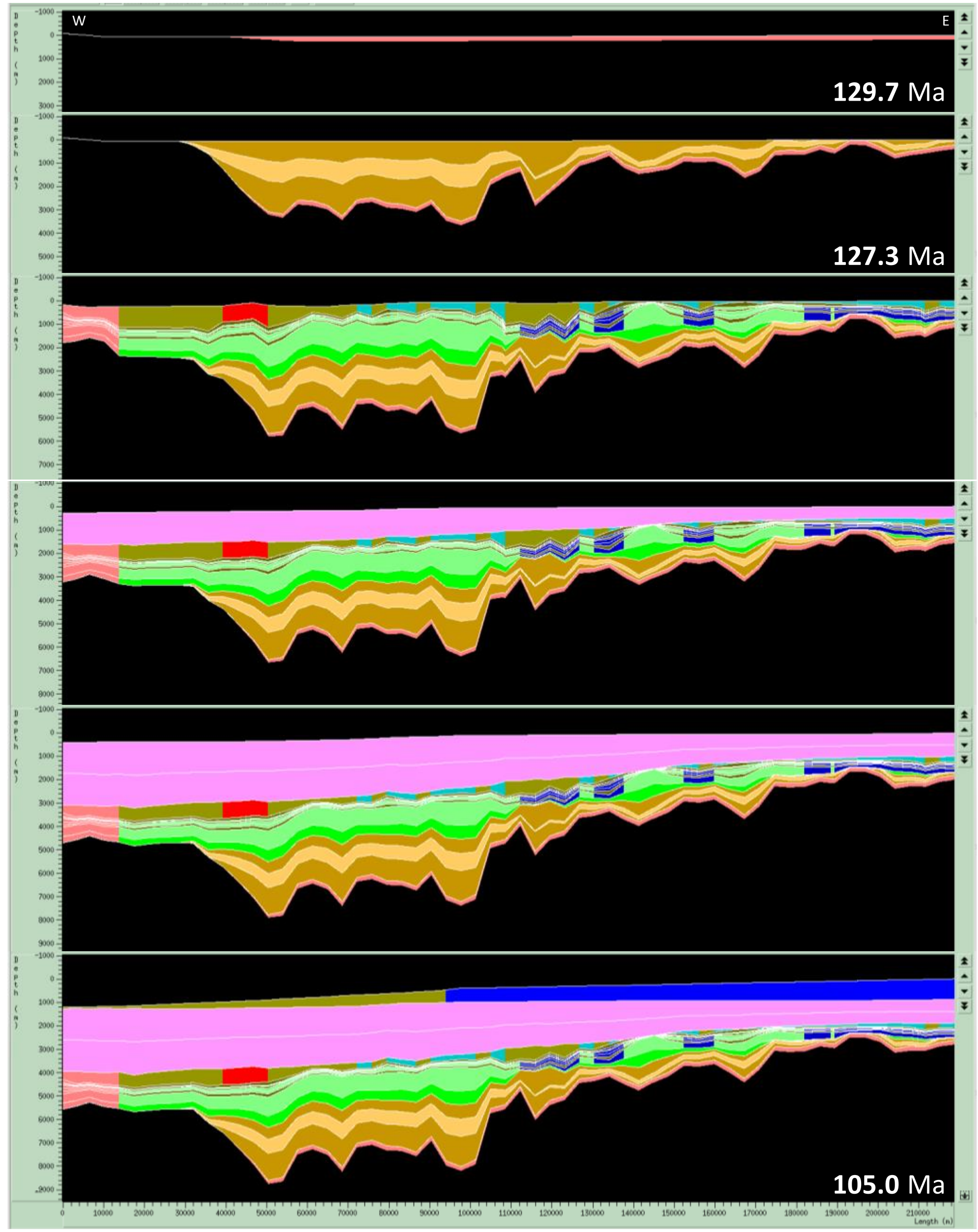
Rift sequence sedimentation, including the Deep Source Rock, over a stretched continental crust;

Sag sequence deposition in a mainly lacustrine environment with internal highs and volcanism. These deposits extend over the newly created intermediate (and oceanic?) crust;

Establishment of evaporitic conditions (and probably marine incursion) led to salt (mainly halite) sedimentation. It is accompanied by a tilting to the West of the basin;

Rapid subsidence led to the deposition of 0,5 to more than 2,5 km of evaporites in the study area (minimum needed to keep volume in excess to the present one). Our reconstruction implies the existence of a distal thick salt domain, where subsidence has been higher and possibly salt accumulation older at the base, contrasting with a thinner proximal domain with less accomodation space;

The Lower Albian carbonates mark the establishment of open marine conditions (fauna from the south, DSDP site 364) with a platform probably still associated to the previous shallow domain;



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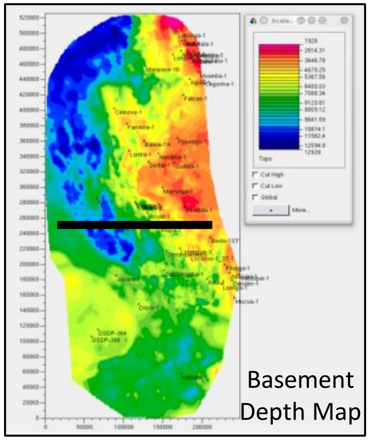
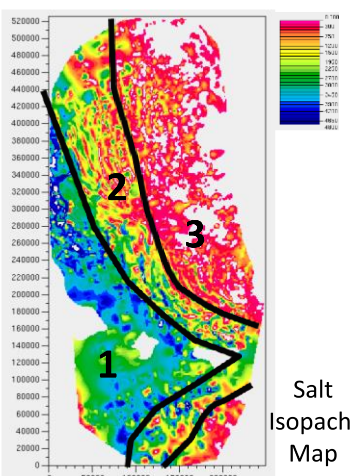
3.2- Basin Evolution In Time: Forward Modelling (2)



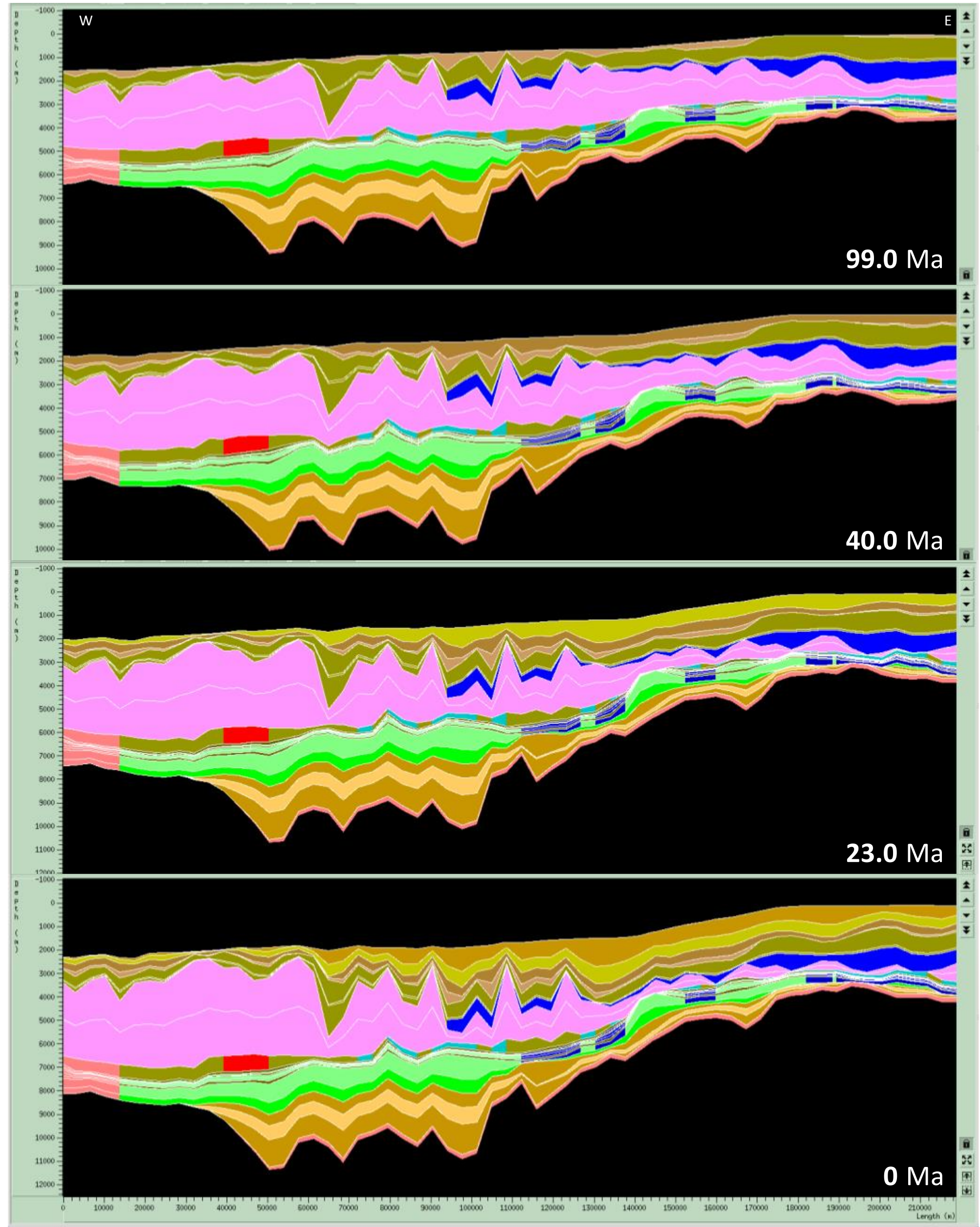
Snapshots at different ages of the above W-E cross section illustrate our reconstruction in time resulting from the previous structural and lithology mapping .



The nearly isopach Lower Albian carbonates are followed by deep marine sedimentation in mini-basins limited by salt pillows and diapirs. Halokinesis is thought to have been triggered by the disruption of the pre-salt sequence and rapid regional westward tilting of the basin that occurred between 105 and 99 Ma. We believe that the present base salt main structures were defined at that time;

Deep marine sedimentation prevailed until the present. Salt mobility also continued and is still active as revealed by sea bottom geometry. It led to the creation of 3 salt domains visible in section today: 1) a thick domain westward, where depositional thickness was the highest (the original distal thick domain), 2) an intermediate diapiric area (with some over 5 km high), and 3) an area of welding and limited salt thickness eastward (the original thinner proximal domain;

Welding age is specific to each salt structure and requires a detail structural analysis to be define. However, from our reconstruction we believe that most of the salt windows were created since 40 Ma.



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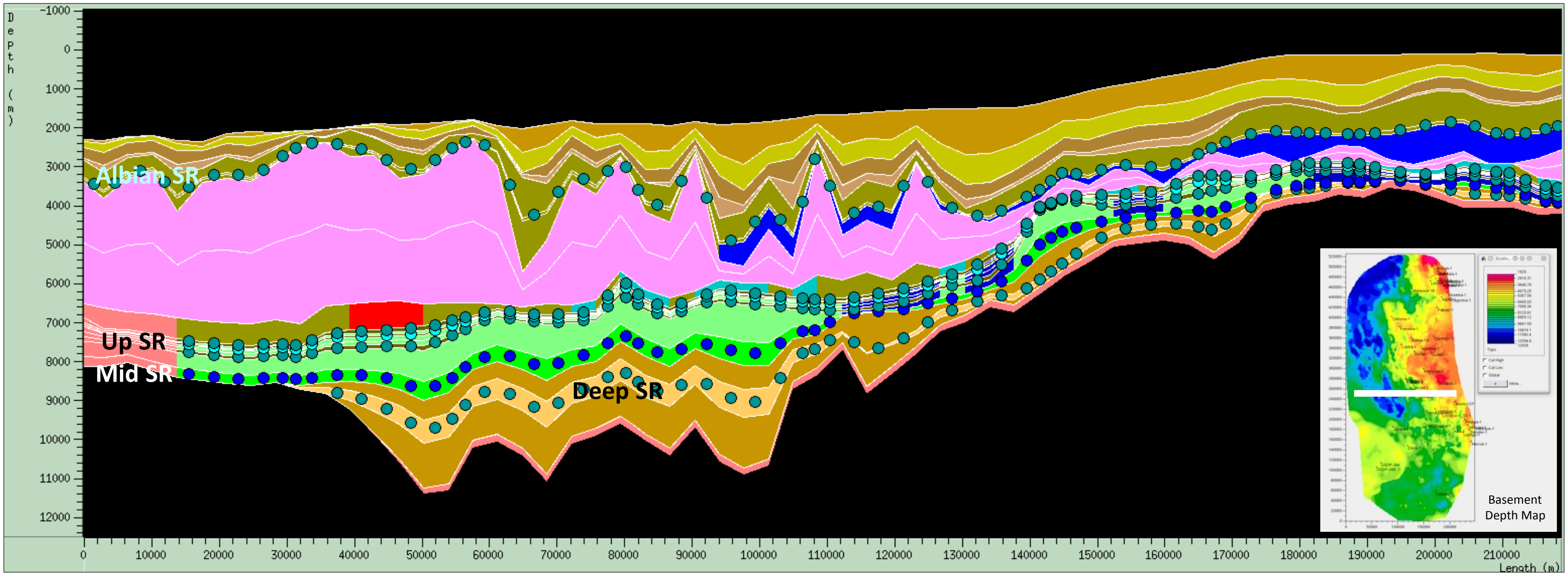
3.3- Source Rocks: Model Characteristics

The following section (the same that illustrated the structural restoration) shows the 3 pre-salt source layers (Deep, Mid and Up SR from bottom to top) and the Albian post-salt source that were considered in the model.

The HI and TOC values assigned are in agreement with the measurements made on rock samples from the study area and compatible with Burwood (1999) data. Notice that the TOC content is in the lower range of those measured in order to compensate the eventually exaggerated thickness of source layers (effective source is half or less the total source layer thickness defined in the model). These are initial characteristics and different *scenarii* were tested.



Name	Color	Comment	Kerogen	Hydrogen Index (mg/gC)	S2 (mg/gC)	TOC (%)
Deep SR		Kwanza pre-salt TY I (Burwood, 1999)	INFRA-CUVO	800.0	8.0	1.0
Mid SR		Kwanza pre-salt TY I-II (Burwood, 1999)	CUVO	300.0	3.0	1.0
Up SR		Kwanza pre-saltTY I-II (Burwood, 1999)	CUVO	300.0	3.0	1.0
Albian SR		Kwanza post-salt TY-II (Burwood, 1999)	ALBIAN-MICRITES	684.0	13.68	2.0

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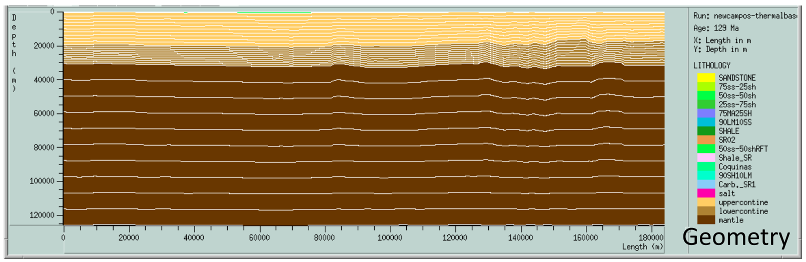
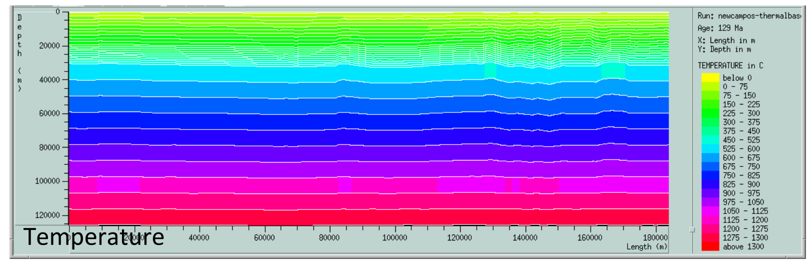
3.4- Basement Architecture: Rifting in Basin Modelling Softwares

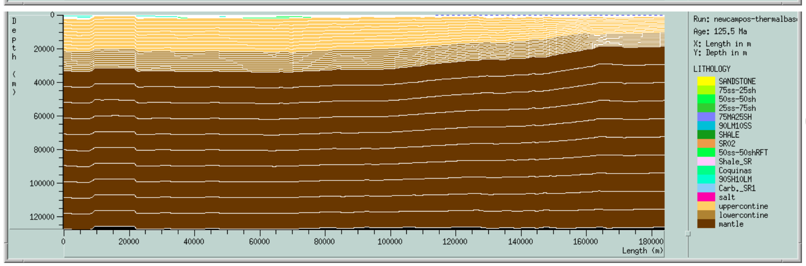
Since the Mc Kenzie thermal equations are the only available to model the thermal regime above a stretched lithosphere they are the one implemented in softwares able to reproduce the crustal thinning and the upper mantle transient state.
This option was preferred to using highly speculative and unconstrained heat flow maps at the base of the sediments.

The software we used in this study is Temis 3D by BeicipFranlab/IFP that allows setting initial thickness maps (before rifting) of the crust and upper mantle, starting and ending age(s) for rifting(s) event(s), lithosphere lithologies and related radiogenic heat production and conductivity, crust and upper mantle thinning defined by thinning factor maps.
Using these parameters and the Mc Kenzie thermal equations, the software calculates the rise and return to equilibrium of the 1330ºC isotherm fixed at the base of the lithosphere, and hence the temperature and heat flow affecting the entire sedimentary column through time. It also has the advantage of coupling the effect on thermicity of the basement to that of the sedimentation.

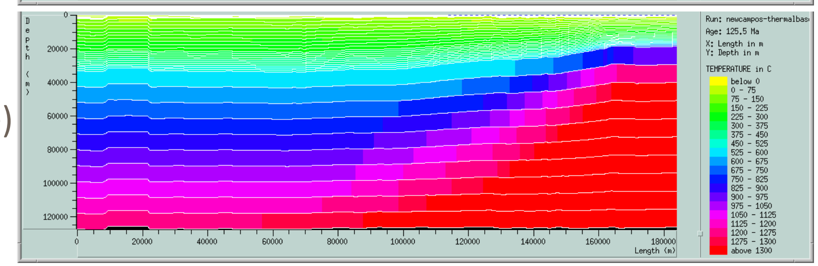


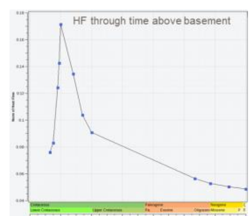
Before Rifting

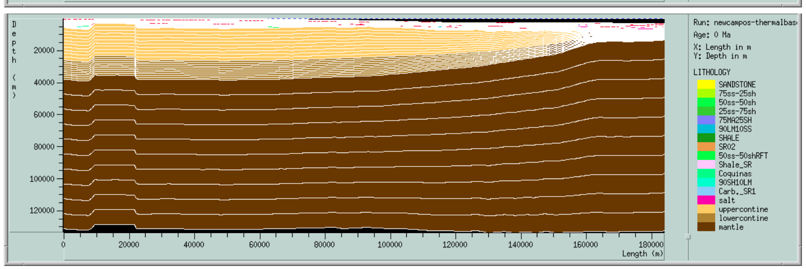




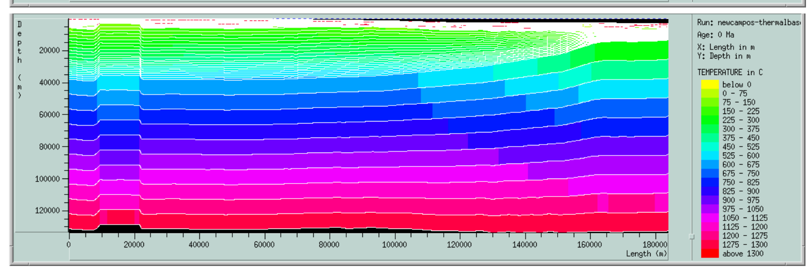
During Rifting
(max. Temperature)







After Rifting
(base lithosphere returned to initial position but crust is thinner)



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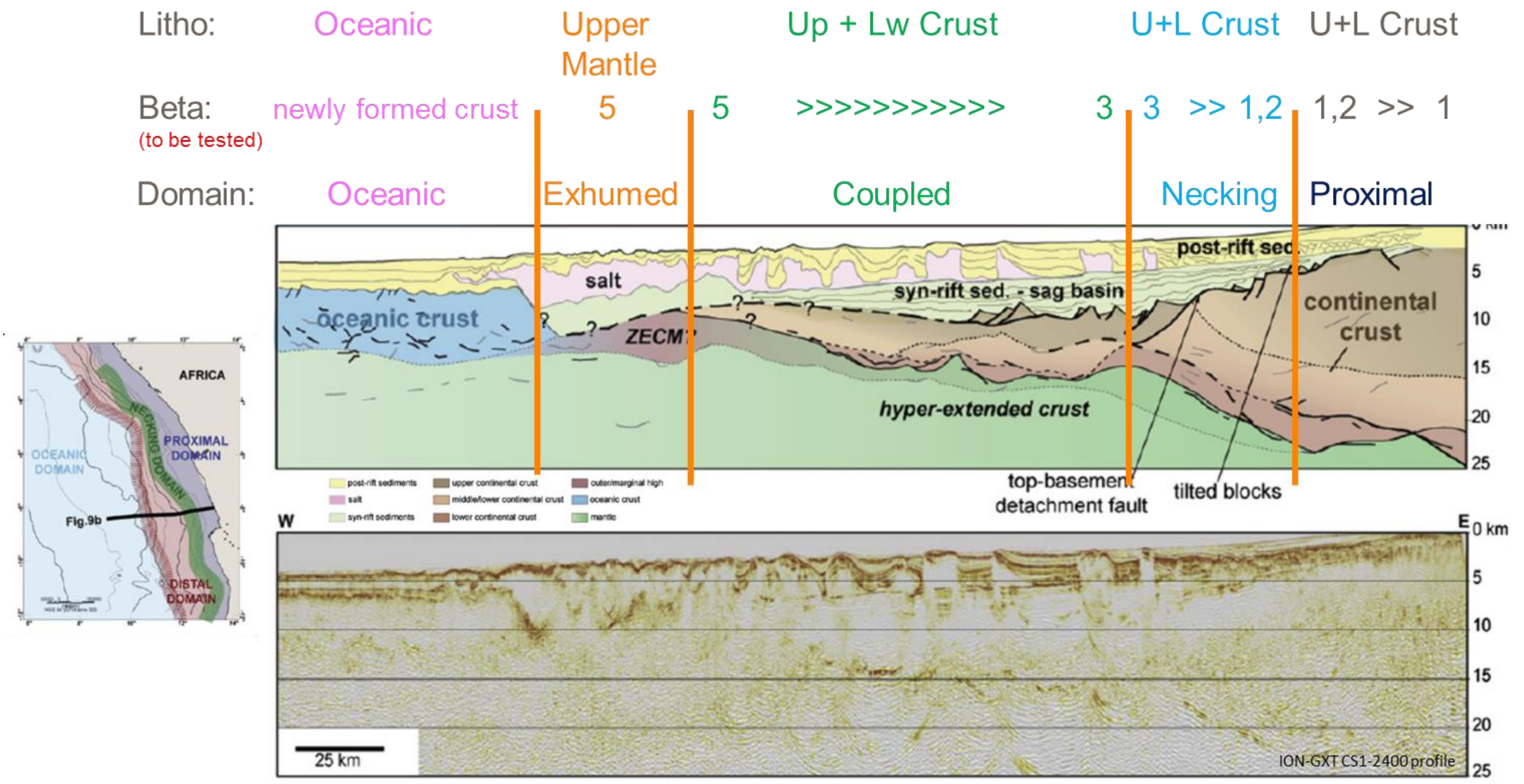
3.4- Basement Architecture: Preferred Hypothesis



after Unternehr et al. (2010)

The section from Unternehr (2010) shows the interpreted crustal profile that we used to define the basement architecture in our model and the related domains (sensu Peron-Pinvidic et al., 2013). ZECM is Zone of Exhumed Crustal Mantle.

The thinning factors (Beta) initially applied were estimated from an original 27 km thick continental crust becoming null for a factor of 5. The Upper Mantle Beta was proportional to crustal one (Non-Uniform stretching) and different hypotheses tested

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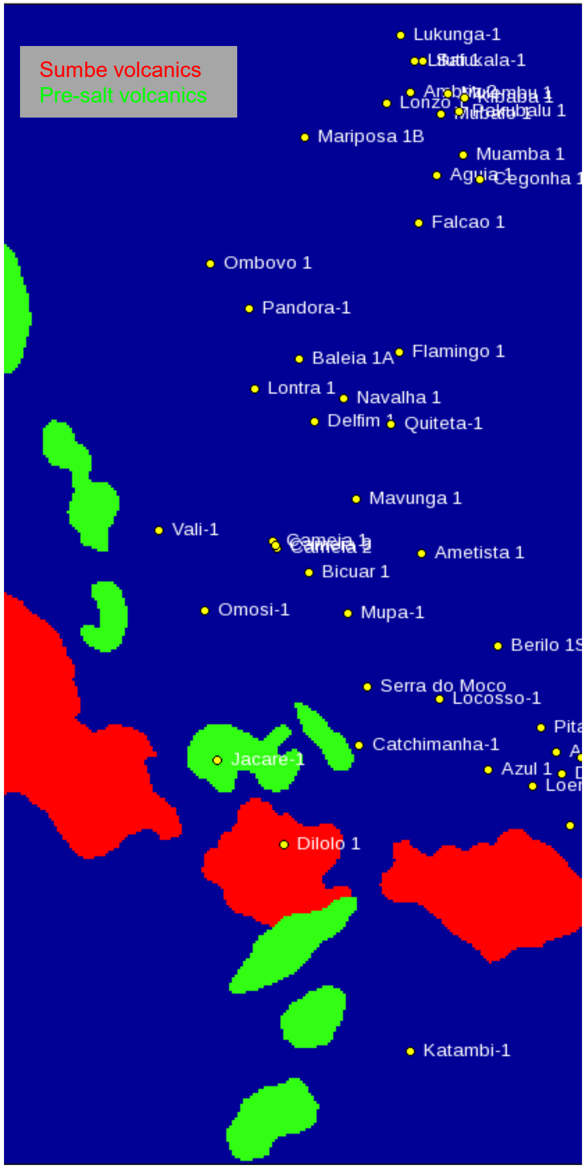
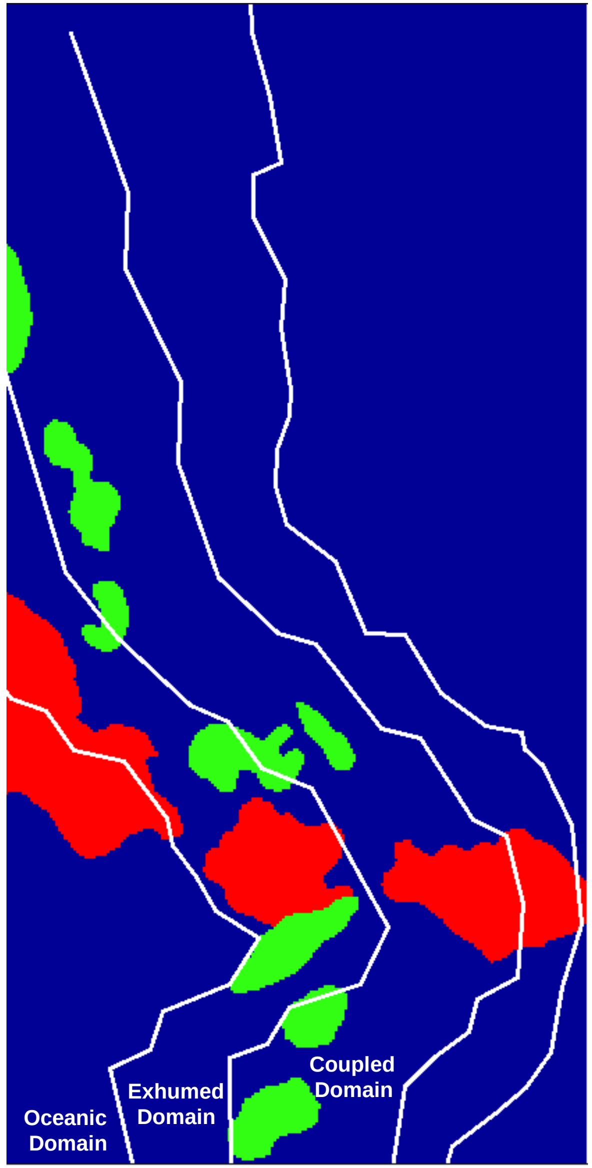
3.4- Basement Architecture: Relation to Volcanism



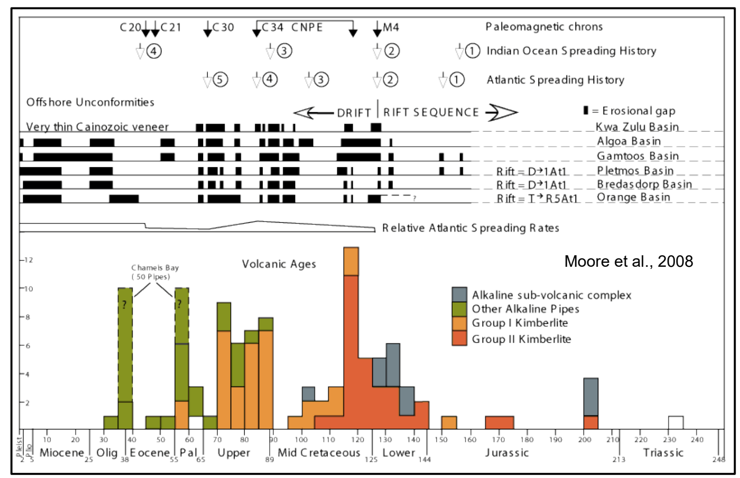


Pre-salt volcanics interpreted in this study are located near the coupled-exhumed domains boundary, suggesting a genetic relationship with mantle exhumation.

Vesicular alkali basalts alternating with caerbonate-lamproite breccias (diatreme?) were described in wells, indicating a mantle contribution.
Moore et al. (2008) reported mantle magmatism (kimberlite II group) with a peak at 120 Ma.

All these data suggest that this volcanism could be a consequence of the mantle up-rising related to hyper-extension.

The Sumbe volcanism is different and has been active (displacing from West to East) at least until the Late Cretaceous and probably more recently.



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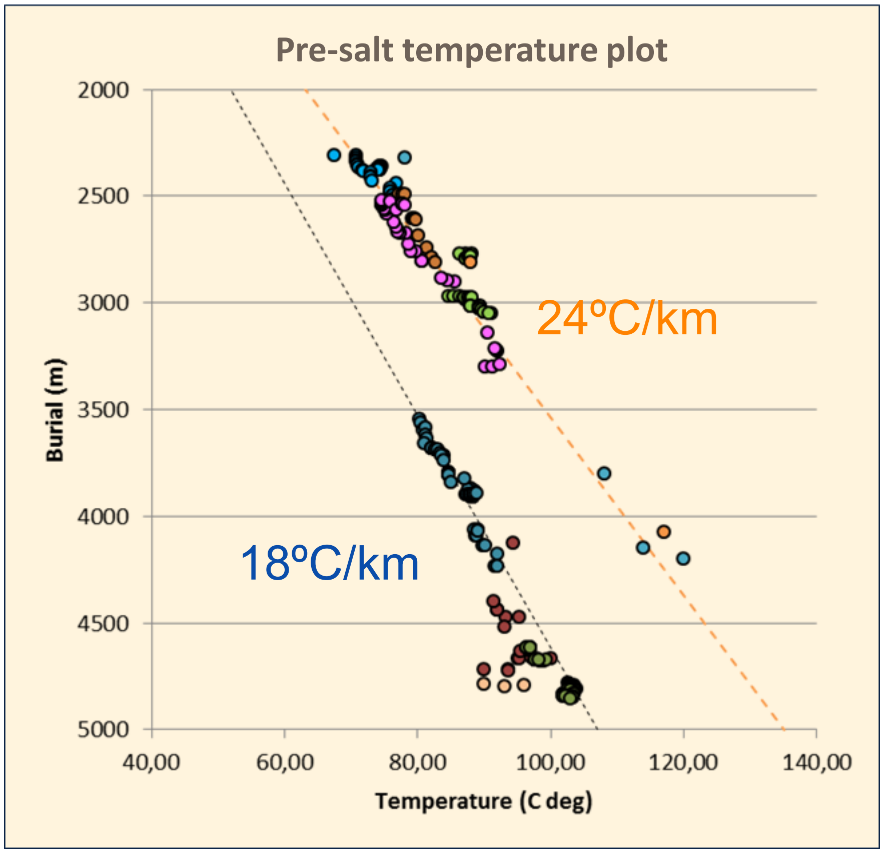
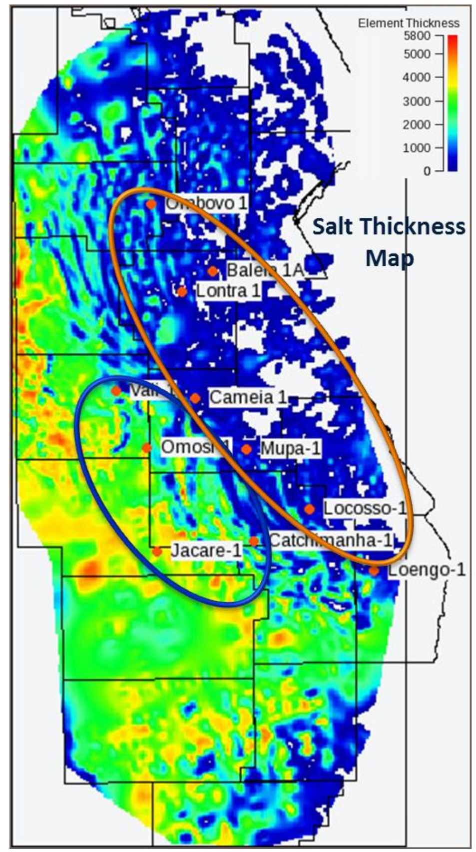
4.1- Model Calibration: Present Day Thermal Regime

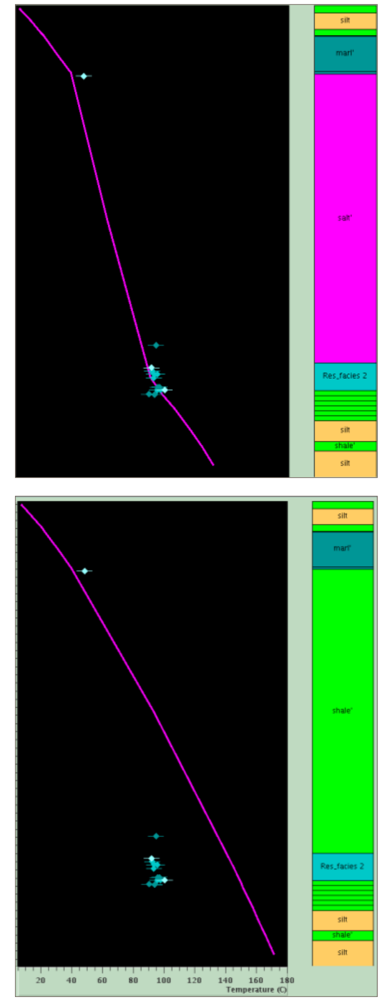
The temperature vs burial depth plot below shows 2 trends in the pre-salt:
- the warmest (24°C/km) gathers wells from the proximal domain,
- the coolest (18°C/km) includes the most outboard wells.

This regime can be explained by a major continental crust volume providing radiogenic heat but also by the cooling effect of the high conductivity salt.

The example below right shows a difference of about 55°C when replacing the salt by a shale lithology. It shows the need of an adequate time reconstruction of the salt deformation.







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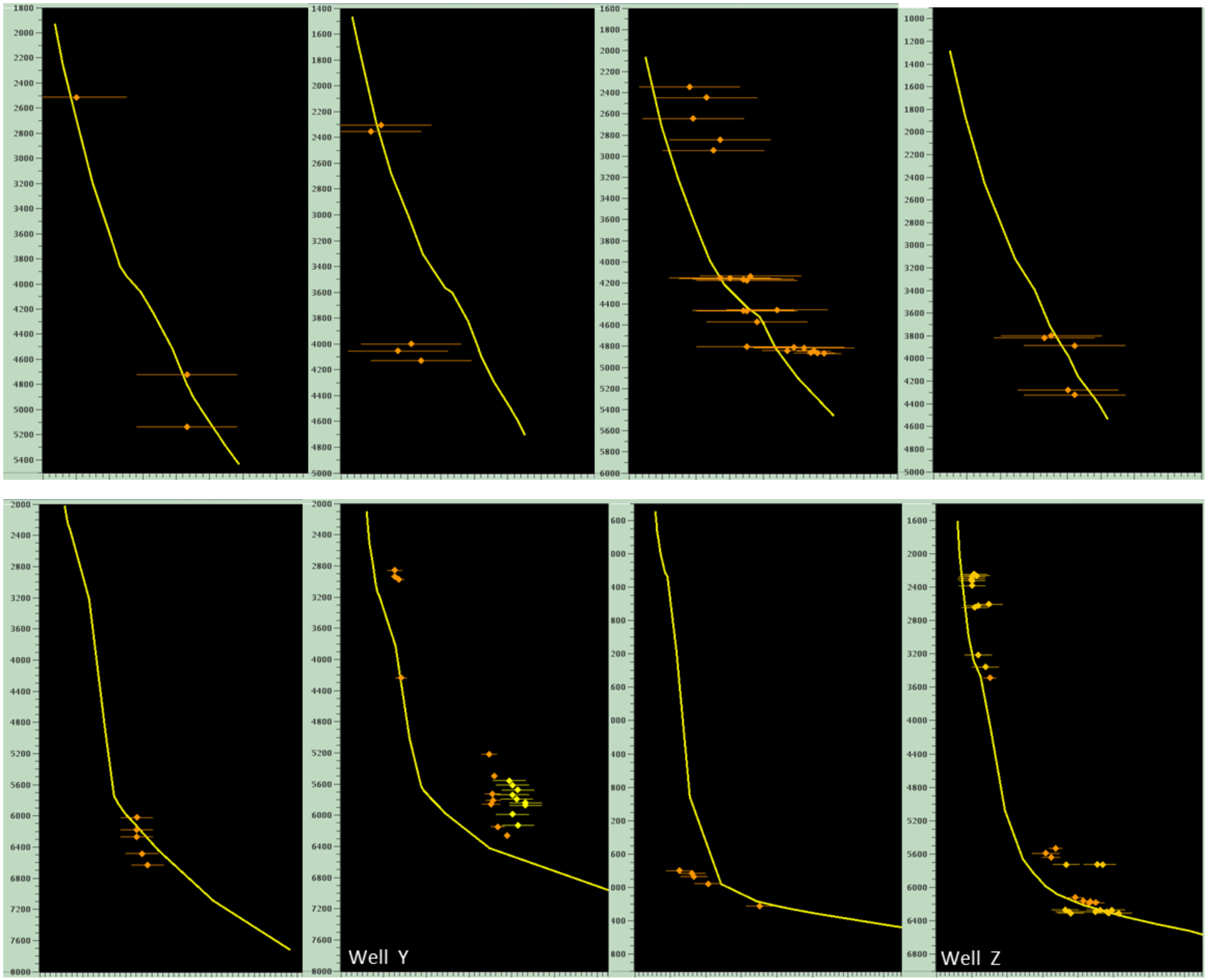
4.1- Model Calibration: Maturity



PROXIMAL AND NECKING DOMAIN WELLS

HYPER-EXTENDED DOMAIN WELLS

Excellent Calibration in Proximal-Necking domains, Very Good elsewhere (except well Y)

Orange:Vitrinite Reflectance,
Yellow: bitumen VR eq.

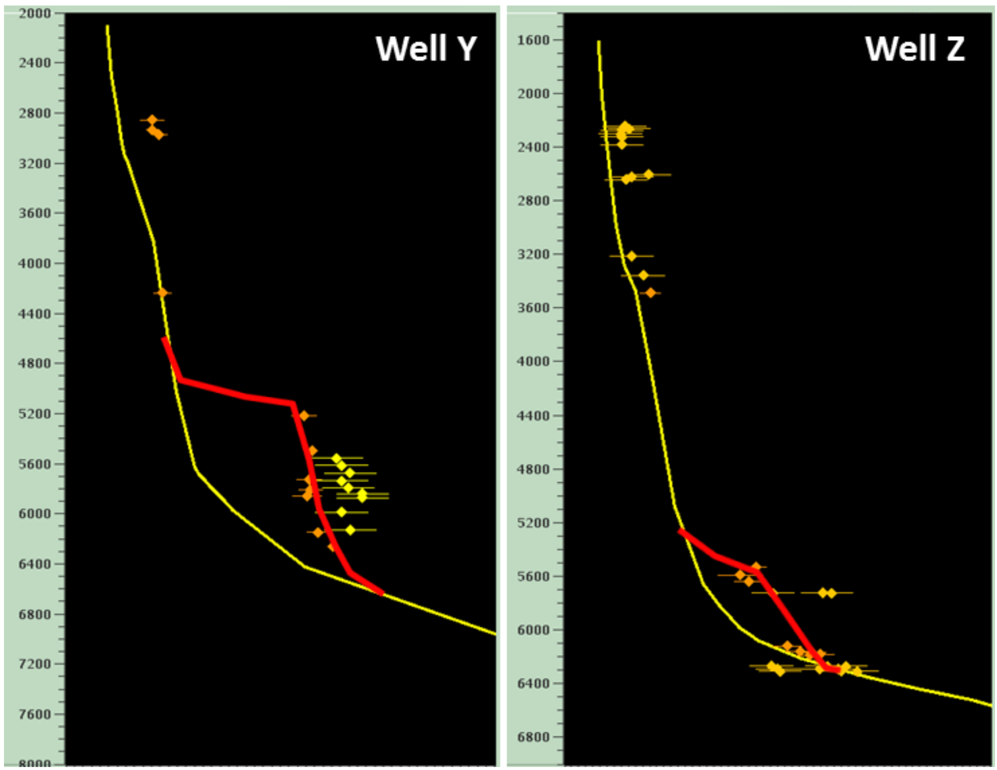
4.2- Model Calibration: Hot Fluid Flow ?

AAPG Europe Region

Additional sampling and analyses aimed at creating a maturity profile revealed a **jump in maturity below the salt and a nearly vertical trend**, especially marked in Well Y.
Moreover, some samples from interbedded shaly layers at the base of the salt also showed displaced values.

The nearly vertical trend below the salt is impossible to match whatever the crust architecture or thinning factor we tried.

We interpret this **"anomaly" as being related to a non-crustal parameter but more probably to a local mechanism**.



Considering that the effect seems to be increasing outboard (not seen in proximal wells), as does the late diagenesis and CO2 proportion, we interpret this event to be related to a fluid flow (hydrothermal? CO2? other?) below the salt that crossed the reservoir at a temperature high enough to modify the maturity trend.

This is also supported by the fact that in a third well, where no reservoir (hence permeable) facies was found this effect seems to be much more limited.

The fact that the base of the salt is apparently affected suggests that the phenomenon occurred during the initial part of salt deposition and logically it could be **related to mantle exhumation**.

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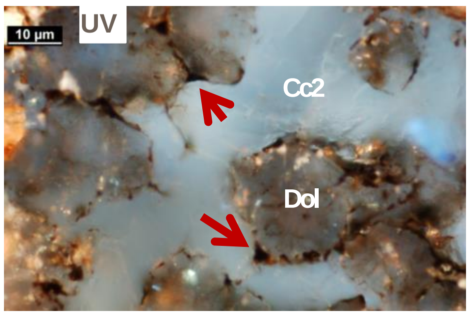
4.2- Model Calibration: Hydrothermalism, Late Diagenesis and Bitumen

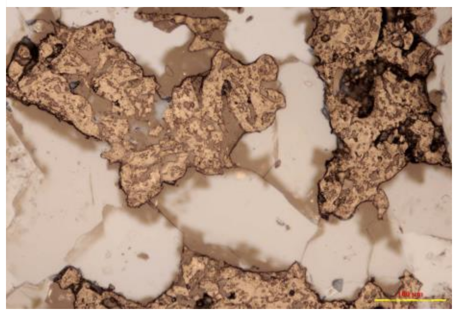
There is an apparent East-to-West increasing trend in the intensity of diagenetic silicification (pore volume filled and rock substitution), suggesting that silica-rich fluids where dominant in the external domains.

Late calcite precipitation seems to be more abundant in the internal domain, and synchronous with the main hydrothermal silicification episodes in the coupled domain.

The volume of pyrobitumen (thermal degradation of liquid hydrocarbons) compared to bitumen (other processes) increases in pre-salt reservoirs from proximal domain, where it is almost absent, towards coupled domain.

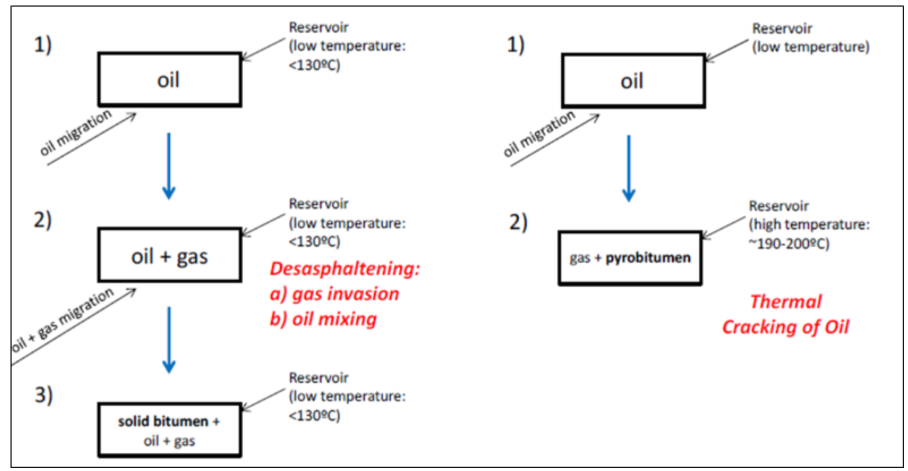


Internal domain: Bitumen impregnation prior to poikilotopic calcite cement (Cc2).



Outer domain: Pyrobitumen in close relationship with late-quartz.

Internal Domain   Outer Domain



The diagenetic cementation, corrosion and hydrocarbon degradation are related to thermal and fluid flow events. Ascendant hotter fluids were dominant oceanward, with silica and pyrobitumen as by-products, whereas colder and modified brines dominated in the proximal domain.

This areal distribution suggests that late diagenetic processes potentially affecting the reservoir were directly associated to the intensity of crustal extension.

Hyperextended Margins Petroleum Systems, Angola, Kwanza Basin

5- Conclusions and Limitations

An integrated Basin Analysis Study of the Kwanza Offshore Basin has been performed including a 3D basin modelling with a specific workflow for this hyper-extended margin. Main conclusions are the following:

- The **simple shear lithospheric rifting model** has been successfully implemented and calibrated;
- **Challenge**: estimate the limits of the different domains, extent of the rise of the base lithosphere (isotherm 1330 ºC) and the timing of tectonic rifting. Couple lithospheric and sedimentary evolution (calibration data are here!);
- Thermal calibration using different data (well measurements, paleo-temperature from Fluid Inclusions, biomarkers and high resolution organic geochemistry maturity data) is very good confirming the **validity of the model in its architecture but also that of the thermal equations used.**
  The calibration of existing accumulations in their location is satisfying;
- The maturity data revealed the **existence of a thermal event not directly related to crustal extension (but probably a consequence of it)**;
- This event **might be related to the flow of a hot fluid which exact nature is still uncertain (hydrothermal? CO2? other?).** The effect is major outboard, suggesting a relation with exhumation/oceanization. It occurred after a first charge of hydrocarbons in several accumulations and probably caused their partial alteration (cracking and/or flushing). We are not able to reproduce at the moment such a phenomenon in our model;
- However a **good compositional calibration** is obtained in **areas** where such phenomenon seems to have had **minor effect**;
- Depending on the nature of the fluid, **temperature might not be the only or main cause of alteration**. Flushing by CO2 for example is a known phenomenon in several basins;
- **Hyperextended margins are "hotter" than we thought beyond necking zone** and observations point to **several late diagenetic processes directly associated to thermal and fluid flow events originated by hyper-extension and mantle exhumation**.

Modelling Petroleum Systems of Hyperextended Margins: the Angola Case Study

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THANK YOU!

REPSOL

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