Numerical Modeling of the Brazilian Offshore Continental Margin – Campos, Santos, Pelotas Basins*

R. Zühlke[1], J. Contreras[1,2], S. Bowman[3], and T. Bechstädt[2]

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[1]GeoResources STC, Heidelberg, Germany (zuehlke@georesources.de)
[2]University of Heidelberg
[3]Petrodynamics Inc., Houston

Abstract

The Campos, Santos and Pelotas segments of the Brazil continental margin show significant variations in basin architecture and infill during passive margin development, in spite of their closely related syn-rift record. Based on 2D seismic and well data, the Barremian-Holocene basin fill has been analyzed by high-resolution sequence stratigraphy and inverse flexural basin modeling. The results provide key input parameters and bounding conditions for forward stratigraphic modeling. Iterative batch modeling and sensitivity analyses provide a best-fit numerical model for the current basin configuration. Forward modeling results confirm the individual crustal evolution and subsidence trends in each of the three margin segments. Late Barremian to late Aptian depth-dependent continental stretching generated sag basins with evaporite deposition on the Santos and Campos margin segments. The thermal effect of heat advection beneath the thinned continental crust delayed crustal subsidence and generated sag-salt depocenters with largely constant subsidence rates. In contrast, the Pelotas Basin features thickened high-density volcanic crust, controlled by long-term post-rift thermal contraction and differential sediment accommodation. For the Albian post-rift to Holocene drift development, the most important controls on basin architecture and infill include: (i) increasing flexural subsidence superimposed on decreasing thermo-tectonic subsidence; (ii) episodic rejuvenation of sediment source areas affected sediment input and flexural loading, triggering coastal progradation and turbidites; (iii) basinward tilting and landward flexural rebound was associated to shelfal erosion, sediment bypass and downslope mass transport; (iv) salt remobilization triggered shelf instability, basin-floor topography and lithofacies distribution; (v) bottom currents strongly redistributed the deepwater deposits. The integration of offshore seismic and well data with onshore data in stratigraphic modeling improves the understanding of source-to-sink processes, shelf-to-basin depositional systems, lithofacies heterogeneities and reservoir distribution on the Brazilian continental margin. Integrated numerical modeling provides a coherent model for the evolution of the Early Cretaceous rift, sag, and salt basins. It also improves the understanding of the strong lateral heterogeneities on the Late Cretaceous to Neogene passive margin.

References

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GeoResources STC, Heidelberg
University of Heidelberg
Petrodynamics Inc., Houston

Data, Methods & Objectives

Well & Seismic Stratigraphy

Reverse Basin Modeling (RBM)

Forward Stratigraphic Modeling (FSM)

Stratigraphic Prediction at basin scale

Basin Development along the Brazilian margin

Data, Methods & Objectives

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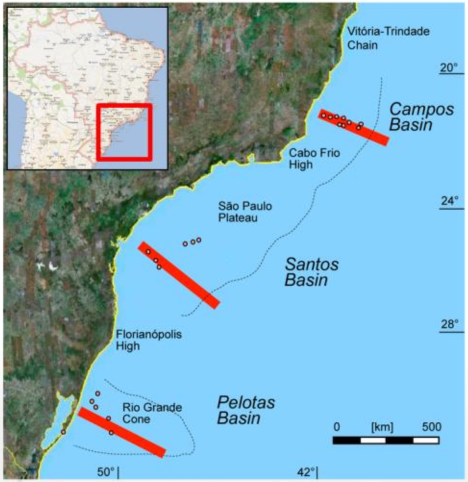
Seismic Data

- Regional lines
- 300-340 km each
- Acquired by TGS NOPEC
- Provided by BHP Billiton & ANP
- Limited resolution sub-salt

Well Data

- 21 calibration wells
- Logs, biostratigraphy
- Limited to shelf top & upper slope
- 5 wells reach Barremian succession



Presenter's notes: Key data include: regional 2D seismic data from the Campos, Santos and Pelotas continental-margin segments, acquired by TGS Nopec and provided by BHP Billiton and ANP; logs and biostratigrphic data from a total of 21 calibration wells. Key methods are: sequence stratigraphy (2nd order resolution), reverse basin modeling, forward stratigraphic modeling. Key objectives are: stratigraphic and reservoir prediction at basin scale and the analysis of the basin development. The focus here is on basin development.

Guideline

Data, Methods & Objectives

Well & Seismic Stratigraphy

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Basin Development

Well & Seismic Stratigraphy – Pelotas Basin

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Well and Seismic Stratigraphy

- 12-14 seismic sequences

  Erosional unconformities

  Maximum flooding surfaces

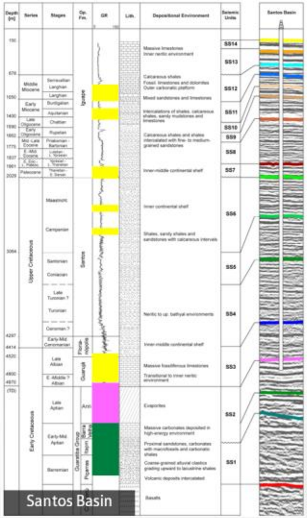
  Retro-, ag-, progradation trends

Forced, normal regression

- Time resolution 4.5-23.5 Ma

2nd order supersequences

Reservoirs
Evaporites (sag basin)
Main source rocks



Presenter's notes: 12-14 seismic sequences have been defined for the southern Brazilian margin. They are based on major erosional unconformities, maximum flooding surfaces, long-term shelf-margin migration trends (or trajectories) and normal and forced regressive trends. Time resolution is on the order of supersequences or 2nd order cycles between 4 and 23 my. according to current time scales. Calibration wells are located on the shelf top to upper slope; only 5 of them actually reach the lowermost Barremian part of the basin fill.

Key source-rock intervals in the basin are in the: 1) lower Aptian widespread lacustrine basin fill, 2) thick upper Aptian evaporites in the Camps and Santos Basin. Key reservoirs are: 1) post-salt Albian carbonate-ramp succession and 2) Upper Cretaceous to Paleogene turbidite systems.

Our focus here is not on the pre-salt succession because it was not sufficiently well resolved in the available seismic data.

Well & Seismic Stratigraphy – Santos Basin

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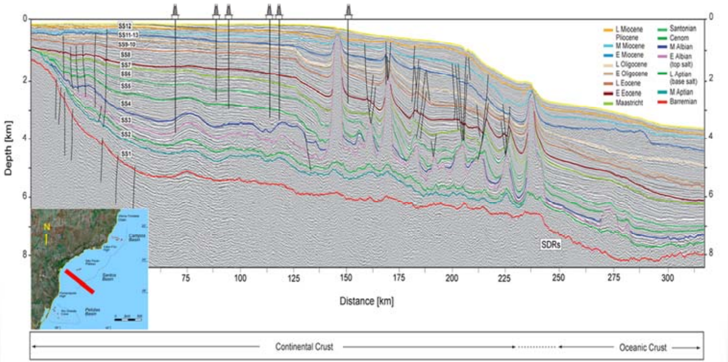
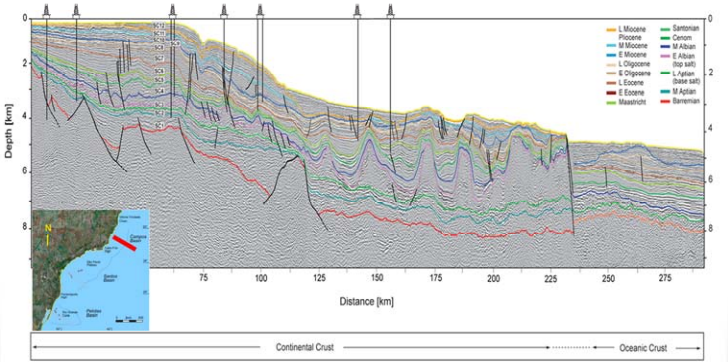


- Barremian to Holocene thickness 800-1700 m (inner shelf), 5300-9400 m (max.)
- Evaporite basin fill 200-240 km (width), 520-2200 m (depositional thickness)
- Volcanic margin (PB), non-volcanic margin (SB, CB)

Presenter's notes: For the southern offshore Brazilian margin, Barremian to Holocene thicknesses vary between 800-1700 (at minimum) and 5300-9400 m (at maximum). The seismic profile is an interpreted line for the Santos Basin.

Well & Seismic Stratigraphy – Campos Basin



- Barremian to Holocene thickness 800-1700 m (inner shelf), 5300-9400 m (max.)
- Evaporite basin fill 200-240 km (width), 520-2200 m (depositional thickness)
- Volcanic margin (PB), non-volcanic margin (SB, CB)

Presenter's notes: The evaporite basin fill is only present in the Campos and Santos margin segment.

Well & Seismic Stratigraphy – Pelotas Basin

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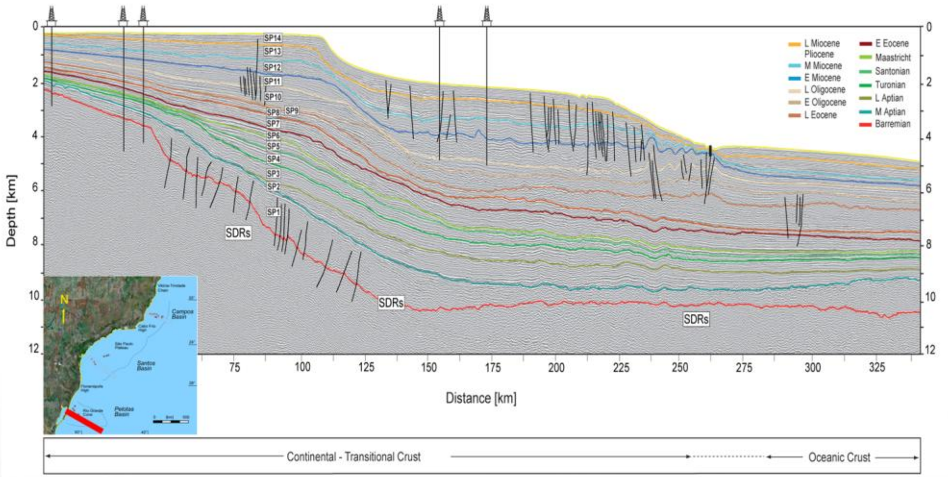
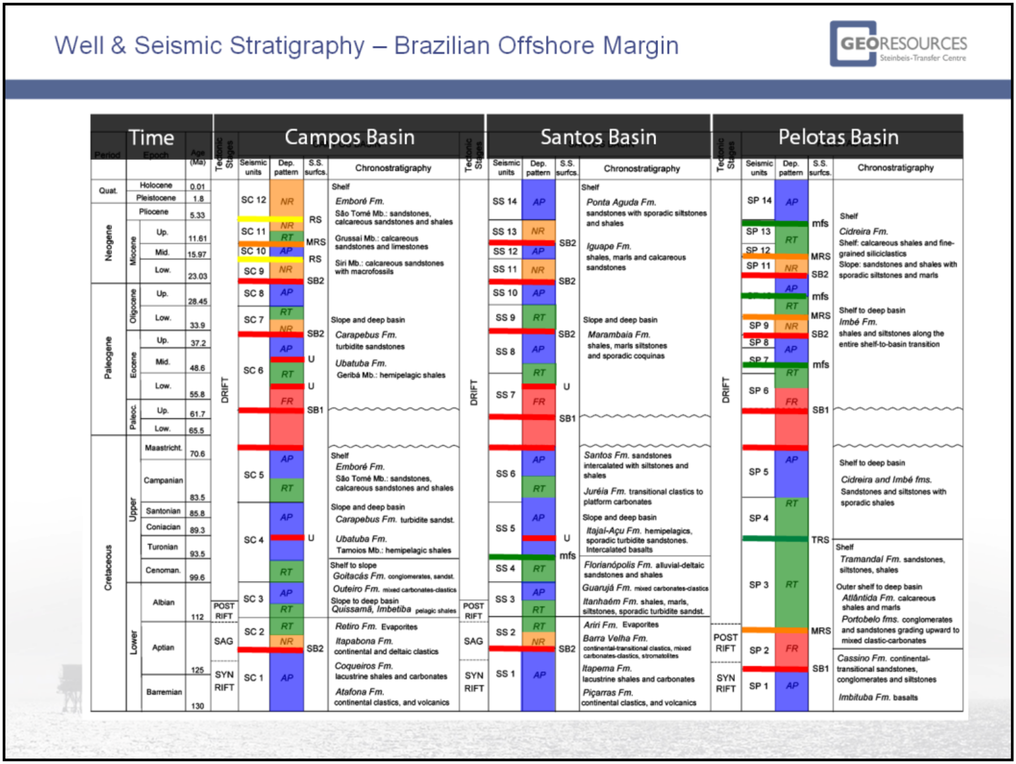


- Barremian to Holocene thickness 800-1700 m (inner shelf), 5300-9400 m (max.)
- Evaporite basin fill 200-240 km (width), 520-2200 m (depositional thickness)
- Volcanic margin (PB), non-volcanic margin (SB, CB)

Presenter's notes: There is a transition from a non-volcanic margin in the northern part to a volcanic margin in the south. The Pelotas Basin is the southenmost continental margin segment studied.



The table, calibrated to time, provides an overview of the 2nd order sequence stratigraphy of the Brazilian margin.

Bluue – aggradation to progradation.

Green – retrogradation.

Red – forced regression.

Orange – normal regression.

In comparison of these trends for the Campos, Santos and Pelota margin segments, it becomes evident that the basin fill show major lateral variations.

The Campos and Santos Basin show some similarity in trends and major unconformities during the Early Cretaceous to Paleogene.

However, the Pelotas Basin fill is clearly different, most obviously shown during the late Early and Late Cretaceous, with a major retrogradational trend.

The Late Paleogene and Neogene development is in all three basins.

A surface which is a major type I sequence boundary in one basin laterally changes to a maximum flooding surface in the adjacent basin.

Guideline

Data, Methods & Objectives

Well & Seismic Stratigraphy

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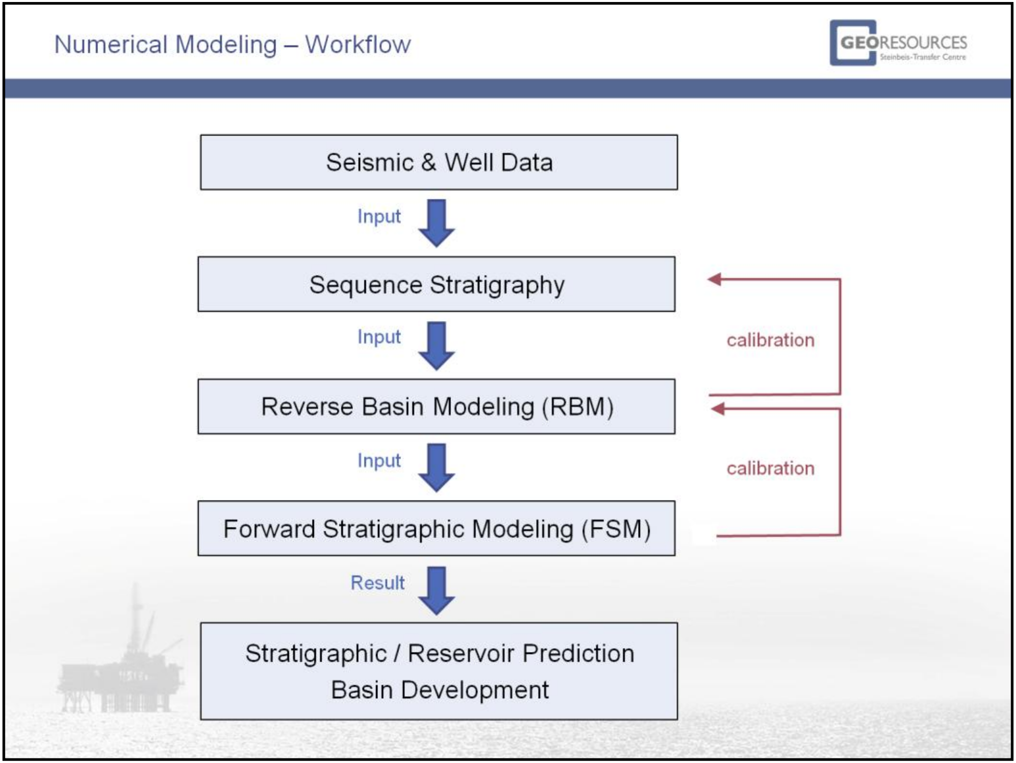
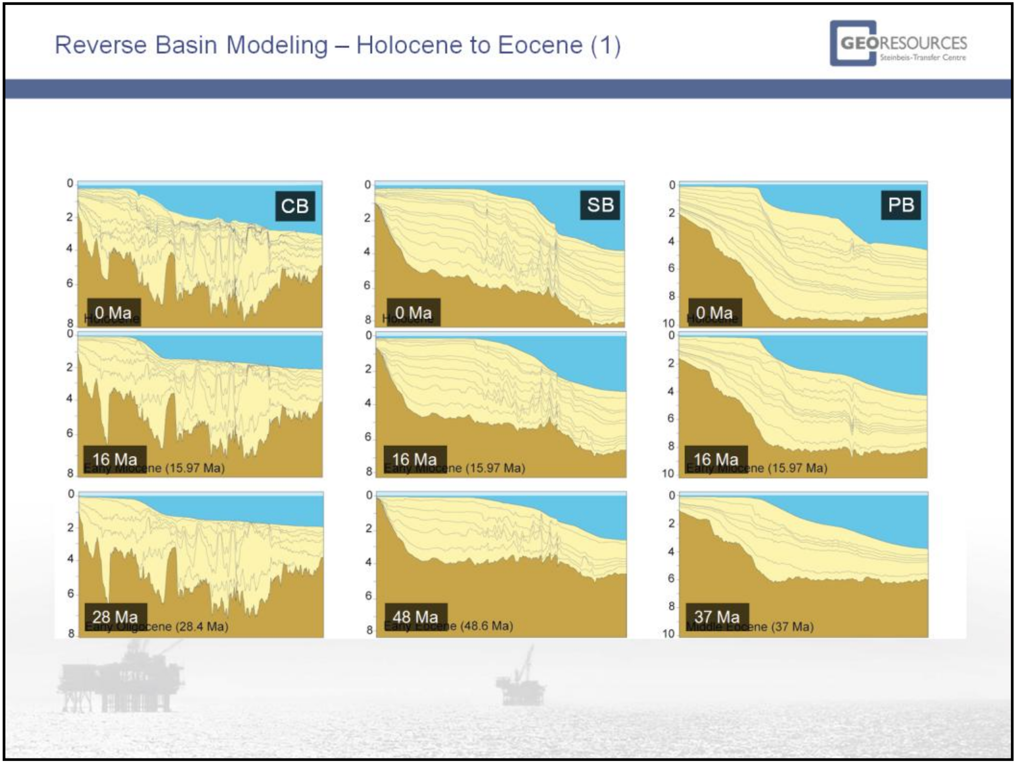
Forward Stratigraphic Modeling (FSM)

Stratigraphic Prediction

Basin Development



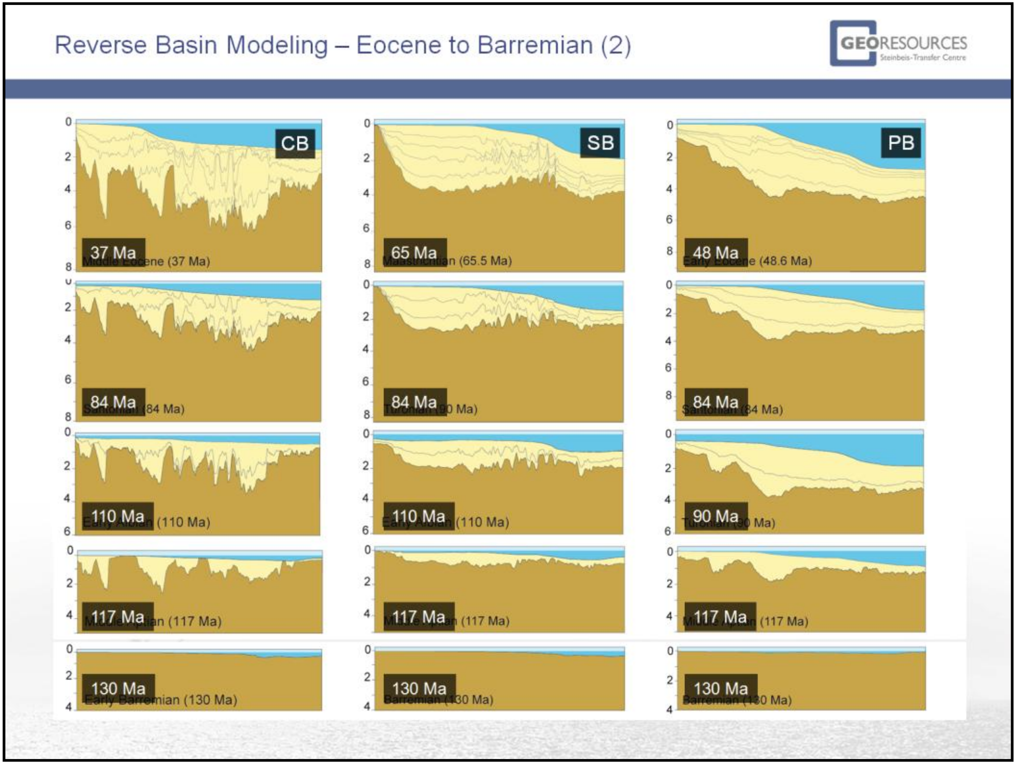
Presenter's notes: Reverse basin modeling, RBM, is based on the sequence stratigraphy of the basin fill. Results form RBM form important input data for Forward Stratigraphic Modeling. There are iterative calibration loops between both numerical modeling approaches. The modeling results, which are presented, represent best-fit, highest-plausibility models.



Presenter's notes: RBM is 2Dmodeling which fully includes flexural loading and unloading of the lithosphere. It clearly differs from 1D backstripping, assuming Airy isostasy. RBM: with the current basin architecture and infill.

Key results include total subsidence, with its genetic components: thermo-tectonic, compaction-induced and flexural subsidence plus sediment flux.

These images are the visualized numerical results for the Campos, CB, Santos, SB, and Pelotas basins, PB--from the Recent to Oligocene, Eocene for the PB.



Presenter's notes: RBM also from the Eocene to the Barremian, in selected time steps.

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Scope & Objectives

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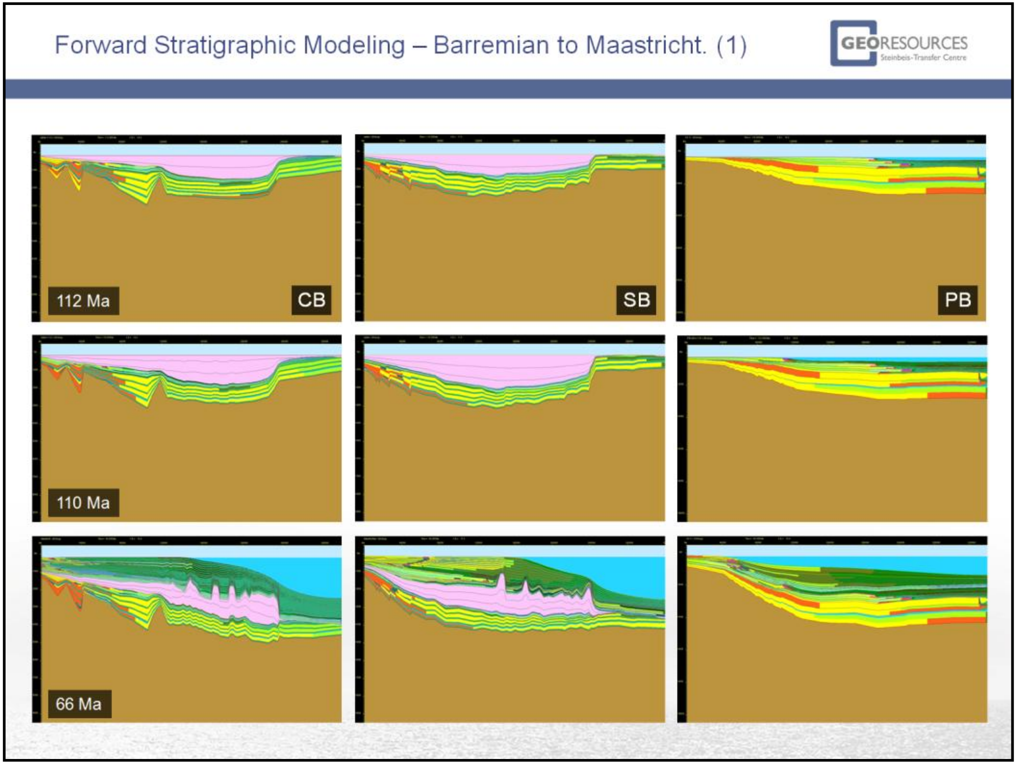

Presenter's notes: FSM builds on the results of reverse basin modeling as far as rates of accommodation and sediment flux are concerned.

In addition, it applies a large number of calculations related to depositional processes, erosion rates, dispersion distance threshold angles for depositional environments and so on.

These images are the visualized numerical results for the Campos, CB, Santos, SB, and Pelotas basins, PB-- from the Barremian, 112 Ma, to the Maastrichtian, 66 Ma.

Forward Stratigraphic Modeling – Paleocene to Recent

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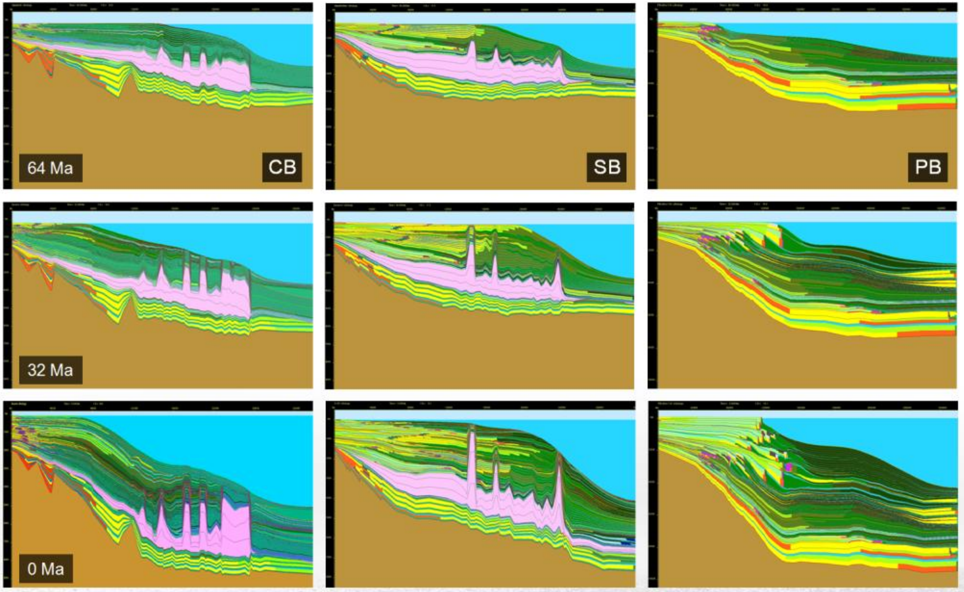

Presenter’s notes: FSM: Also from Paleocene to the Recent.

Guideline

Scope & Objectives

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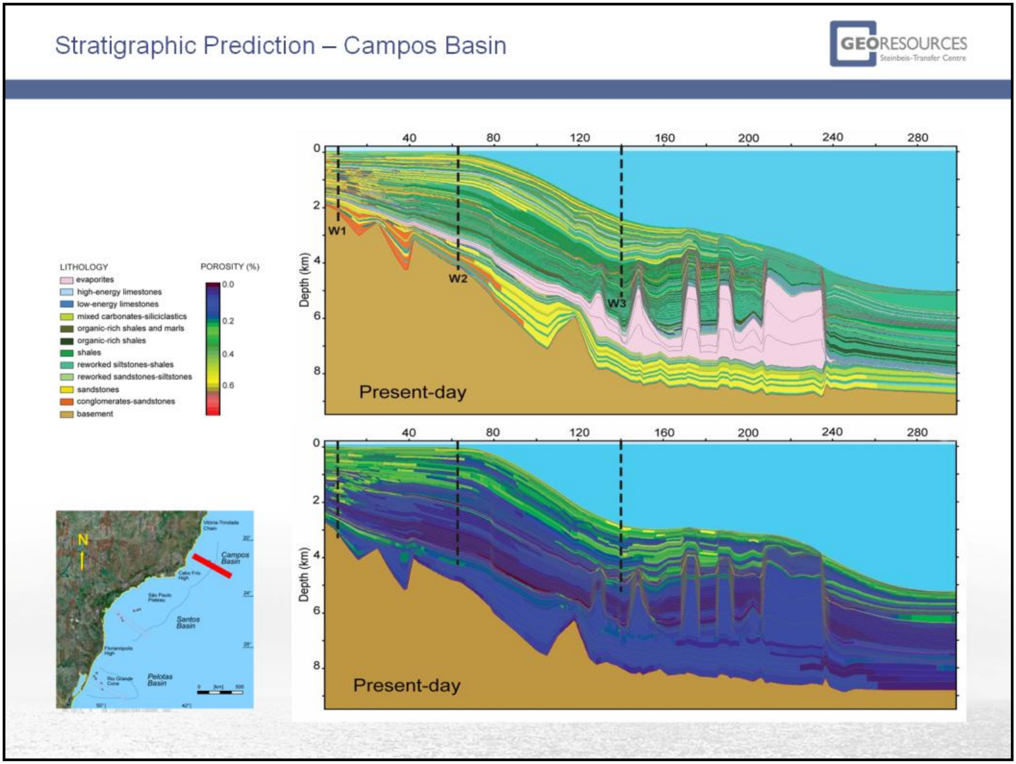
Basin Development



Presenter's notes: The main results and advantages of FSM:

1Well correlation significantly improved

A. Genetic correlation based on depositional processes

B. Chronostratigraphic model beyond biostratigraphy

2 Seismic interpretation significantly improved

A. FSM indicates seismic impedance.

B. Basin-floor fans can be genetically tied to equivalent shelf-top units.

3 Framework for dynamic reservoir and HC systems modeling

Limitations include: resolution and textural porosities only.

For the Campos Basin--calibration wells on the shelf top, at the shelf margin, and the lower slope.

Stratigraphic prediction fully honors well data, seismic architecture and impedance. Thickness in the simulation differs from wells and seismic less than +/- 5-10%.

Stratigraphic Prediction – Santos Basin

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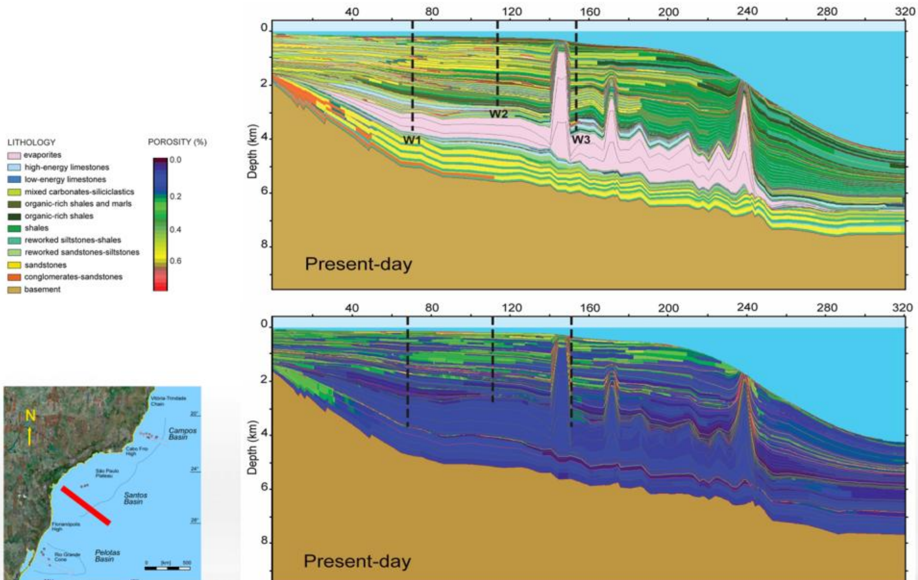
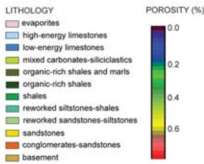
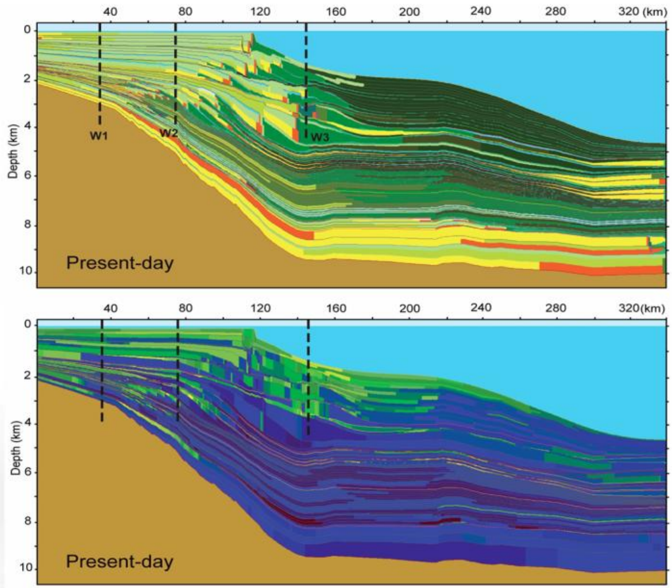


Presenter's notes: For the Santos basin, three calibration wells on the shelf top.

Stratigraphic Prediction – Pelotas Basin





Presenter's notes: For the Pelotas Basin--calibration wells on the shelf top and the upper slope.

Guideline

GEORESOURCES Steinbeis-Transfer Centre

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Basin Development

Basin Development – Subsidence & Accommodation

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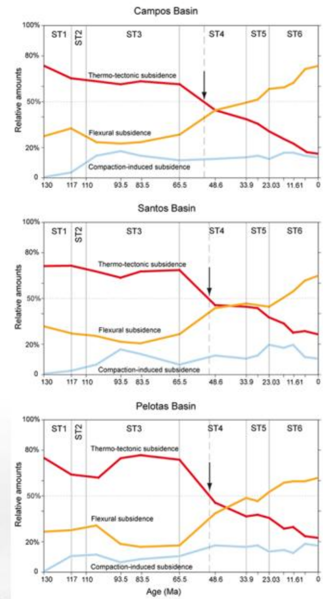
Rift and Early Drift Basin Stage

- Thermo-tectonic subsidence 75-45% of total subsidence
- Barremian to early Eocene basin fill reflects structural changes in margin development and plate-tectonic configuration

Late Drift Basin stage

- Flexural subsidence up to 60-75% of total subsidence
- Middle Eocene to recent basin fill reflects flexural lithospheric loading

Turnover at 48-45 Ma (Eocene)



Presenter's notes: Total subsidence includes three genetic components: thermo-tectonic, flexural and compaction-induced subsidence.
The three graphs show the relative amounts of these three components during basin development
During the rift, post-rift/sag and early drift stages, thermo-tectonic subsidence accounted for 75% of total subsidence, gradually decreasing to 45% until the Eocene.
Therefore the Barremian to Eocene basin fill reflects structural changes in margin development and plate tectonics – sea-floor spreading rates, far-field intraplate balance forces due to the Andean orogeny and so on.
During the Late Drift Basin Stage flexural subsidence is the dominant control on total subsidence, with up to 60-75%.
It is also the dominant control on accommodation on the Brazilian shelf
Structural changes associated with thermo-tectonic subsidence are no longer visible nor can they be interpreted from the basin fill by qualitative means.
The turnover from thermal-tectonic to flexural subsidence occurred at 40-45 Ma in all three basins.
This happens to be the same time interval, when the Lower Cretaceous source rocks in the Santos and Campos Basins reached the oil window.

Basin Development – Effective Elastic Lithospheric Thickness (T_e)

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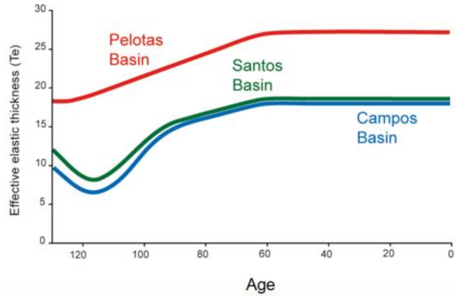
Santos & Campos Basin

- Mature drift basin stage 18 km
- Early drift basin stage increase, 8 to 18 km
- Syn-rift to post-rift & sag Barremian to E. Albian decrease, 11 to 8-6 km

Pelotas Basin

- Mature drift basin stage 27 km
- Syn-rift to early drift stage increase, 18-27 km



Presenter’s notes: The combination of RBM and FSM allows numerical models of changes in the elastic lithospheric thickness during basin history – one of the most important parameters for quantitative basin development. Te shows major changes in time and differences along the Brazilian margin. In the Pelotas Basin, Te increases from 18-27 km between the syn-rift to early drift stage and remained constant until the Recent.
The Campos and Santos Basins show an initial decrease in Te from 11-8 km in the syn-rift, post-rift and sag basin stage.
It increased to 18 km during the early drift stage and remained constant into the mature drift stage.
The higher Te for the Pelotas basin represents a primary control for its basin architecture and infill.

Basin Development – Sediment Flux

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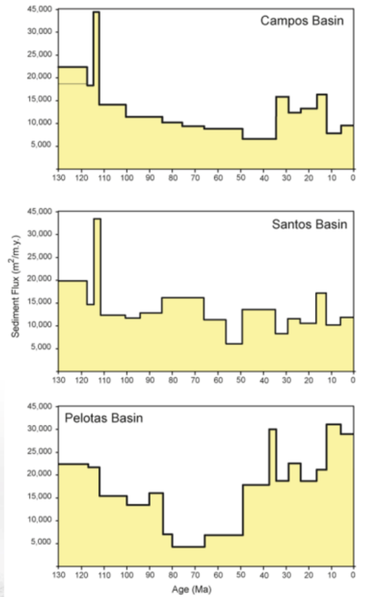
Campos & Santos Basin

- changes with ratios of 1:2 over <10 my.
- decrease, Barremian to Eocene
- largely constant since Eocene

Pelotas Basin

- total sediment flux 2-3x CB & SB
- changes with ratios of 1:3 over <10 my.
- decrease, Barremian to Maastrichtian
- strong increase, Paleogene to recent

Structural evolution of continental source areas, the Andean orogeny and changes in the Paraiba do Sul drainage system control sediment flux and basin fill on the offshore margin



Presenter's notes: Sediment flux to the Campos, Santos and Pelotas basins was highly variable in time and between the three basins.
In the Campos and Santos basins, changes with ratios of 1:2 occurred over time intervals of <10 my.
For instance, an increase in sediment flux for 70% created an increase in flexural loading of 20-25% after a lag time of 6-12my., before the lithosphere had reached a new equilibrium between loading and flexure.
A long-term decrease characterizes the Barremian to Eocene, after which sediment flux remained largely constant in the long run – some increase in Campos Basin, however.
In the Pelotas basin, sediment flux was up to 2-3x times higher during specific periods, especially in the Cenozoic. Changes with ratios of 1:3 occurred over less than 10 my. A long-term decrease occurred during the Barremian to Maastrichtian, a strong increase from the Paleogene to Recent. This is in clear contrast to sediment flux in the Campos and Santos Basins.
Changes in sediment flux over time were related to the structural evolution of continental source areas, the Andean orogeny and the Paraiba do Sul drainage system.
Examples include the Peruvian and Quechuan stages of the Andean orogeny, the uplift of the Sorra do Mar (Coniacian, Santos, 86 Ma), the Serra da Mantiqueira, Ponta Grossa Arch).
Continental source areas: Serra do Mar, Serra da Mantiqueira, Ponte Grossa Arch.
Peruvian phase of Andean orogeny, 90-75 Ma
Quechuan-Incaic phase of Andean orogeny (Cobbold 2007), 25-0 Ma
Alkaline intrusives in eastern Uruguay (Peyve 2010)

Salt Basin, Late Aptian (Top 112 Ma) – Best-fit Model

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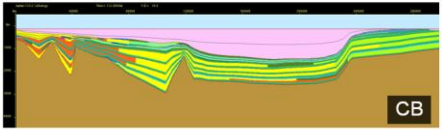
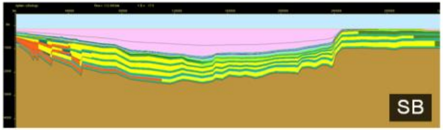
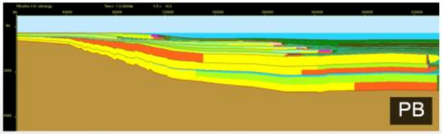
- Late sag basin, T_e 6-8 km
- Subsidence 85 m/my. (shelf) to 120 m/my. (basin)
- Initial bathymetry 100-250 (shelf) to 950 m (CO transition)
- Depositional thicknesses 520-1200 m (shelf) to 2200 m (basin)
- Rate of salt precipitation 560-810 mm/y
- Duration of precipitation 3 my.
- Water recharge by structurally controlled local seaways across the Walvis and Rio Grande Ridges (inferred)







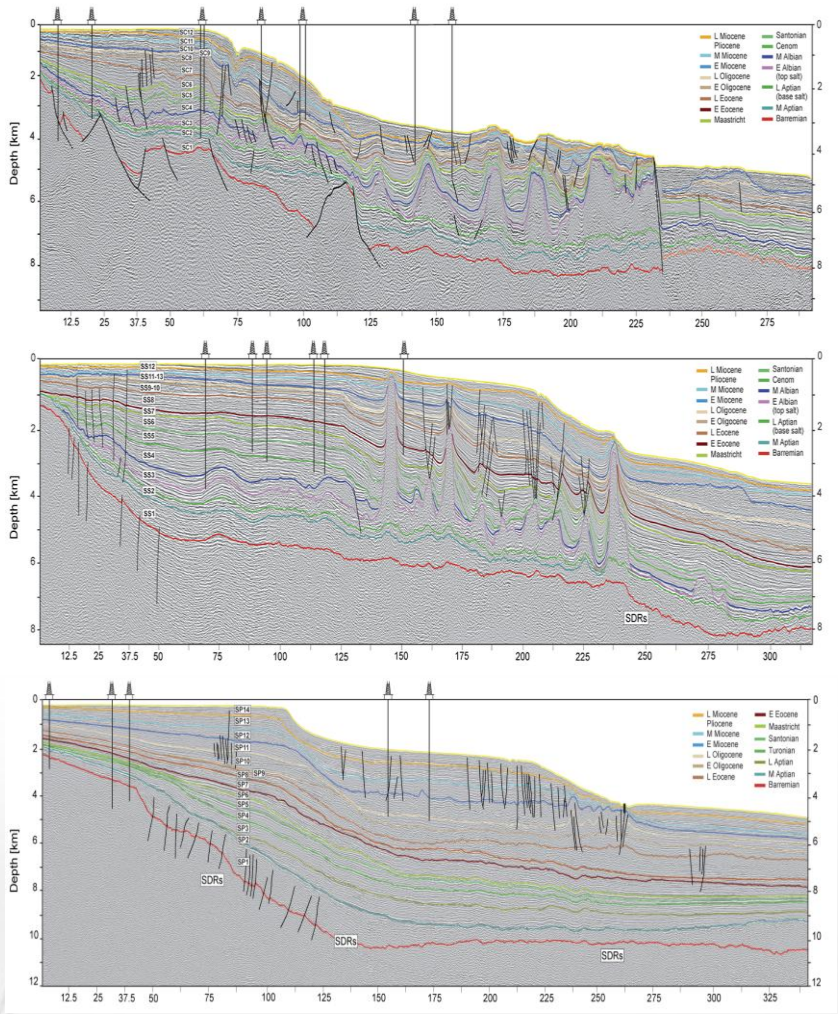
Presenter’s notes: Specific comments about the results from numerical modeling of sedimentary processes are beyond the scope of this presentation. Discussed here are some key parameters of the best-fit model for the late Aptian evaporite basin fill, which is important for the HC systems on the Brazilian margin.

1)Salt deposition occurred during the latter stage of the sag basin fill, shortly before continental break-up.
2) Depth-dependent stretching stretched 13 my. (125-112 Ma) during low Te of 6-10 km.
3)Subsidence rates were 85 m/my. on the shelf top and 120 m/my. on the slope.
4)Initial bathymetry ranged from 100-250 m on the shelf to 950 m at the future continental to oceanic transition.
5)Depositional salt thicknesses were between 520-1200 m along the modern continental shelf and up to 2200 m towards the central basin.
6)Rates of salt precipitation reached max 810 mm/yr (see Nunn and Harris, 2007).e
7)Duration of precipitation was on the order of 3 my.
8)Water recharge by structurally controlled local seaways across the Walvis Ridge - Rio Grande Rise.

Conclusions – 1 of 3

Sequence stratigraphic model of the Brazilian offshore margin at 2nd order resolution (4-23 my.)

- Basin architecture
- Basin fill
- Basin development stages
- Evaporite distribution & thickness



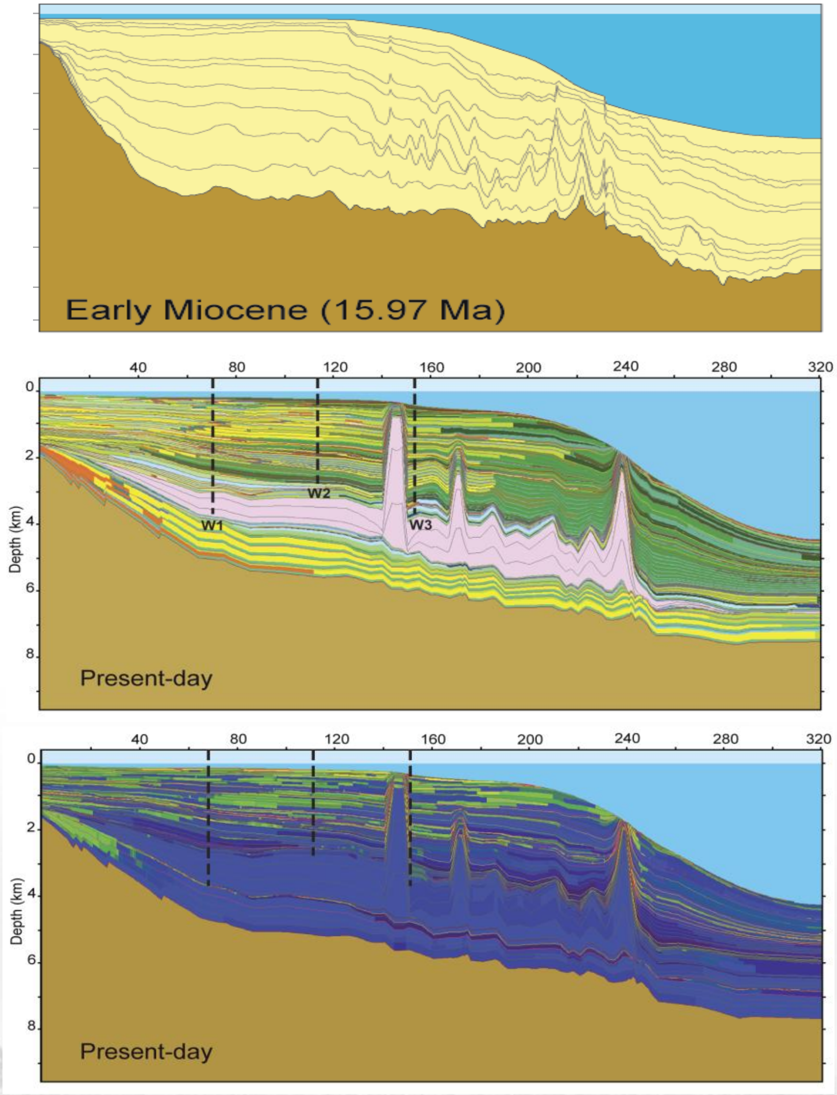
Integrated numerical modeling for basin analysis and reservoir prediction

- Stratigraphic prediction

Reservoir intervals at basin scale
Textural porosity

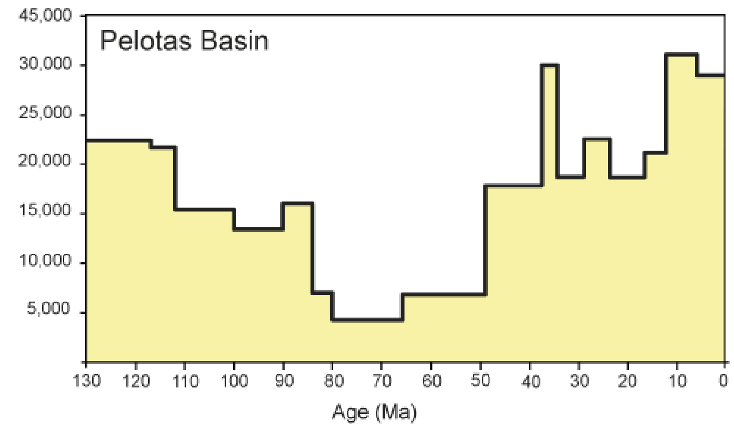
- Basin development

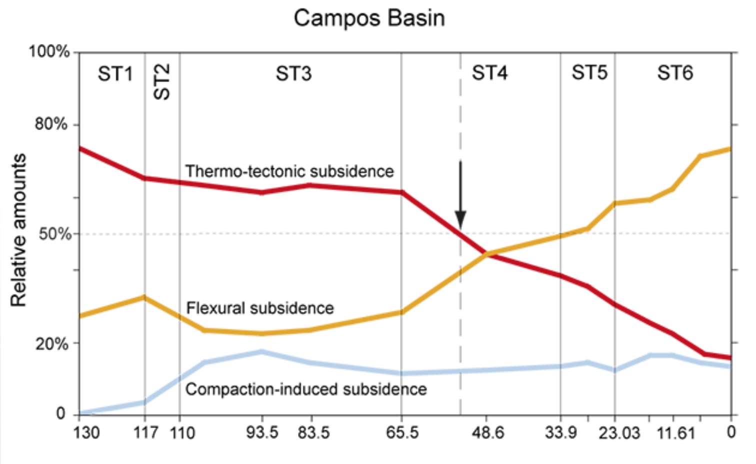
HR genetic subsidence rates
HR sediment flux



Basin Development

- Sediment flux highly variable between three offshore basin (continental source areas)
- Late Drift subsidence (<40-45 Ma) development controlled by flexural subsidence
- Structural changes in margin development and plate-tectonic configuration cannot analyzed qualitatively





... Thank you