

CONTROLS of SALT TECTONICS STYLES & SEQUENTIAL EVOLUTION of SALT SHEETS OFFSHORE MOROCCO

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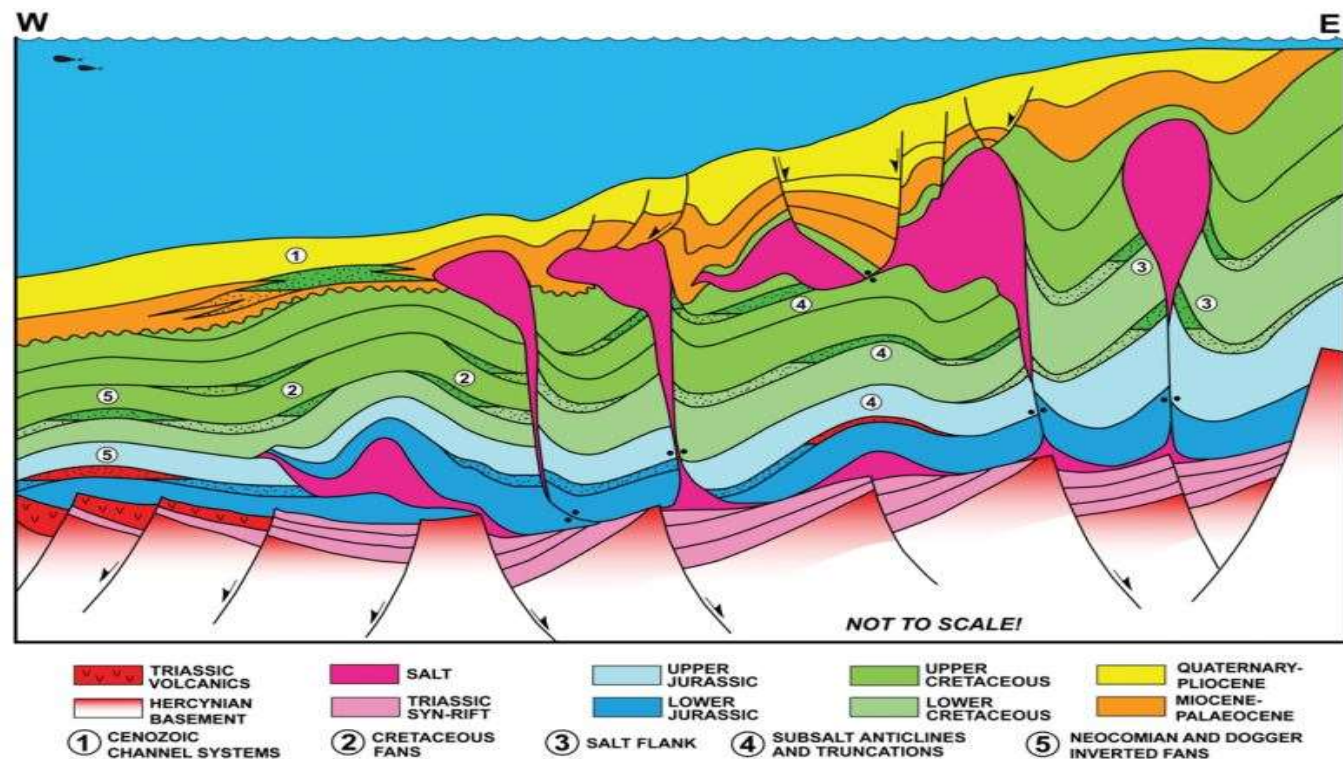


Special Thanks:



MOTIVATION

- Most of the hydrocarbon plays on Morocco are salt-related (Tari & Jabbour, 2013)
- Crucial to exploration to better understand the interplay of **salt tectonics** and **sedimentation** and the **timing** and evolution of specific structures to assess how they control trap formation, migration pathways and reservoir distribution, especially on deep-waters.
- There is a large variety of structural styles along this margin which makes it one of the most interesting places in the world for the study of salt tectonics.

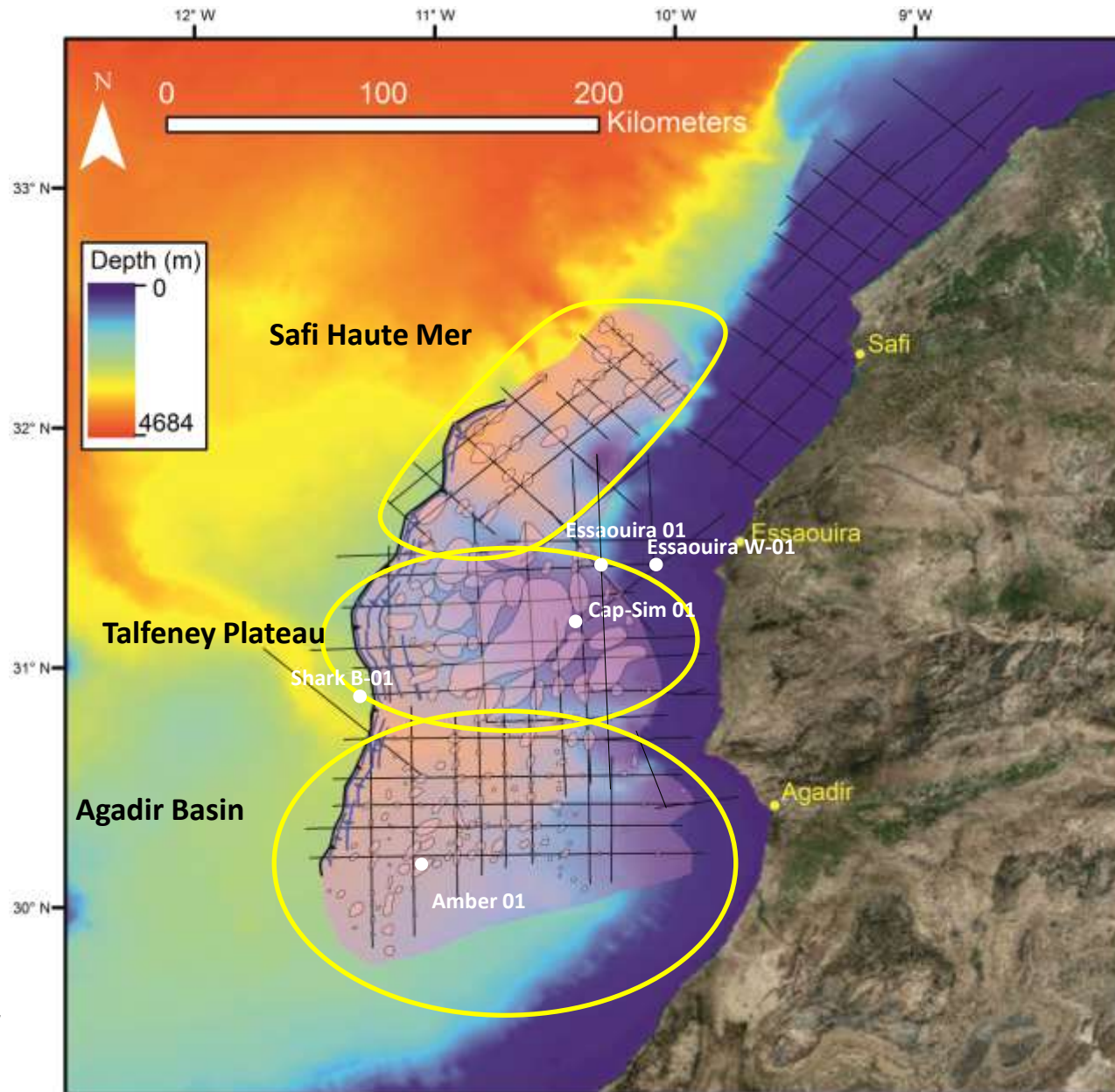


STUDY AREAS

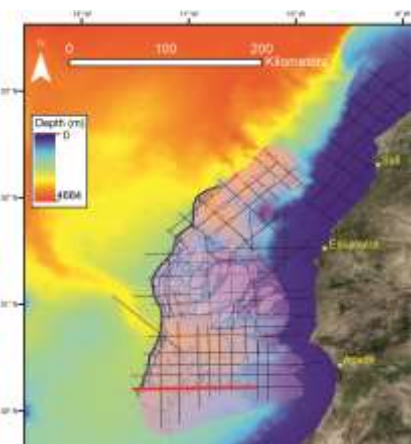
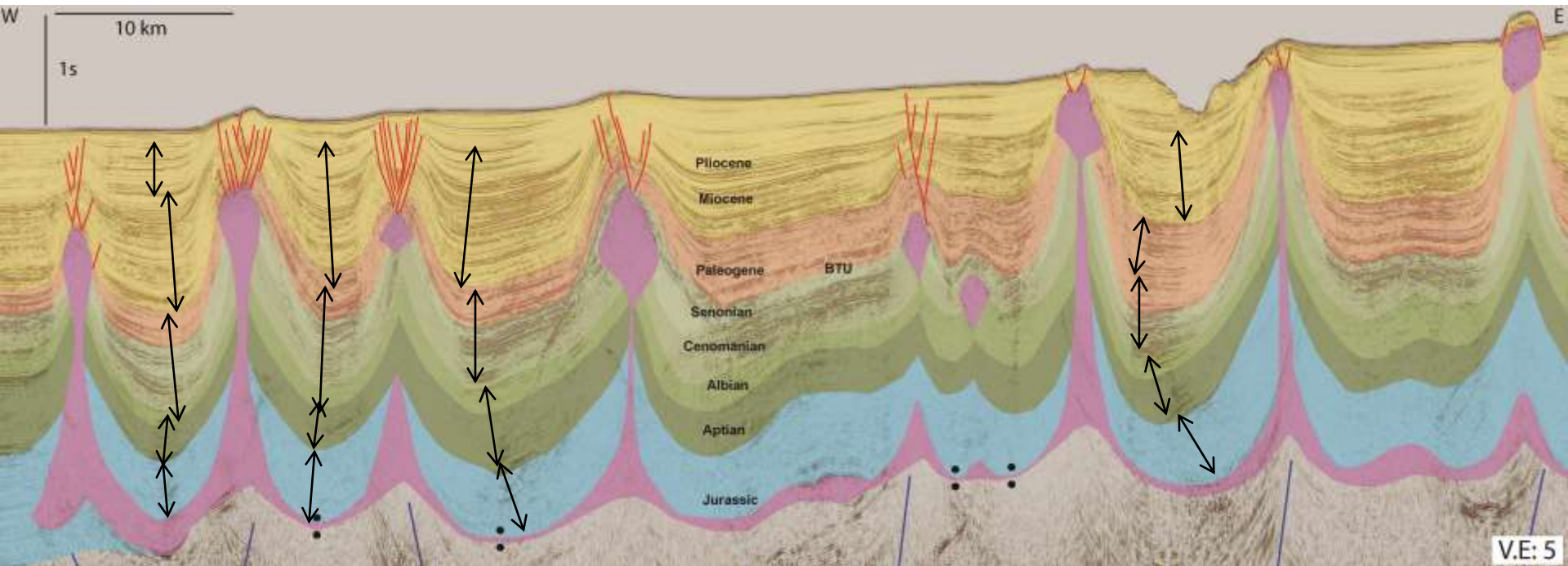
- Lack of 3D control of salt geometries / depositional systems
- Limited seismic resolution and well-control
- Large presence of Allochthonous salt

BUT:

- Many new ideas and concepts of salt tectonics developed recently
- Development of new modelling methodologies

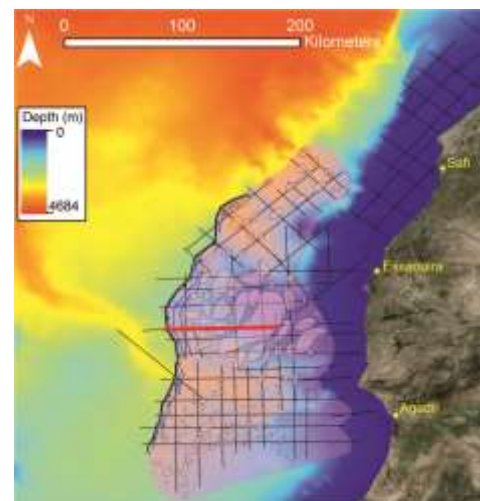
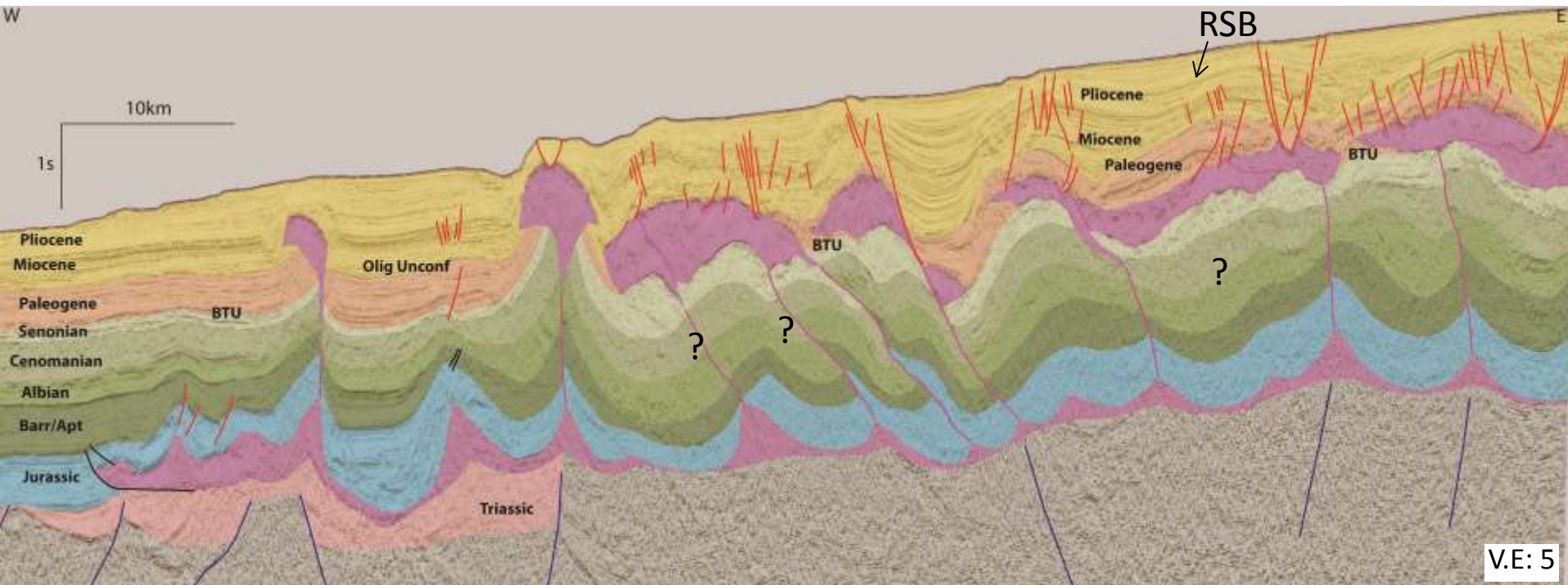


AGADIR BASIN



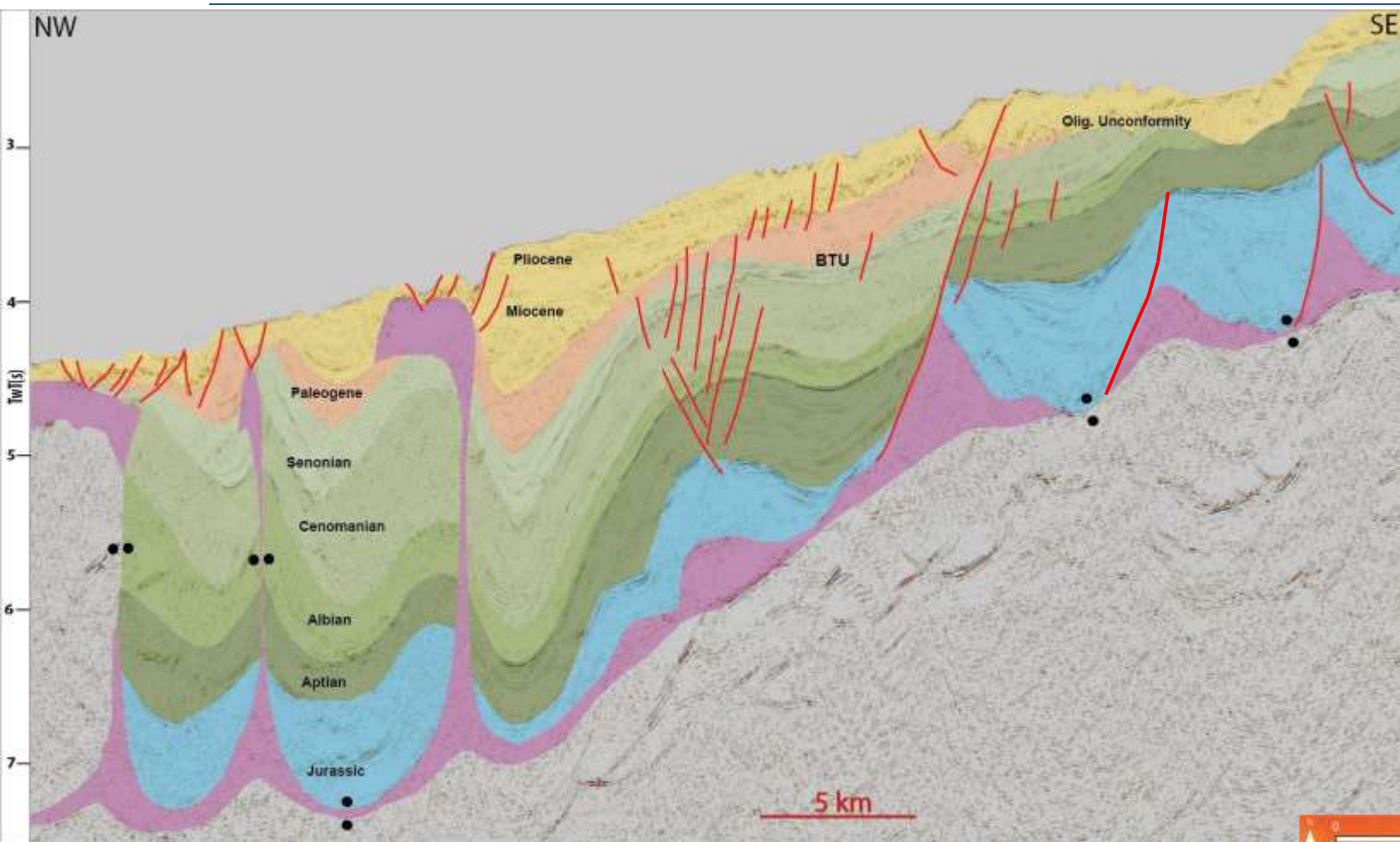
- Squeezed and tea-drop diapirs (symmetric and up-right structures)
- Intense folding & thicknesses variations across minibasins
- Minibasins driven by **DIAPIR SHORTENING** – abrupt depocentre shift
- Reactive diapirism?: Early – Middle Jurassic
- Passive diapirism (turtle structures) – Late Jurassic to Cenomanian
- Active diapirism - Late Cretaceous- recent
- 3 Most distal diapirs – active diapirism since the Early Cretaceous
- **Thick** Cenozoic package: 2s average - **2.2km**

RAS TALFENEY PLATEAU

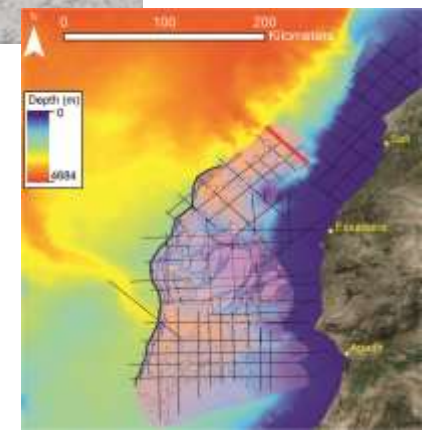


- Seaward-leaning salt tongues and sheets coalesced to form canopies
- Counter-regional & Roho-systems (*sensu* Schuster, 1995)
- Precursor salt walls/stocks with different origins:
Contraction x Expulsion
- Complex distribution of contractional/extensional domains?
- Ramp-syncline minibasins (RSB) above canopy: 10 km of translation
- Nappe & fold-belt active until Late Cretaceous: 12-15 km translation

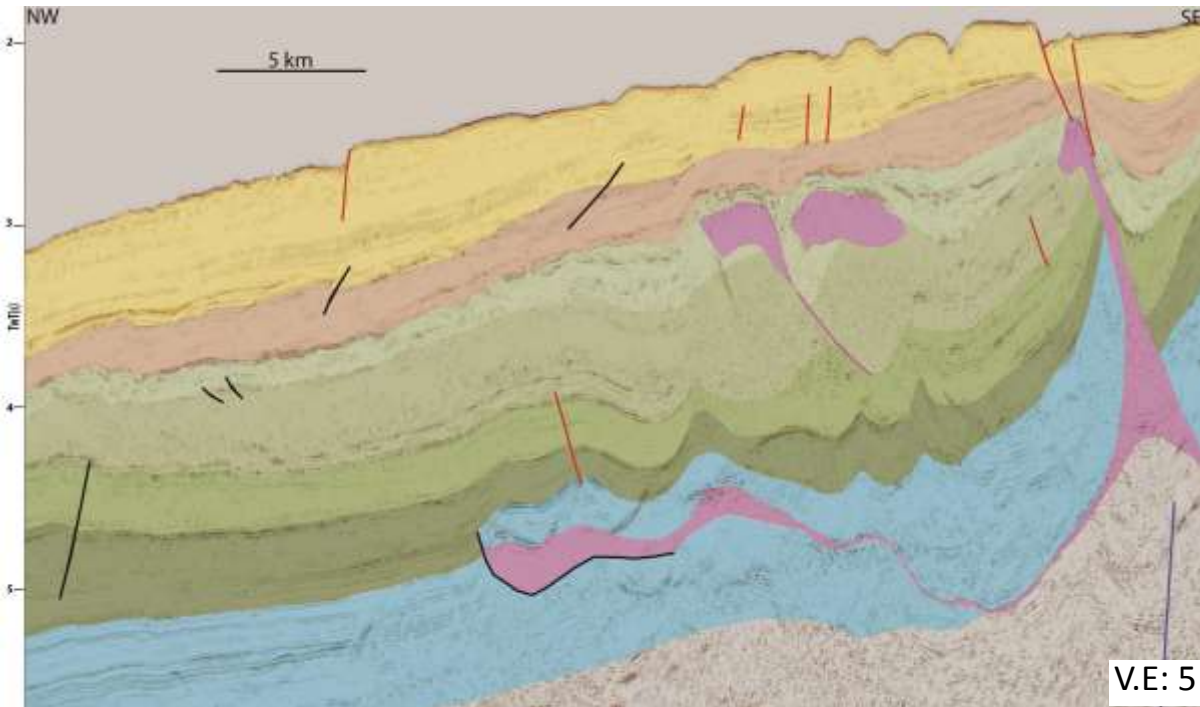
SAFI HAUTE MER



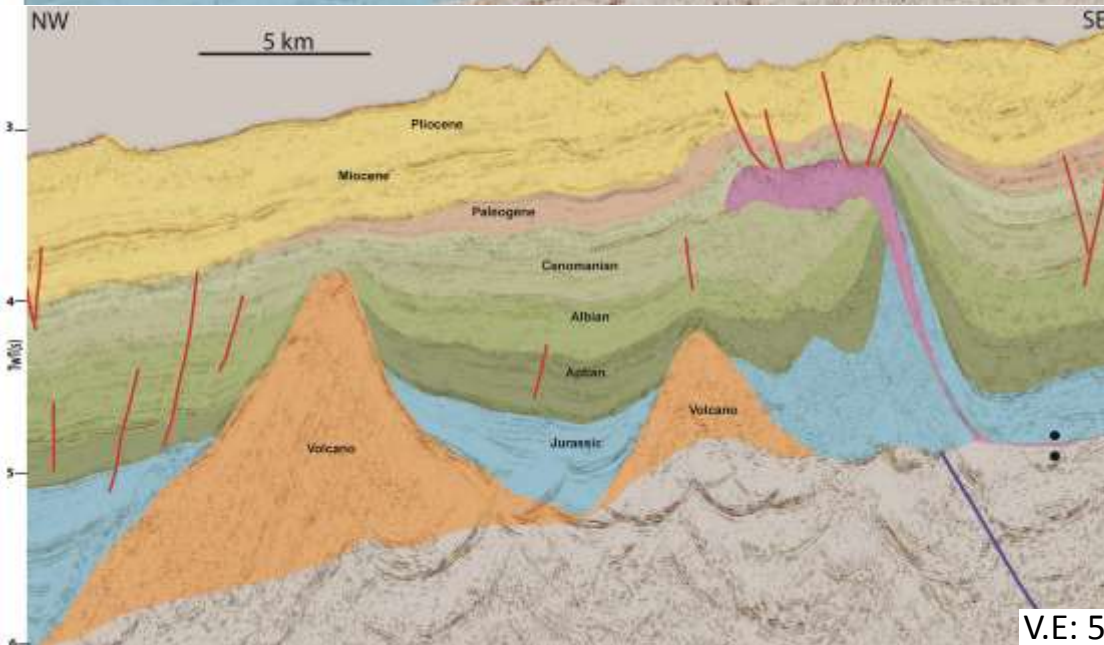
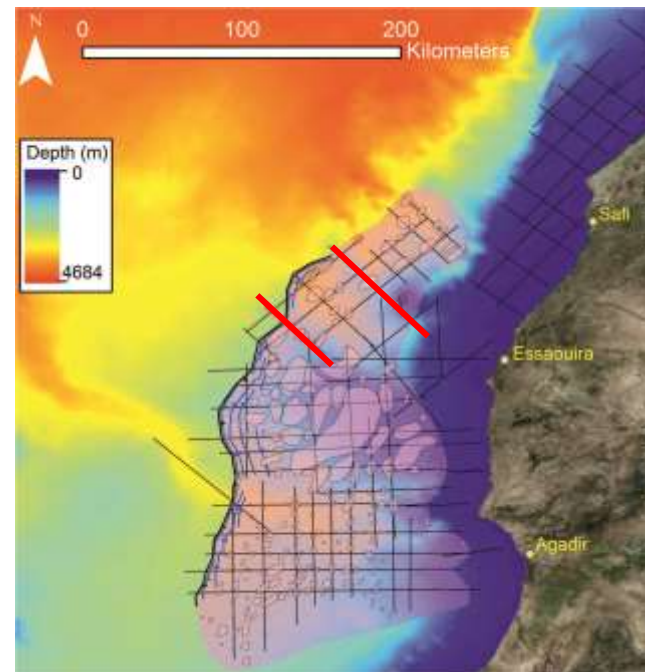
- Salt rollers, pillows and raft structures (shelf-break to upper-slope)
- Hybrid turtle anticline (middle slope)
- Salt tongues with sub-vertical welds (lower-slope)
- Basal detachment = 5° - 10° - 1° W = favoured gliding & updip extension
- **Thin** Cenozoic sequence: 0.9s average (2200m/s) = **1km thick**



SAFI HAUTE MER



V.E: 5

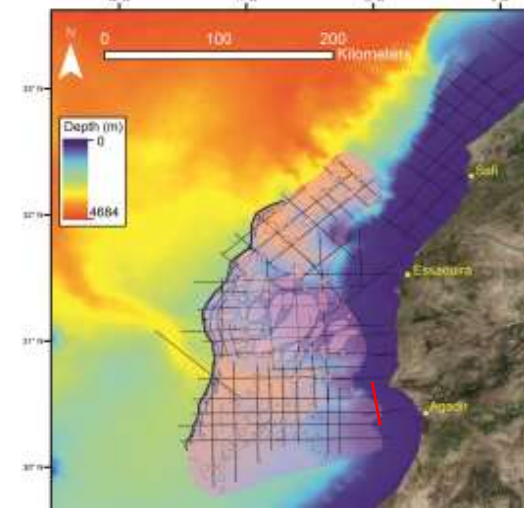
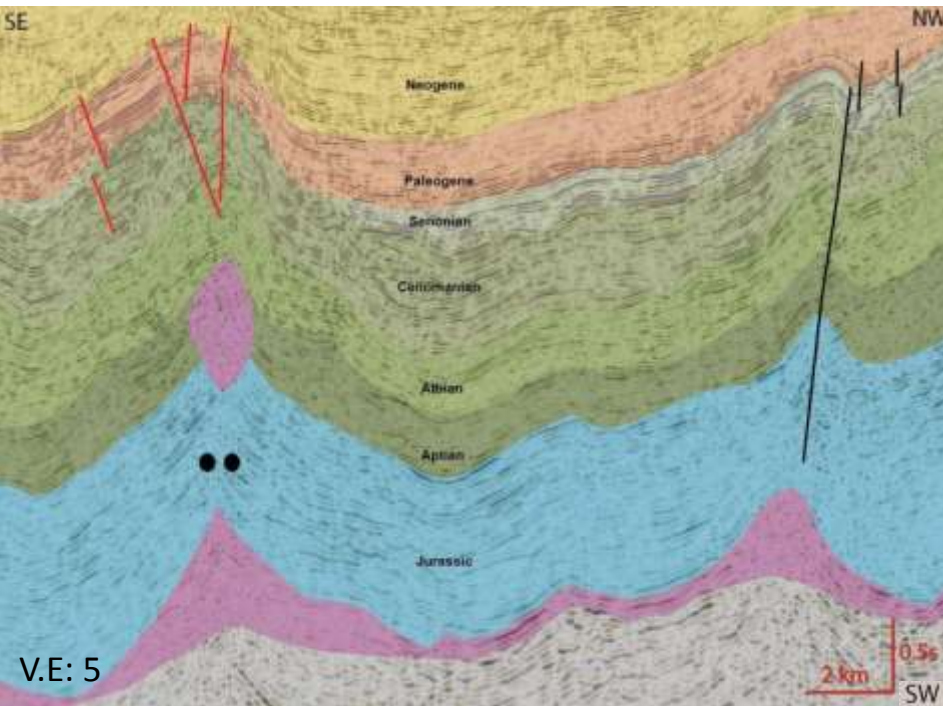


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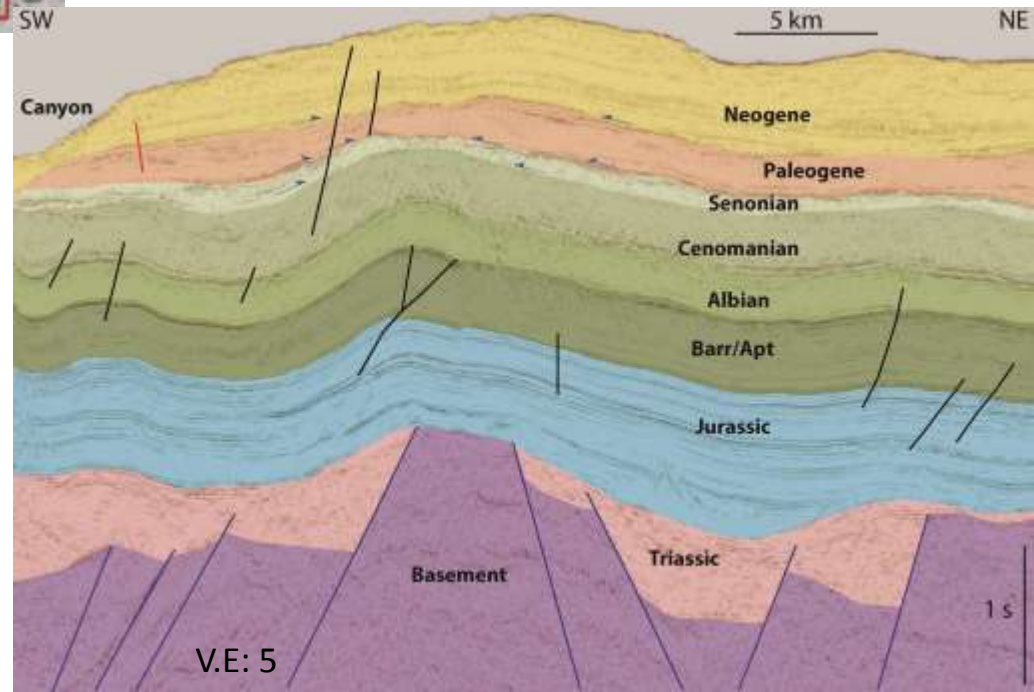
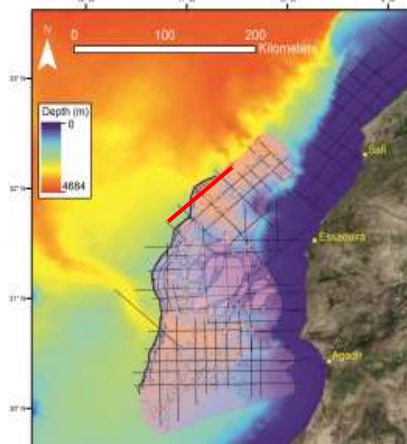
- Salt tongues with **squeezed counter-regional** feeders
- Early history: Differential Loading x Thrusting
- Salt nappe with low-amplitude fold-thrust belt (15 km of translation)
- Tall (~3,5km) paleovolcanoes acting as buttresses to seaward translation

Evidences of Thin-Skinned Shortening

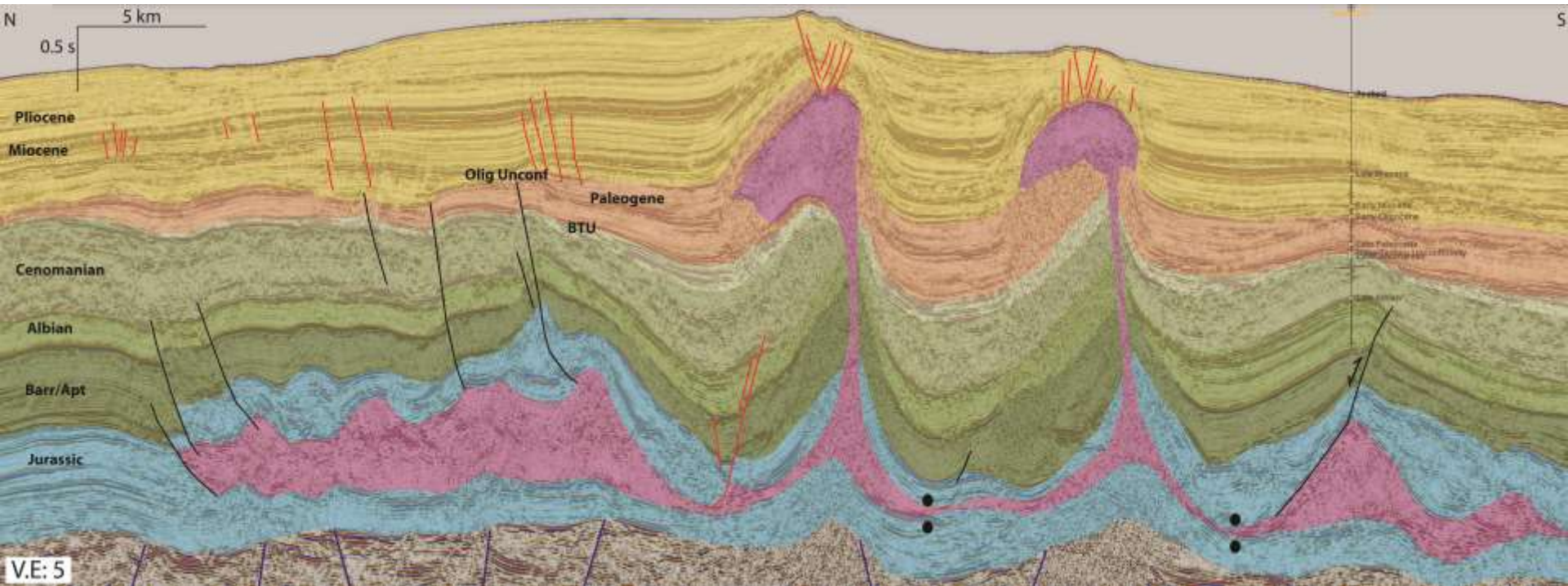
- Contractural structures (*NE* box-fold and squeezed diapirs/walls) in the shelf



- NW trending anticlines folding basement to Cenomanian interval outboard of the salt basin (fault inversion involved)

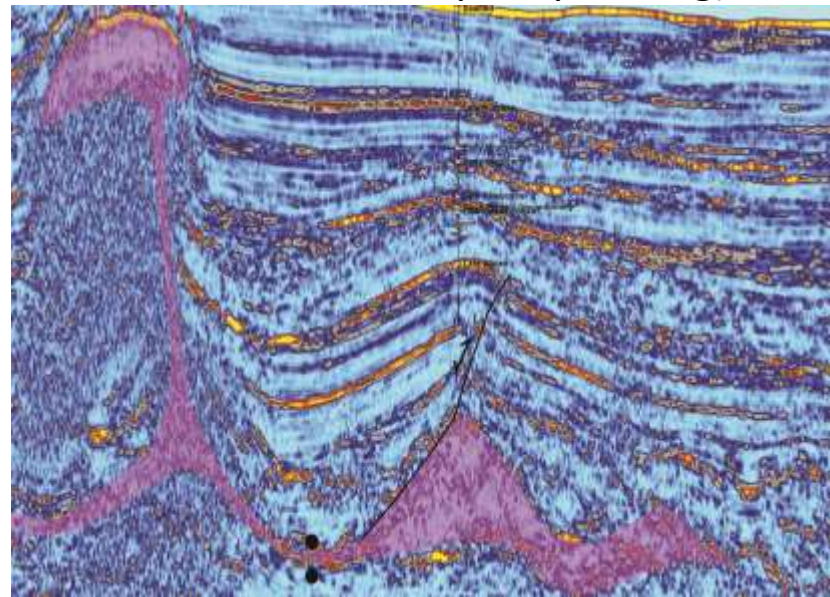


Evidences of Thin-Skinned Shortening

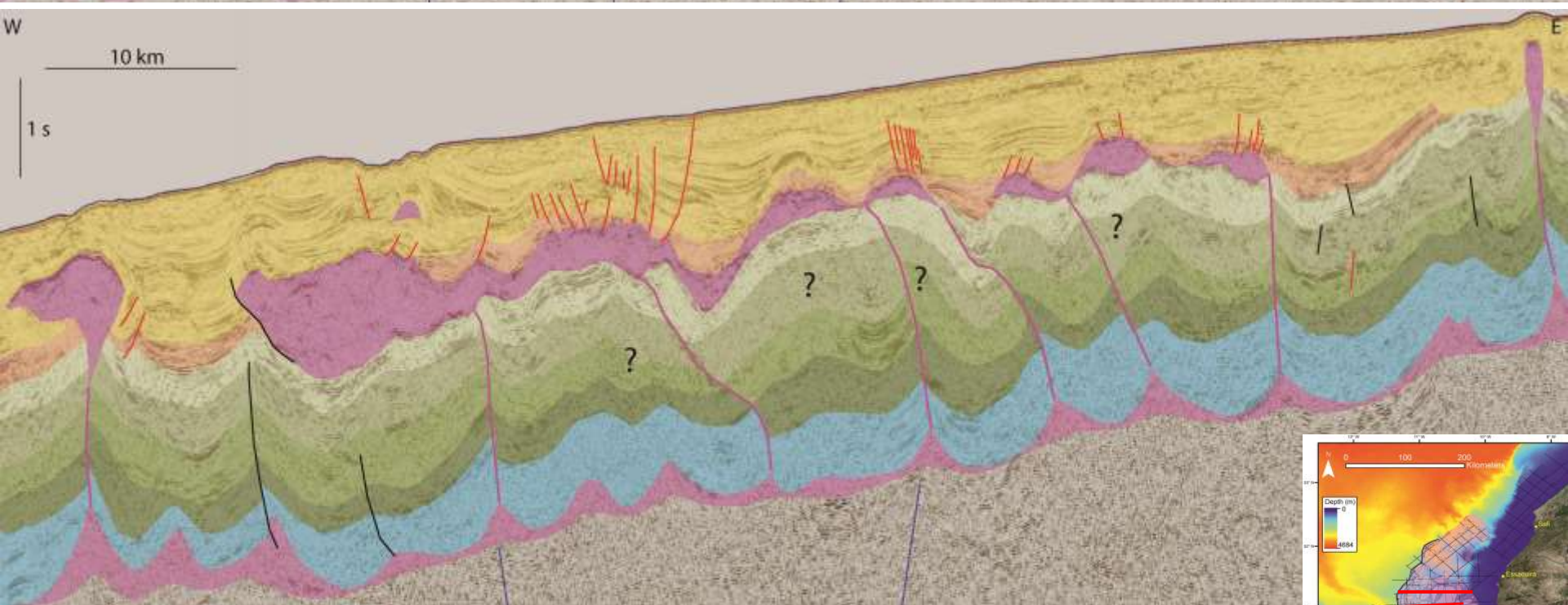
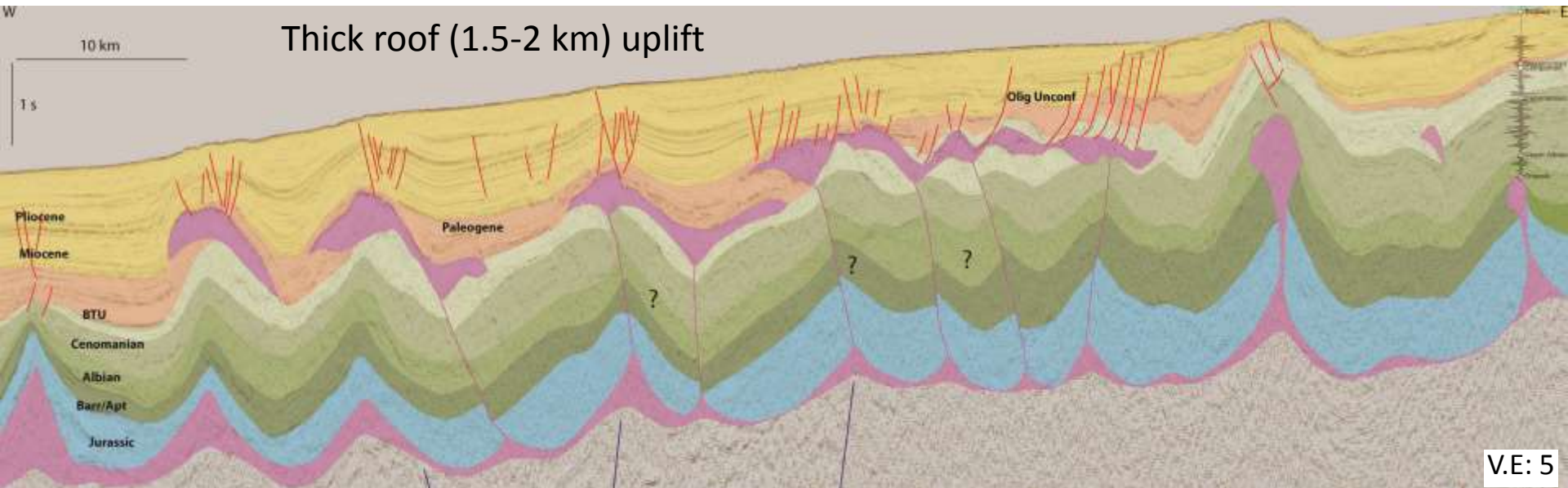


- Roughly E-W contractional structures salt-related (salt-cored folds and diapir squeezing)
- Not salt-related contractional structures
- Sea-floor expression
- Fault inversion
- **SHARK B-01 – DRY** : Other possibilities?

Potential channels/fans onlapping the anticline (Aptian/Albian & Late Cretaceous)

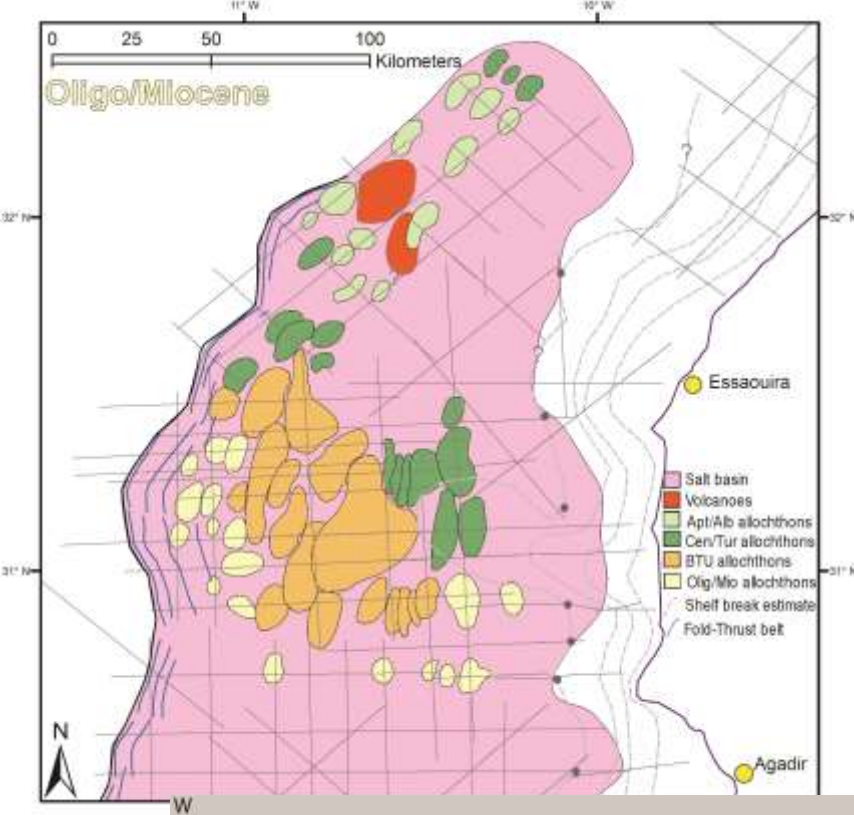


Thick roof (1.5-2 km) uplift

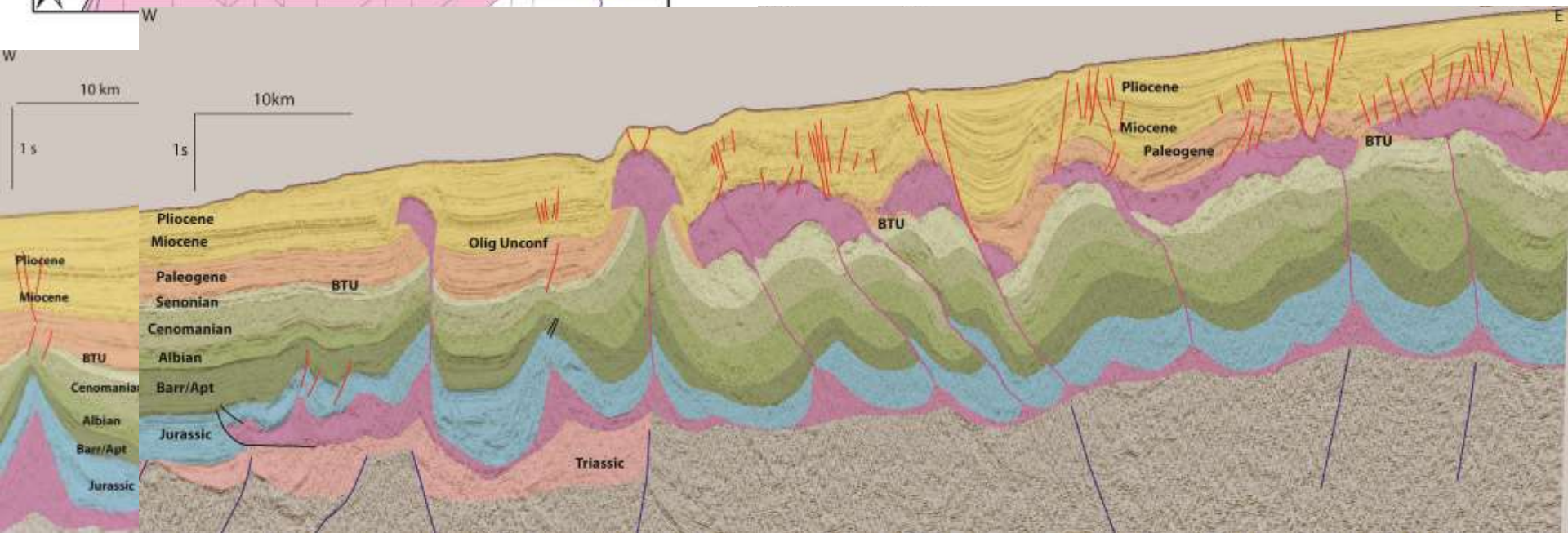


- Squeezed feeders on the entire slope and lack of extensional province
- **Cap-Sim 01**: important to estimate different timing of allochthonous salt

Sequential Development of Allochthonous Sheets

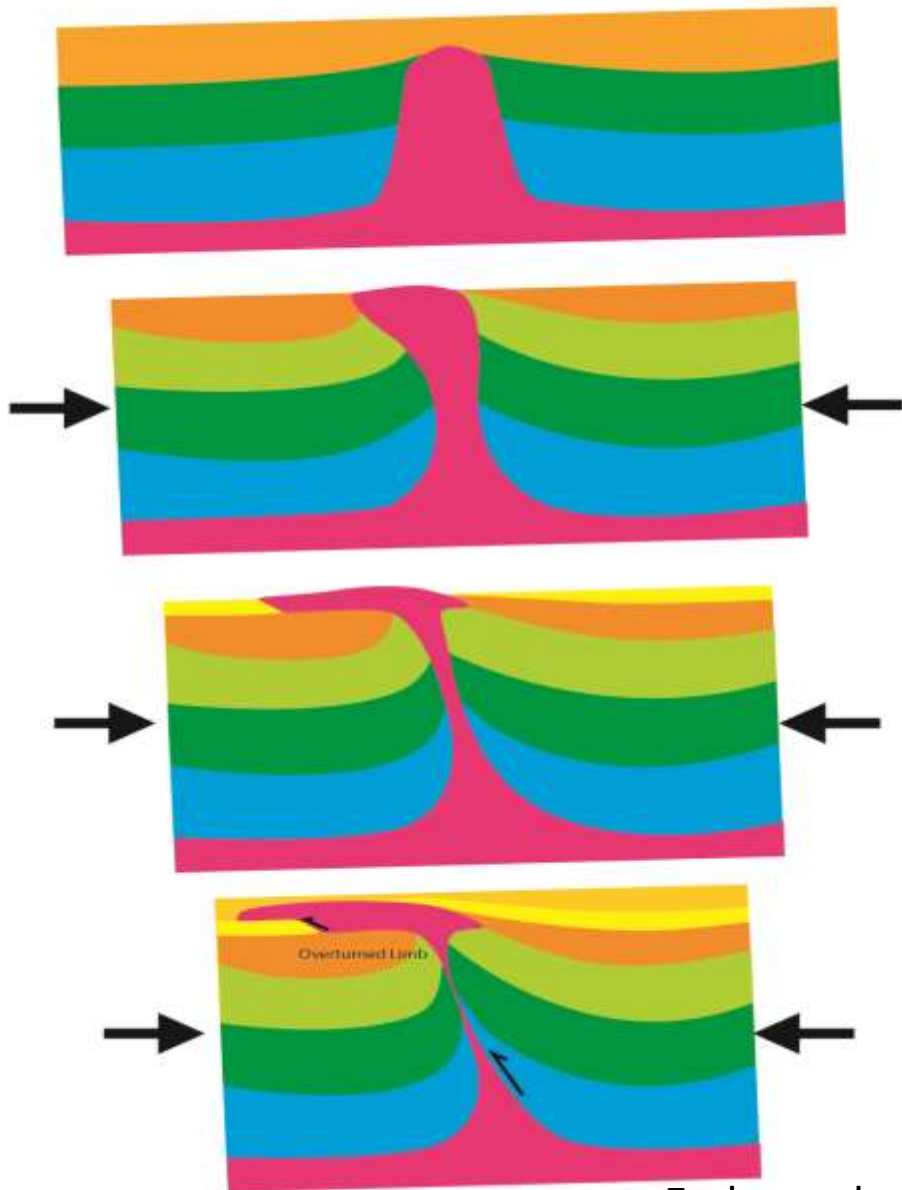


- Phase I (Albian): 1st allochthonous tongues in the North
 - Phase II (Cenomanian/Turonian): new tongues/sheets form to the South
 - Phase III (BTU) – higher volume of salt extrusion
 - Phase IV (Olig/Miocene) – allochthonous sheets continues to propagate **SOUTH** and **SEAWARD**
- Evolution controlled primarily by shortening/squeezing and secondarily by progradational loading
 - The earlier allochthons to the North:
 - Higher steepness of the margin
 - Stronger distal buttress

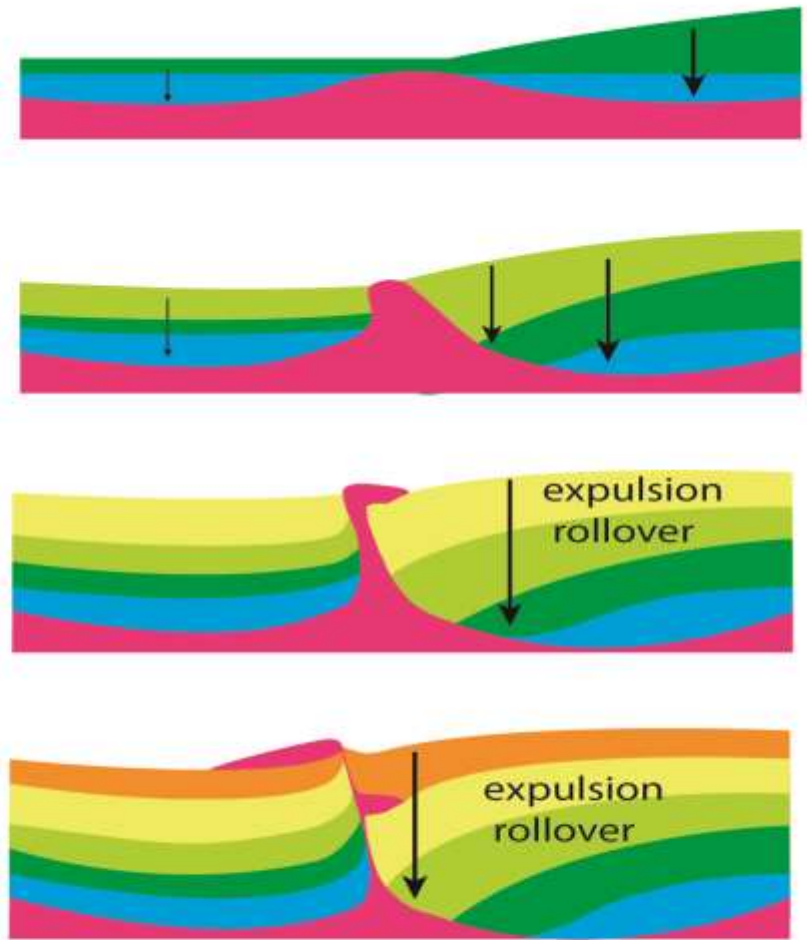


Generation of Allochthonous Salt

Rejuvenation of Buried diapir (shortening)



Differential Loading



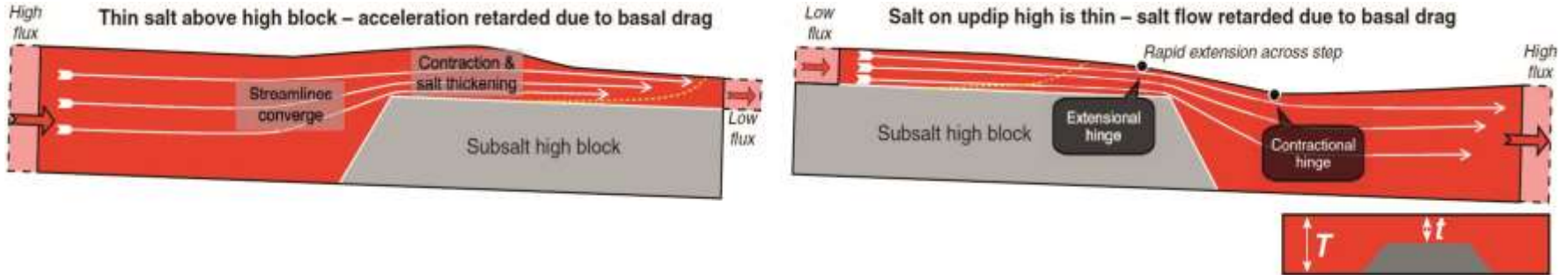
Late inflation (shortening)



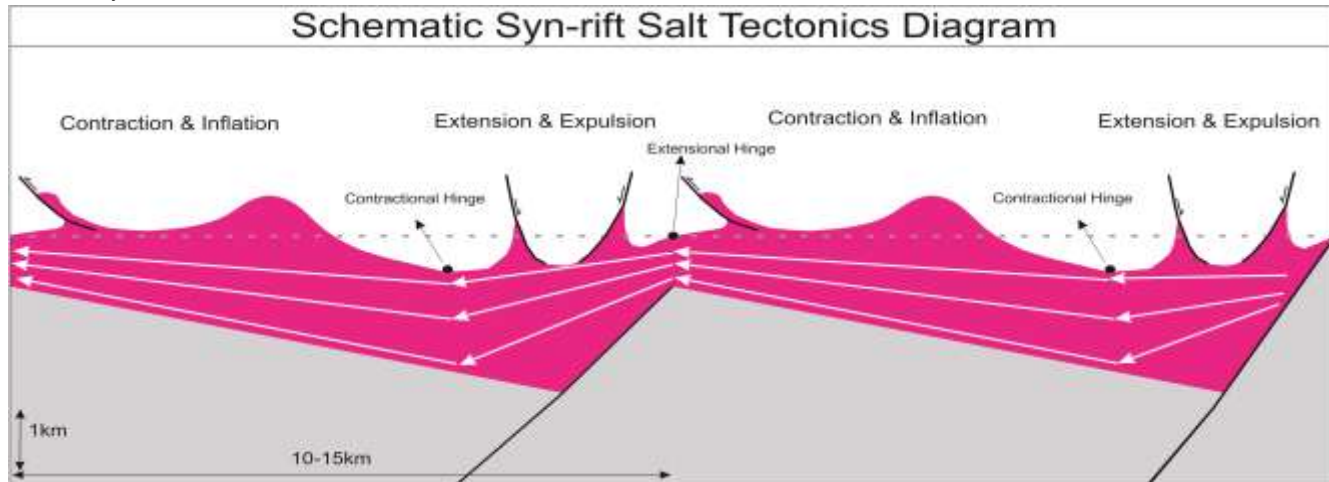
End-member scenarios

Supra-salt Structural Style related Syn-Rift Salt

- More structural complexity than classical models of updip extension & downdip contraction
- Alternation of extensional/expulsion & shortening-driven structures along dip/strike



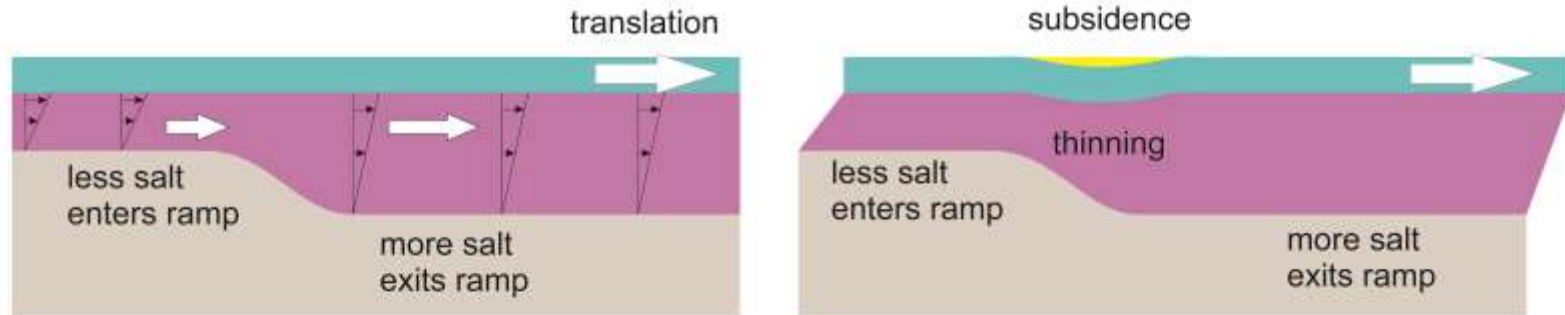
- This can be explained by changes in salt thickness and base of salt relief - generate velocity gradients and convergence/divergence of salt streamlines (Dooley et al. 2016)
- With syn-rift salt, these effects can be even more dramatic:



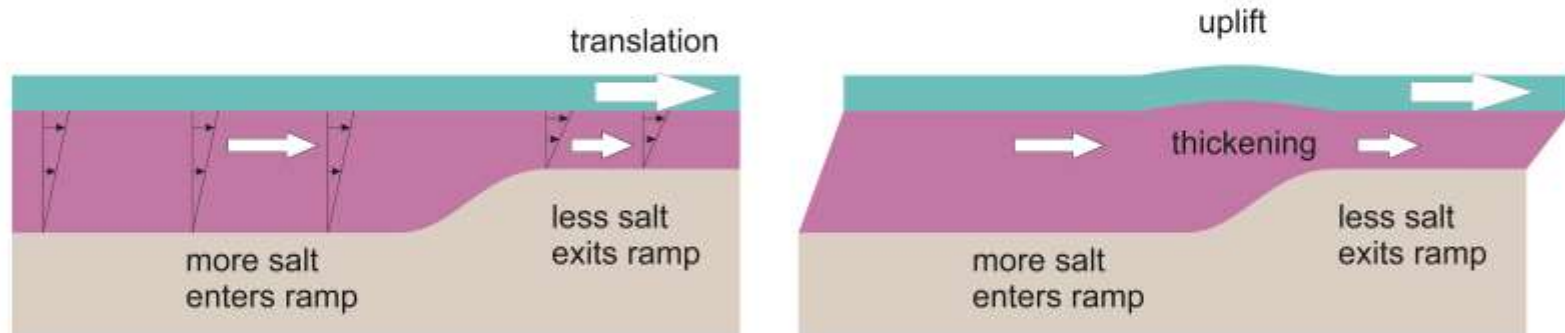
- As the system translates, structures will undergo multiphase history of reactivation
- Similar control of basement structures/steps in nucleation of salt walls/stocks in Nova Scotia (Deptuck & Kendall 2017).

Translation over complex BoS topography

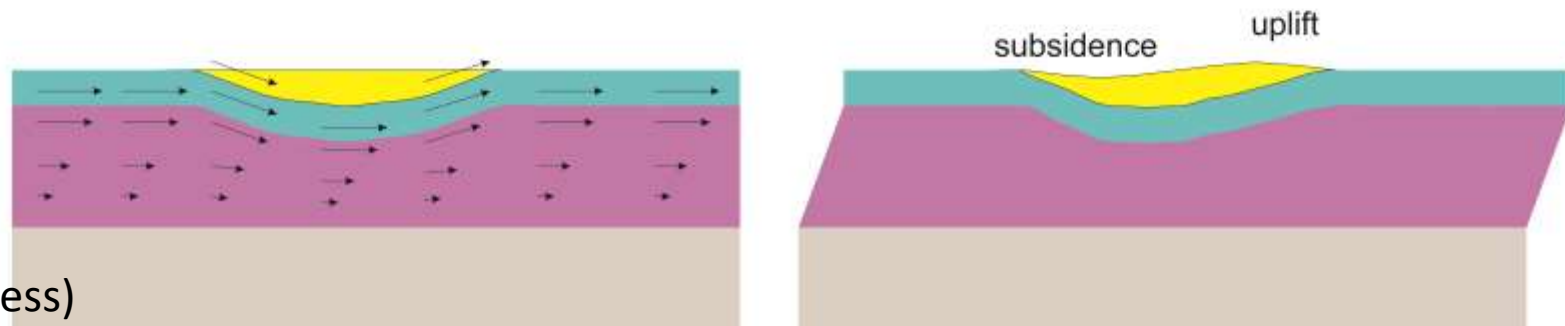
(a) Subsidence due to change in salt thickness with time (downramp)

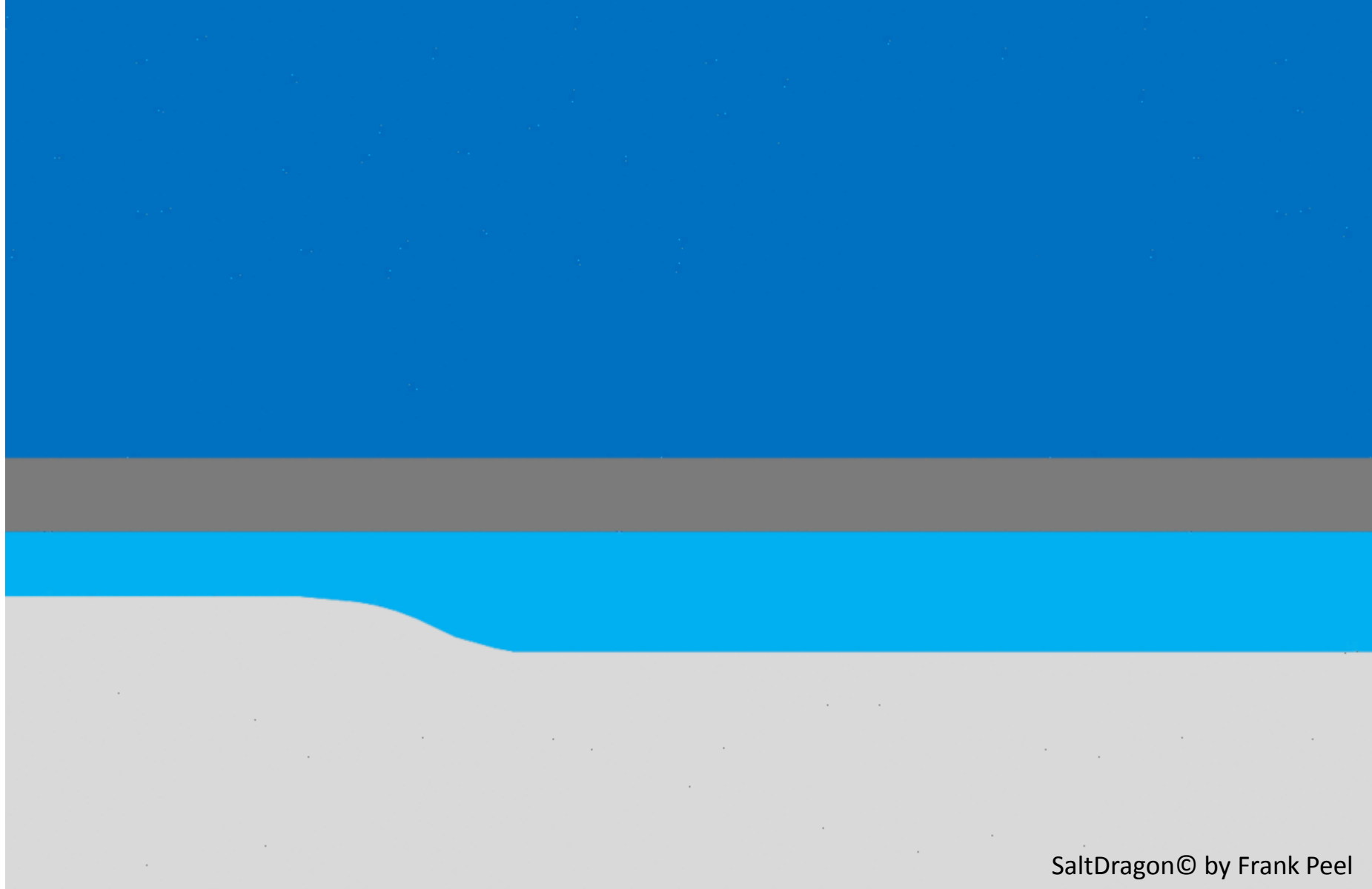


(b) uplift due to change in salt thickness with time (upramp)



(c) subsidence/uplift due to dip of the top salt surface





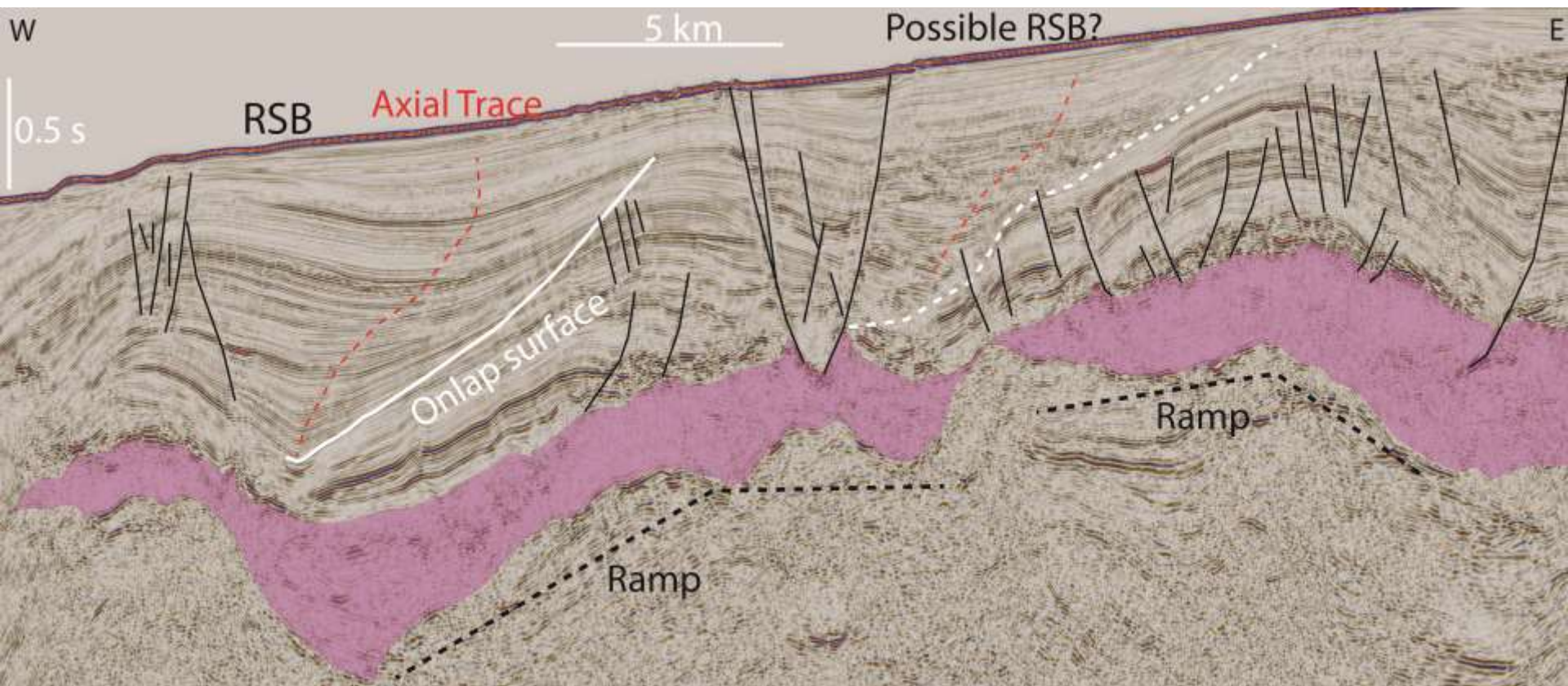
SaltDragon© by Frank Peel

Ramp Syncline Basins (RSBs):

- Form by downdip translation of cover and salt above base-salt ramps
- Provide a confident record of the translation history of salt basins
- Guide identification of pre-salt structures in areas of limited sub-salt resolution



RAMP-SYNCLINE BASINS (RSBs)

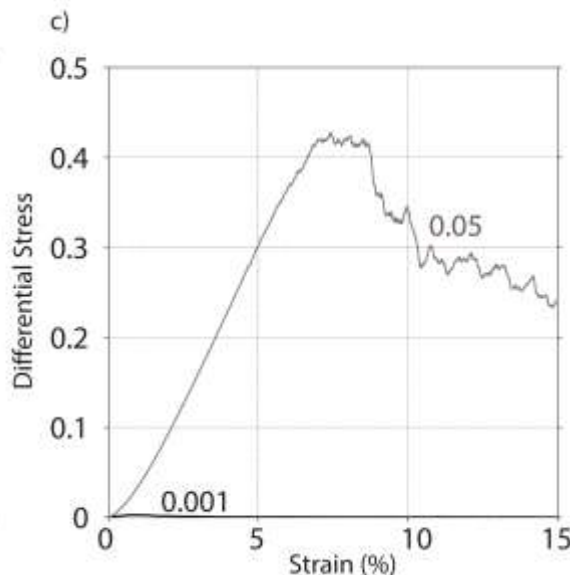
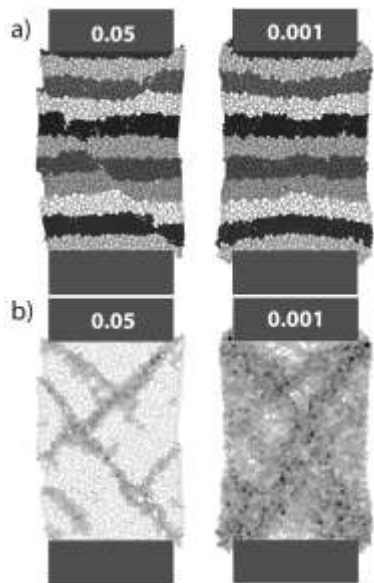


- RSBs above allochthonous salt sheets (~1 km thick) offshore Morocco
- Updip extension, mid-translation (RSB), downdip open-toe advance of sheet with later burial resulting in squeezing, salt inflation and roof uplift
- **10 km of translation** during Cenozoic ~ 0.2 mm/year
- Type-area in **Kwanza Basin, Angola** (Jackson and Hudec, 2005)
- These systems have probably been overlooked in the past decade
- Recently identified in the **Santos Basin, Brazil** (Pichel et al. *Basin Research in press*)
- Other occurrences in **GoM** (Mike Hudec, pers. comm.) and Newfoundland Basin (Canada)

Discrete-Element Modelling (DEM)

- Rocks are treated as an assemblage of elements that interact in pairs as if connected by breakable springs through a repulsive-attractive force (Finch *et al.* 2004; Pichel *et al.*, 2017)
- **Salt** – 0.001 (visco-plastic)
 - Density: 2.16 g/cm³
 - Viscosity: 10⁹ Pa.s
- **Sediments** – 0.05 (brittle)
 - Density: 2.3 g/cm³

$$F_S = \begin{cases} K(r - R), & r < r_0, \text{ intact bond} \\ K(r - R), & r < R, \text{ broken bond} \\ 0, & r \geq R, \text{ broken bond} \end{cases}$$



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The influence of shortening and sedimentation on rejuvenation of salt diapirs: A new Discrete-Element Modelling approach

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Outline

Highlights

Abstract

Keywords

1. Introduction

2. Methodology

3. Model results

4. Discussion

5. Conclusions

Acknowledgements

References

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Table 1

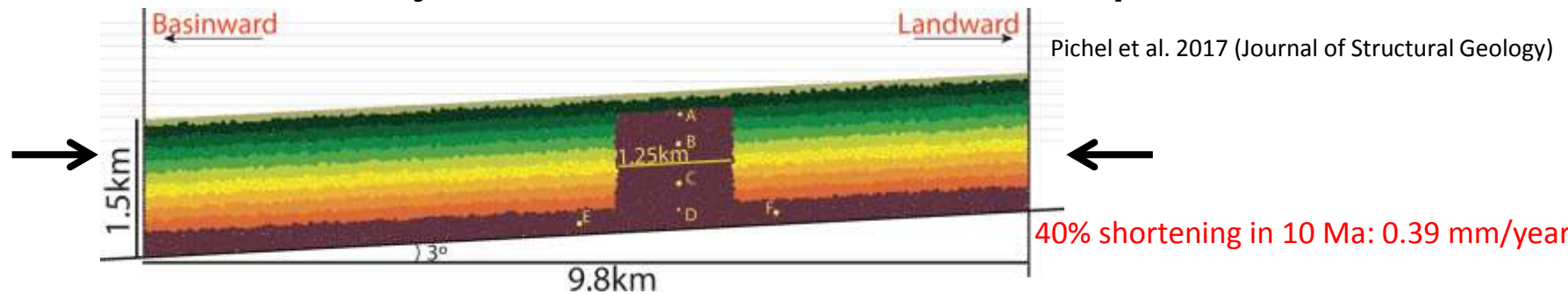
Abstract

This study employs a novel Discrete-Element Modelling approach to investigate the interplay of sedimentation with rejuvenation of diapirs by shortening. The inherent complexity of salt tectonics, the complications encountered when imaging structures beneath salt, and the lack of outcrop analogues, coupled with its importance to petroleum systems, make salt tectonics one of the most interesting and debated topics in basin studies. Model results successfully reproduce the geometric and dynamic behaviour of active diapirism and show the effects of sedimentation thickness, rate and timing on the generation of distinct diapir geometries, including i) salt tongues and ii) squeezed upright diapirs. Models with late sedimentation or a lower sedimentation rate relative to salt mobility show development of asymmetric diapirs with allochthonous salt tongues, whereas models with earlier sedimentation or a faster sedimentation rate generate upright squeezed diapirs. Early sedimentation at a moderate rate results in a symmetrical hour-glass shaped structure, resembling a tear-drop diapir. Results are fully reproducible and comparable with many natural examples, and include overburden deformation which is difficult to simulate using other numerical techniques. Extending this approach to different problems and basinal contexts could improve our understanding of deformation mechanisms and sediment distribution around salt structures.

Keywords

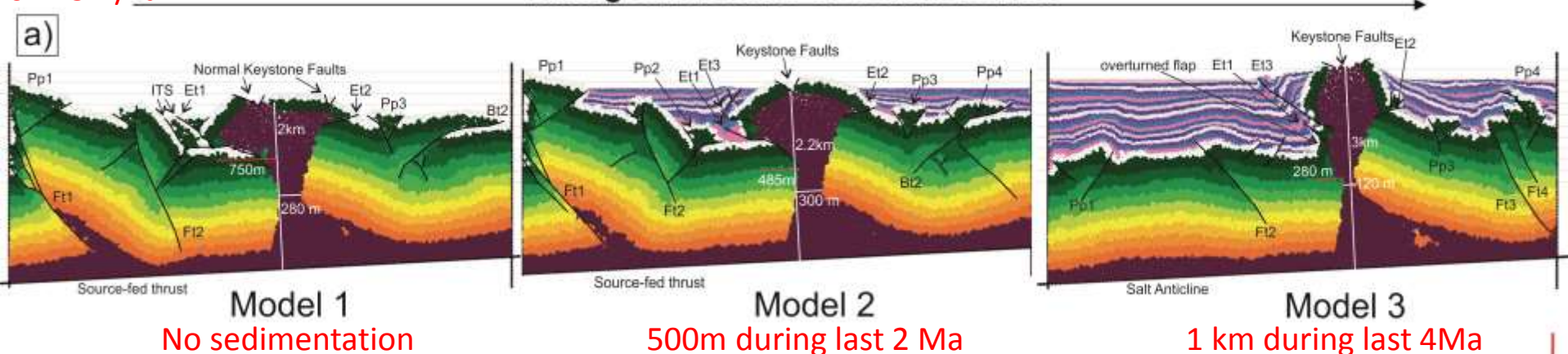
Salt tectonics; Discrete-Element Modelling; Salt tongue; Tear-drop; Diapir

DEM of Rejuvenation of Buried Diapirs

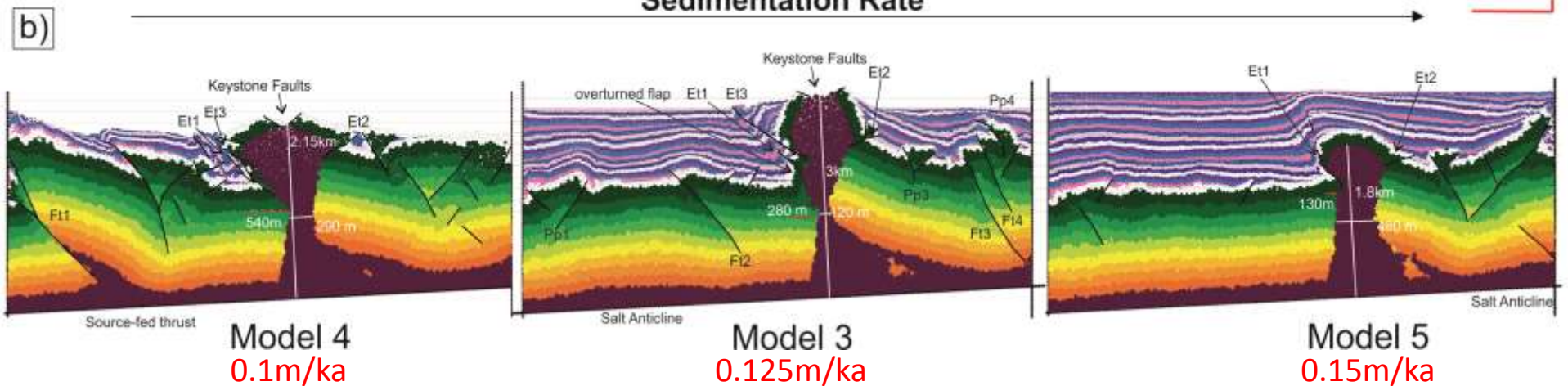


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Timing and Volume of Sedimentation



Sedimentation Rate



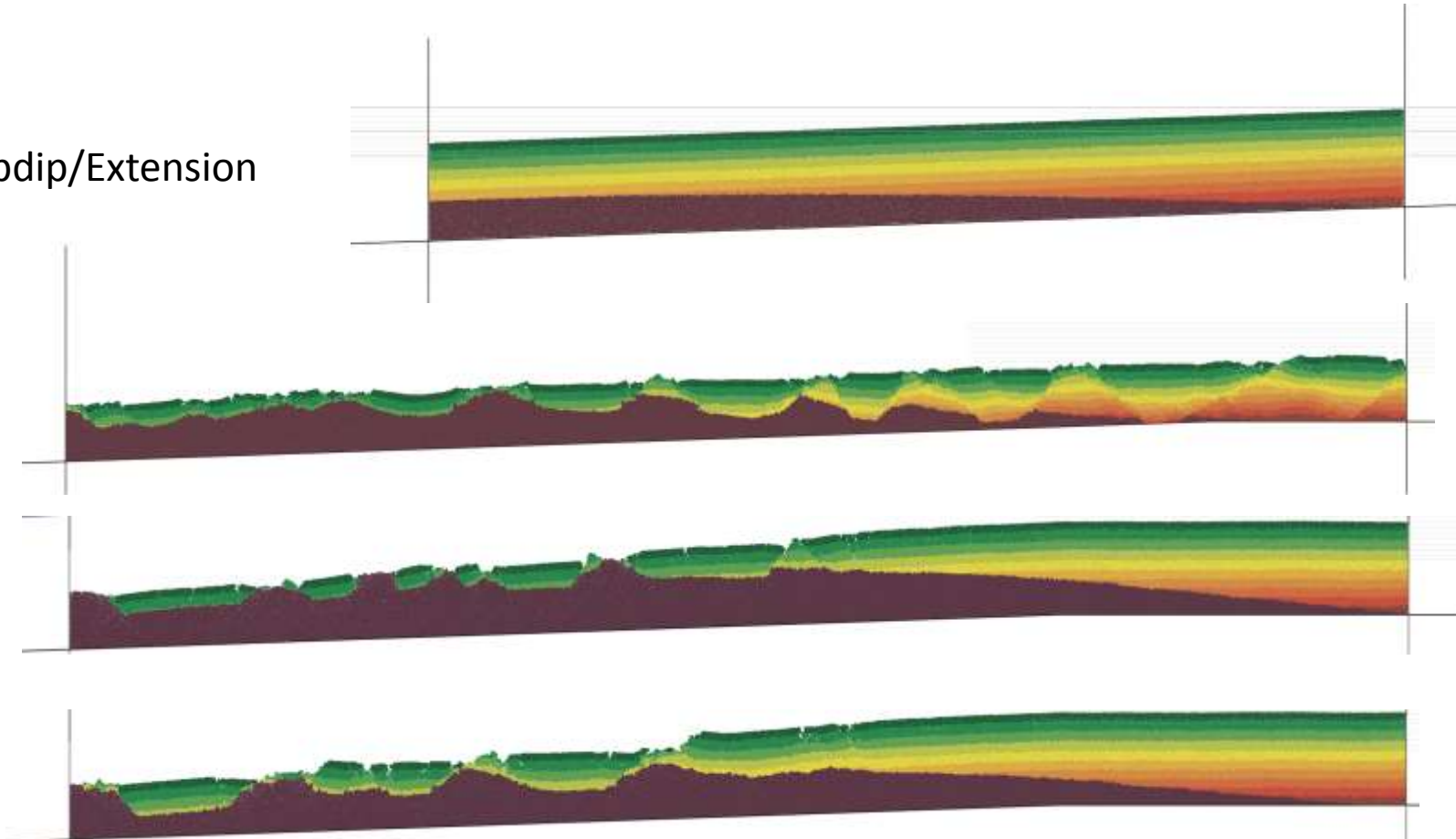
CONCLUSIONS

- Strong segmentation and variation of structural styles along the margin:
 - Syn-rift salt architecture
 - Variable topography of base-salt and salt thickness
 - Presence of volcanic ridges affecting translation rates and downdip contraction
 - Variations of sedimentary input along the margins (DEM)
- Multiple evidence attest the impact of crustal shortening on salt deformation offshore Morocco
- Generation allochthonous salt features spans from Albian to Olig/Miocene
- Sequential evolution of allochthonous salt towards south and basinward is controlled by the timing of contraction (thin or thick-skinned) and secondarily by sedimentary loading
- Despite the limitation of sub-salt seismic resolution and lack of wells penetrating the interval, we observe complex diapir evolution along the margin
- This is easily explained by the syn-rift nature of salt and consequent variations of salt thickness and base salt topography

Next steps:

- Pichel L.M., Huuse, M., Redfern, J. (*in prep*) **Different styles and Sequential Evolution of Allochthonous Salt Sheets offshore Morocco**
- 1 month placement in ONHYM to work on 3D data-set
- New Modelling Scenarios:

Gliding and Updip/Extension



- Testing influence of thickness ratio on diapirism/faulting styles related to **gliding**
- Testing influence of **BoS topography** and **syn-rift** salt architecture