PS Salt Tectonics Offshore Morocco: Insights from Seismic Interpretation and Discrete-Element Modelling*

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Search and Discovery Article #42095 (2017)**
Posted June 19, 2017

*Adapted from oral presentation given at AAPG Annual Convention and Exhibition, Houston, Texas, April 2-5, 2017

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Abstract

Salt-related deformation plays an important role in the geological evolution and structural style of the Moroccan continental margin and is a critical factor controlling reservoir distribution, migration pathways and trap formation. A recent surge in interest by the petroleum industry has provided a wealth of new data and some surprising results, necessitating a new look at the geology of the region. This study adopts an interactive seismic stratigraphic and forward modelling approach, using the Discrete Element Technique (DEM), to the study of salt-related deformation with the aim of characterising and modelling the salt tectonics and associated sedimentation and fluid flow. It was possible to define and characterize the evolution of different structural scenarios for two segments of the Morocco margin:

1. The Talfeney Plateau, characterized by large allochthonous salt sheets, tongues and canopies, with associated counter-regional systems, which are landward-dipping expulsion faults, and roho-systems, which are seaward-dipping listric faults detaching on the allochthonous salt, as well as salt-cored fold-thrust belts at the seaward edge of the salt basin; and
2. The Safi Haute Mer, with smaller allochthonous salt features, a well-defined extensional, transitional and contractional domain, with salt rollers, pillows, rafts and turtle anticlines updip passing downdip to squeezed salt tongues and allochthonous sheets, which were influenced by the occurrence of paleovolcanoes that acted as a buttress for the seaward migration of the salt, favouring its movement upward in the stratigraphy.

The integration with forward modelling of salt deformation affords better constraints on back-stripping the margin evolution and allows for more confident input into petroleum system models, allowing a spatial and temporal reconstruction of fluid expulsion, migration and accumulation which helps support future exploration of offshore Morocco.

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Salt Tectonics Offshore Morocco: Insights from Seismic Interpretation and Discrete-Element Modelling

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Introduction

Salt tectonics plays a major role on the structural and geological evolution of many continental margins around the world and is a critical factor controlling reservoir distribution, migration pathways and trap formation.

The Moroccan continental margin is an outstanding example of the complex evolution and interplay between salt-related deformation and sedimentation.

In this study we adopt an seismic stratigraphic and forward modelling approach, using the Discrete-Element Technique (DEM).

Analysis of 2D regional seismic transects offshore Morocco (Fig. 1) allowed the definition of at least two different structural scenarios along the margin.

DEM corroborates the interpretation of salt structures identified in seismic and affords a better understanding of their evolution.

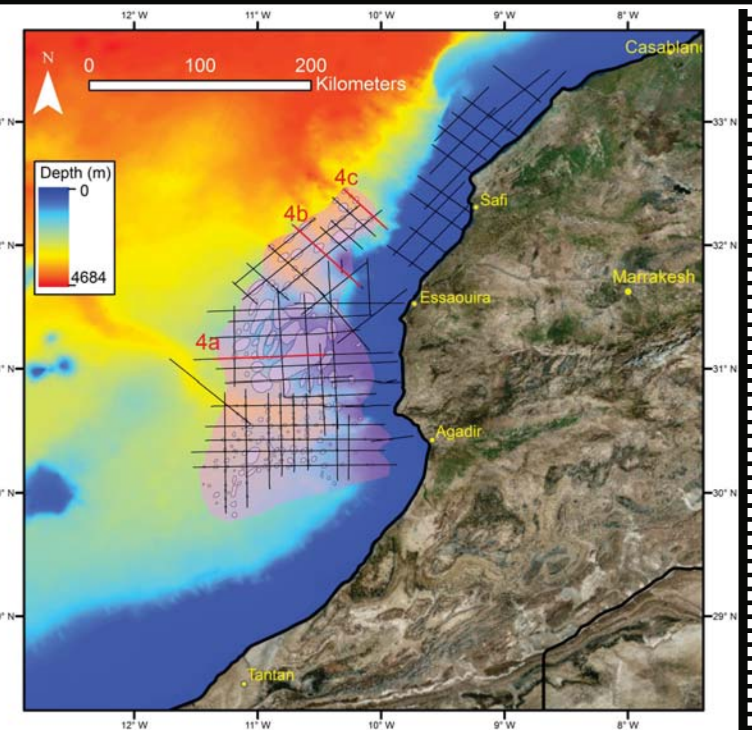

Figure 1: Study area map with seismic secions in black

Discrete-Element Modelling (DEM)

Treats the rock mass as an assemblage of circular elements of different size that interact as pairs connected by breakable elastic springs and through a 'repulsive-attractive' force obeying Newton´s Laws of motion (Finch et al., 2003, 2004 and Hardy & Finch, 2006).

DEM is a discontinuum technique that allows modelling of the dynamic evolution of a system since it is based on simple particles interactions and does not require complex re-meshing unlike other continuum techniques, such as Finite-Element modelling.

It can also be applied to study salt tectonics if the limitation of being a discontinuum method is tackled by reducing the breaking separation to the point that the material behaves plastically.

The stress-strain plot (Fig. 2) from compressional tests on materials with different breaking separations from Finch et al. (2004) shows that a breaking separation of 0.01 is enough to reproduce plastic behaviour since strain continues to accumulate without changing in the stress.

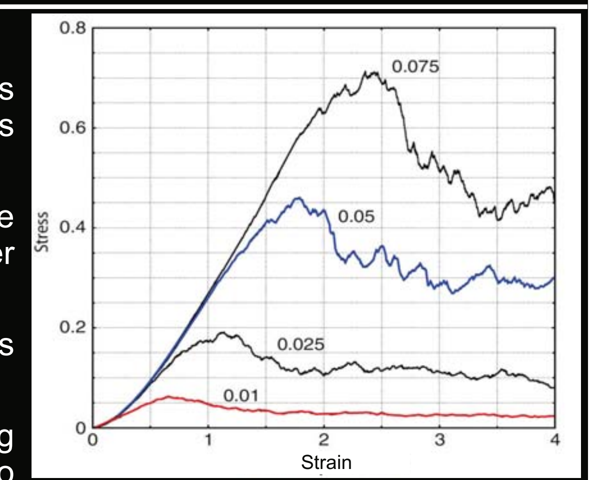

Figure 2: Stress-strain plot adapted from Finch et al., 2004.

In our models the overburden has a constant breaking separation of 0.05, typical of brittle material, and a density of 2300 kg m^{-3}, whereas the salt has a breaking separation of 0.001, lower than required for plasticity, and density of 2160 kg m^{-3}.

The media (Fig. 3) consists of 9817 elements dipping 3° basinward. The height corresponds to 1.5km and length of 9.8km. The initial width of the salt is 1.25km.

The walls move towards each other to simulate compression of a buried diapir.

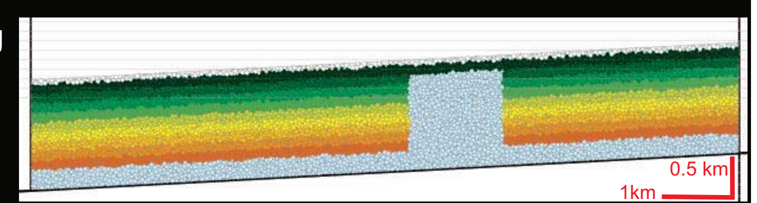

Figure 3: Initial model setup

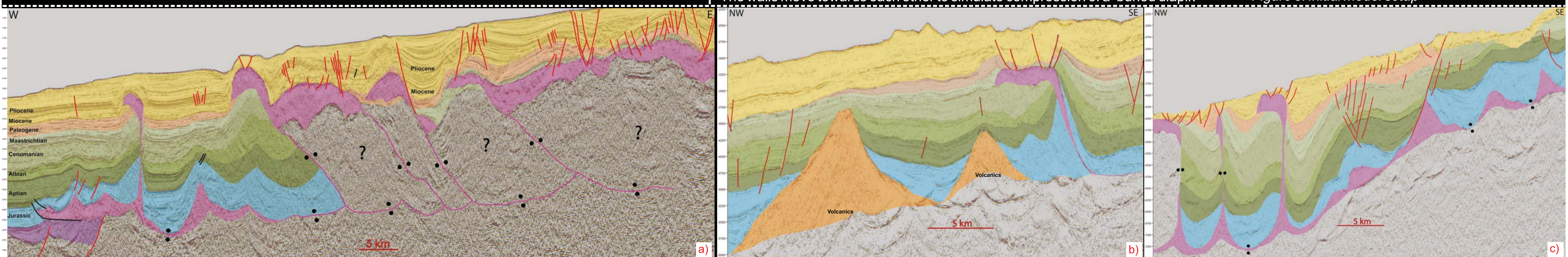

Figure 4: Seismic transects offshore Morocco showing the variations of structural style along the margin: a) southern segment (Talfeney Plateau) with a large canopy passing downdip to salt tongues with associated roho and counter-regional systems (Schuster, 1995) and a salt nappe with a fold-thrust belt and the seaward end of the basin; b) northern segment (Safi Haute Mer) with the occurrence of an isolated salt tongue that is affected by outboard paleovolcanoes; and c) northern segment showing a smaller volume of salt that results in smaller salt tongues and allocthonous features and a well defined transition from the extensional domain with rafts, pillows, rollers, to a translational domain characterized by a turtle anticline passing to a contractional domain where salt tongues have vertical and squeezed feeders. Pink colour represents salt rock and red and black lines correspond to normal and reverse faults, respectively.

Discrete-Element Modelling Parameters and Results

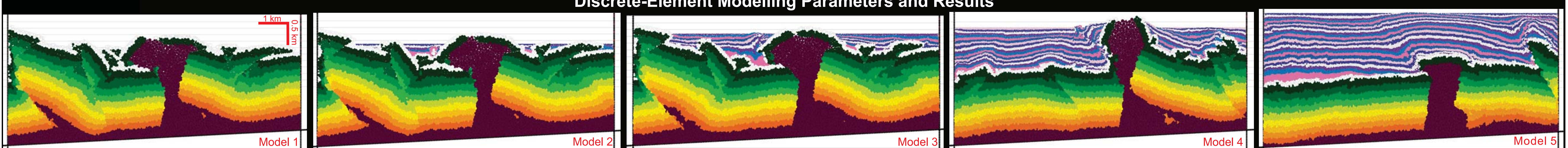

Figure 5: Final models results.

Scaling and Parameters

The models are run for 5 million time steps, where one time step is equivalent to a year. Compression is acted on both walls at a rate of 0.000006 units/time step resulting in 0.39mm/year compression on each wall, which corresponds to 4% of compression/Myr and a total of 20% of compression during 5 Myr.

Aggradation occurs at an initial sea-level that progressively rises at 49 m when sediment is added to the system. The frequency of addition is every 200.000 years.

Model 1 has no syn-kynematic sedimentation over 5 Myr.

Models 2, 3 and 4 sediments are added after 4 Myr, 3 Myr and 1 Myr, respectively.

Model 5 experiences continual sedimentation.

Modelling results

Experiments (Fig. 5) show that rejuvenation of a buried diapir by compression (thin- or thick-skinned) results in squeezing of the feeder to a point near weld formation due to upward expulsion of salt (Fig. 6).

In scenarios where sediment input is low or absent, salt is thrusted seaward generating salt tongues that resemble the ones found in the Moroccan continental margin (Fig. 4).

In the experiments with lower and later sediment input (1, 2 and 3) there is more intense folding and faulting (mostly reverse with a few normal faults) as well as the occurrence of thrust piercement of salt at the seaward end of the model, which corresponds to the early stages of nappe evolution.

Salt pillows develop at models 2, 3, 4 and 5, which show that their development is related to differential sedimentary loading.

In model 4 differential loading allows salt to move higher in the stratigraphy generating a tear-drop diapir with overturned flaps.

Higher and earlier sediment input generates a stronger overburden that suppresses diapirism and deformation (model 5).

Salt uprising and tilting of the margin control sediment distribution by generating an earlier distal depocenter strongly affected by thrusting/folding, whereas a proximal depocenter is generated later.

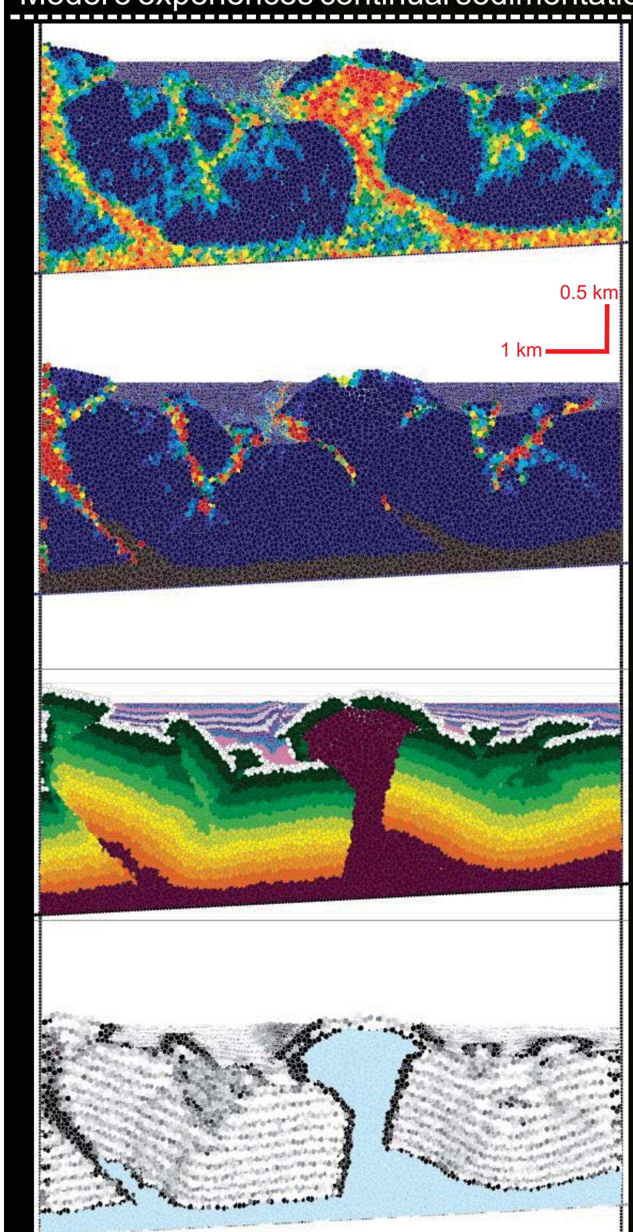

Figure 6: Different plots extracted from the model 3. From top to bottom: strain, stress, normal and coherence plots.

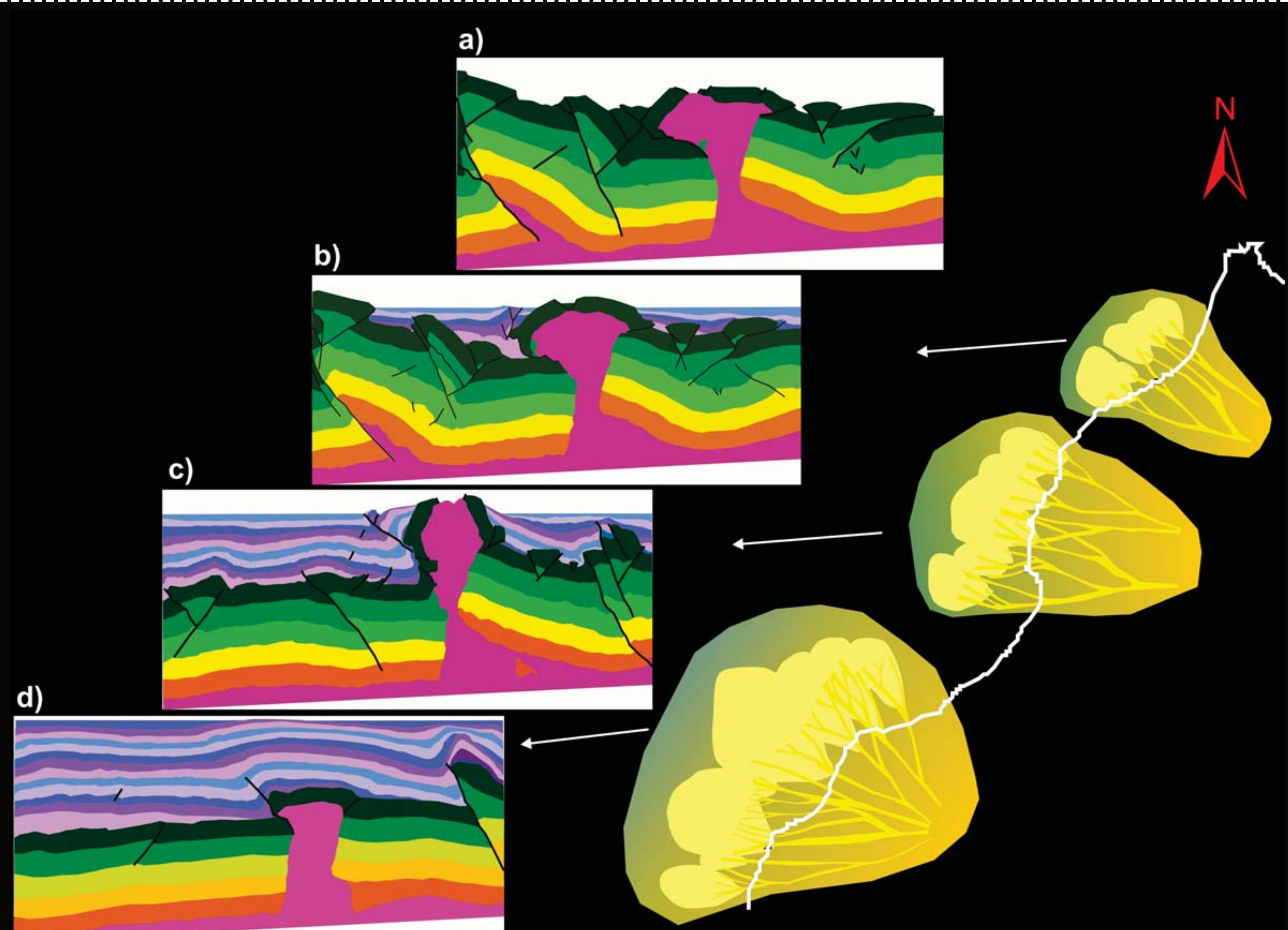

Figure 7: Schematic diagram correlating different sediment inputs along the Moroccan continental margin during the Late Cretaceous and Tertiary to the different structural styles and salt structures interpreted on seismic and produced by the models. Lower sediment input in the Talfeney Plateau and Safi Haute Mer is associated with development of salt tongues, whereas higher sediment input to the South suppresses tongue development. Interpretation of experiments in a) model 1, b) model 3, c) model 4 and d) model 5.

Discussion and Conclusions

- Salt tectonics in Morocco is a very complex phenomenon due to many factors: 1) the syn-rift nature of the salt, 2) the effects generated by late uplift and compressional tectonics, and 3) the existence of volcanoes contemporary with salt deposition.
- Moreover, differences in syn-rift salt geometries and thicknesses as well as Cretaceous and Cenozoic sedimentation patterns appear to have a profound effect on the structural style of salt deformation.
- DEM is a powerful tool to assess the evolution of salt structures and their interplay with sedimentation.
- Models show a sequential evolution of the structures and are easily reproducible, allowing analysis of stress/strain through time.
- Figure 6 shows the different plots that can be produced during the experiments.
- Models confirm that squeezing of buried diapirs can generate salt tongues and that low sediment input favours their development, whereas high sediment input suppresses diapirism.
- Schematic diagram (Fig. 7) exemplifies that variations in sedimentation during the Late Cretaceous and Tertiary (Tari and Jabour, 2013) in the Moroccan continental margin can be linked to the different salt geometries found along the margin.
- Future work should consider different density contrasts and how syn-rift salt distribution and different sedimentation patterns affected salt tectonics to explain along-strike variations of salt volumes, tectonic style and overburden architecture on a more regional scale.

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Acknowledgements

We would like to thank the PhD sponsor CNPq and NARG sponsors:

A special thanks to Chevron and ONHYM for access to sesimic and well data