Deepwater Niger Delta fold-and-thrust belt modeled as a critical-taper wedge: *The influence of a weak detachment on styles of fault-related folds*

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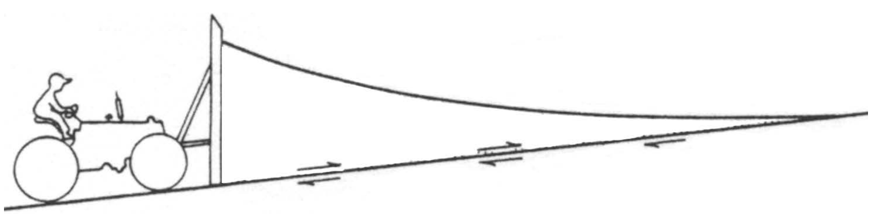
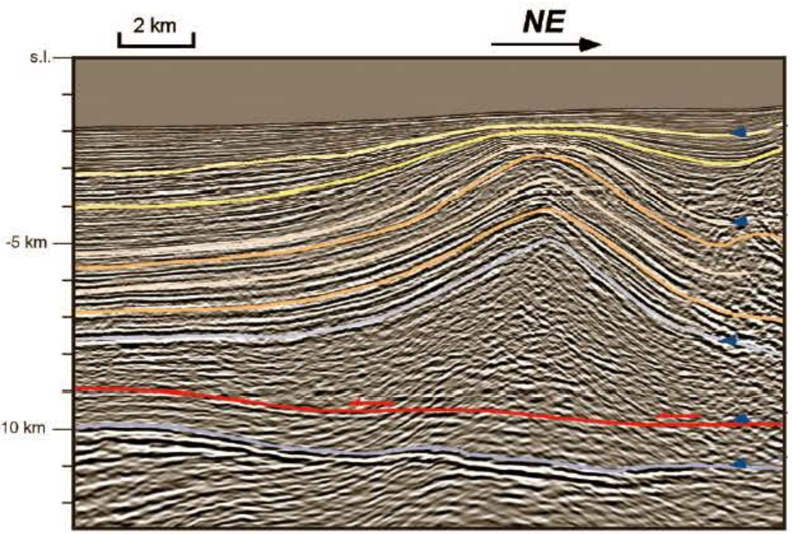
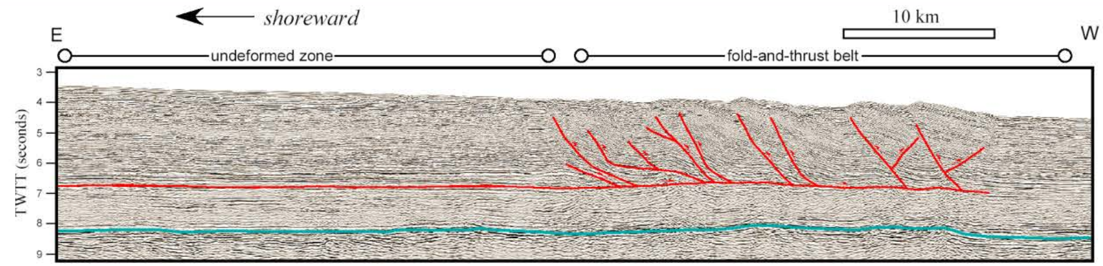


Niger delta “outer” fold-and-thrust belt

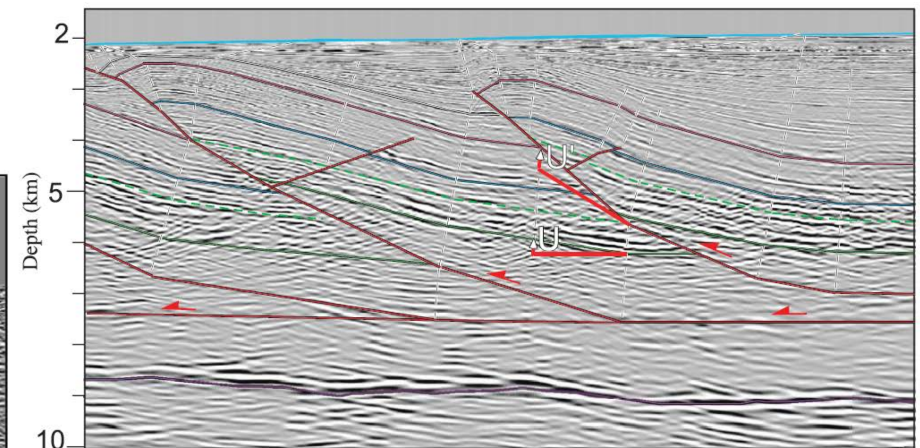


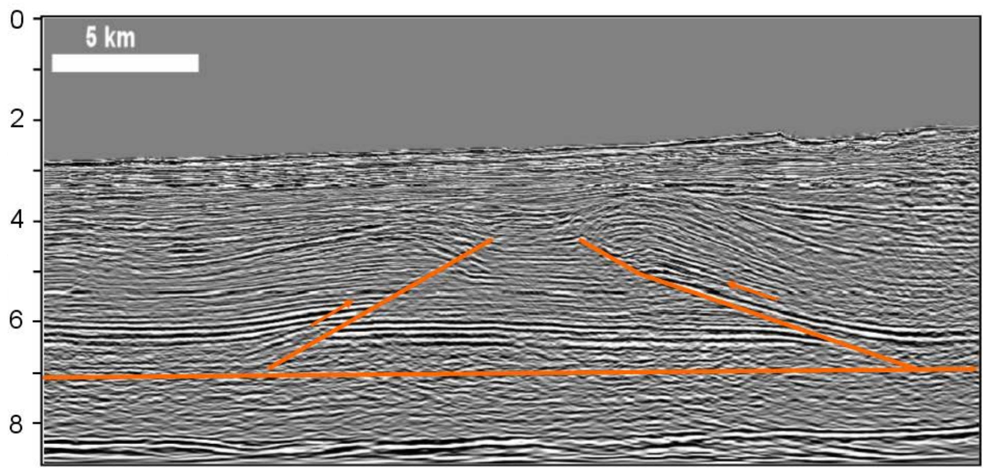
“Ductile” thickening

very low taper



Odd fault-related folds



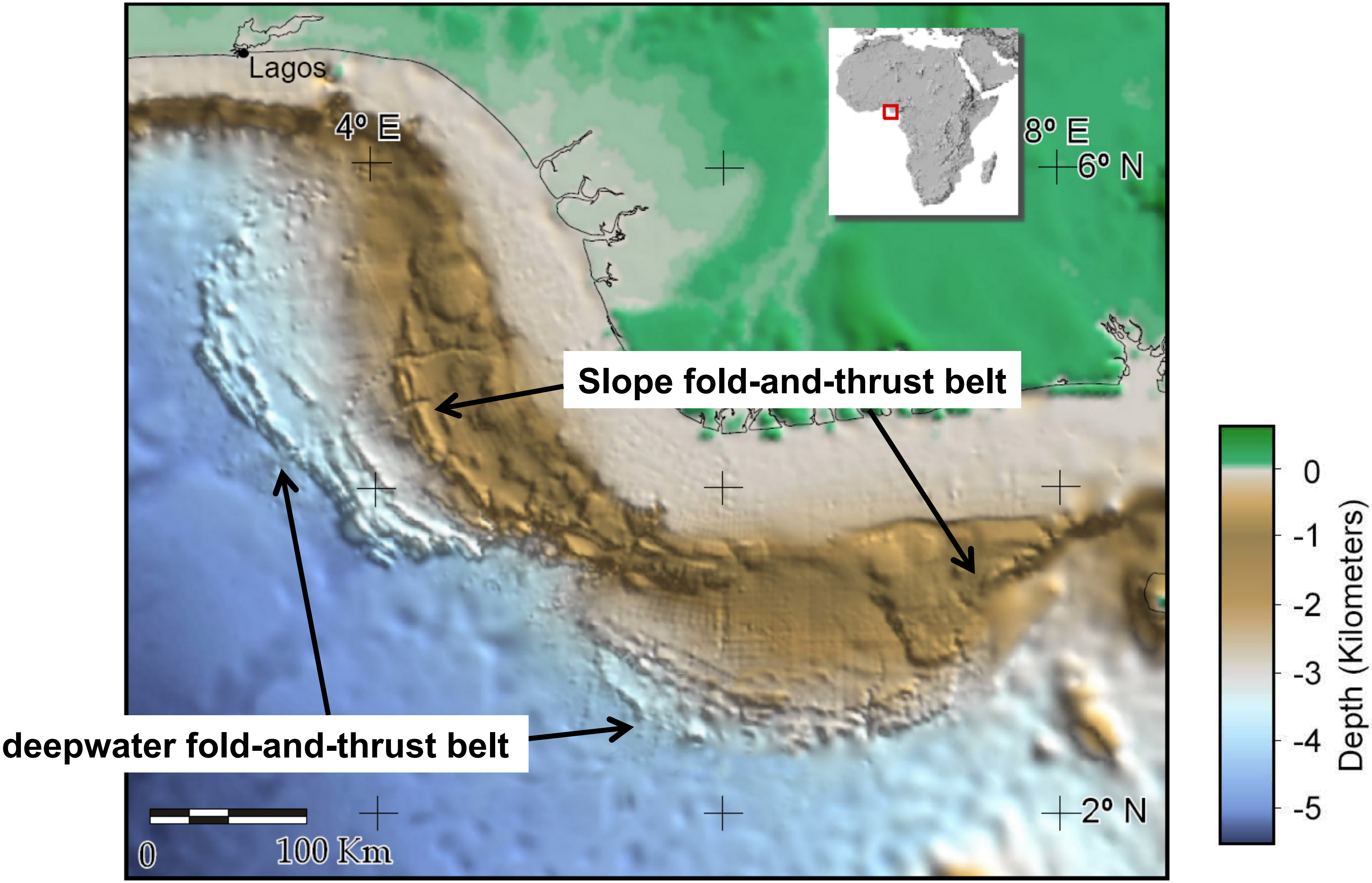


Forethrusts and backthrusts in close proximity

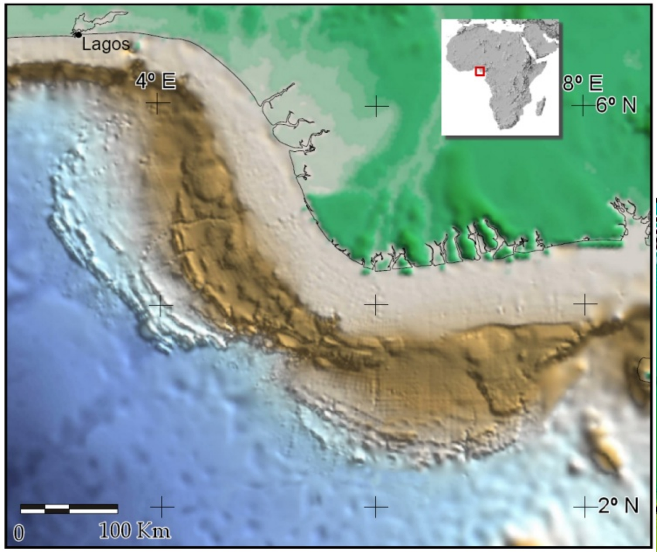
Outline

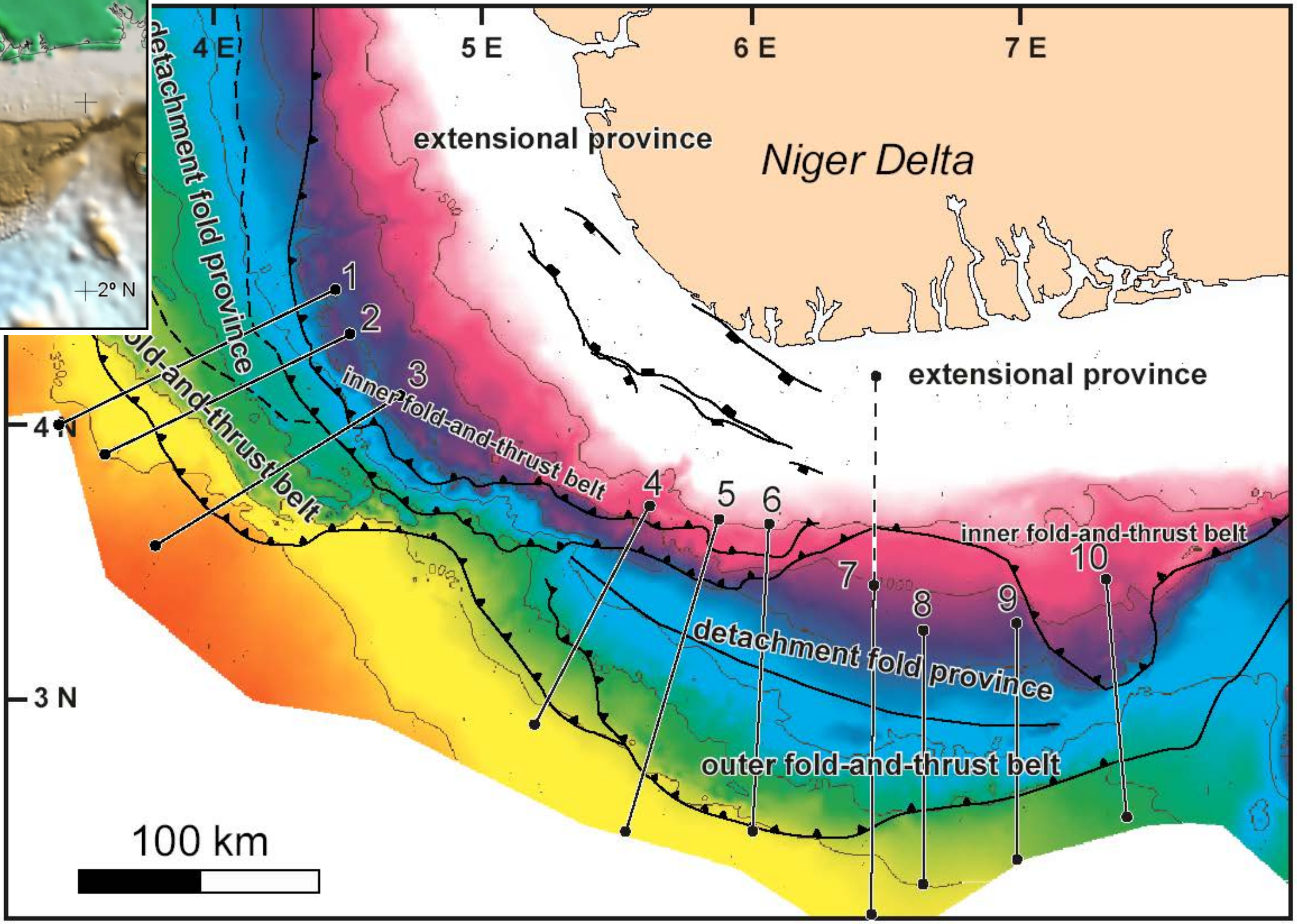
- The nature of the toe of the Niger Delta
- Basics of critical-taper wedge theory
- The Niger Delta outer fold-and-thrust belt is at critical taper
- Model parameters and results *(high basal fluid pressure)*
- Applicability in 3D & subsequent work
- Implications of high basal fluid pressure for contractional fault-related folds

Niger Delta Bathymetry

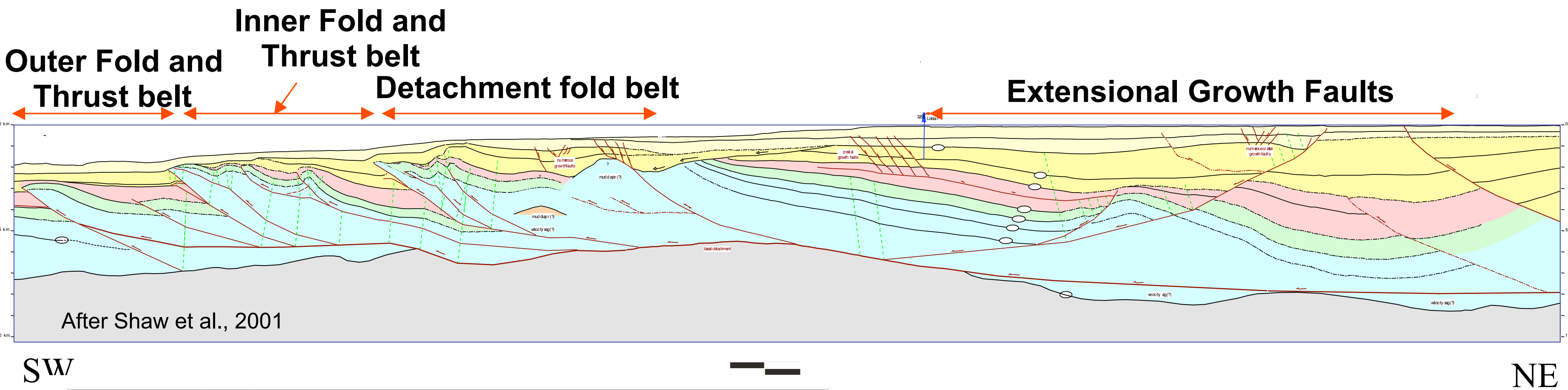


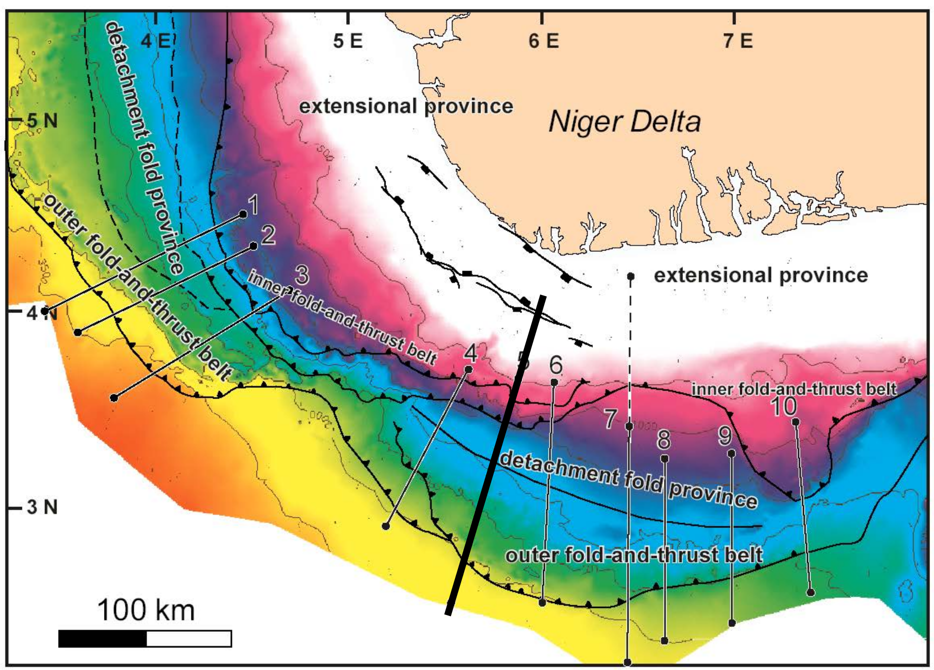
Fold-and-thrust belts of the Niger Delta

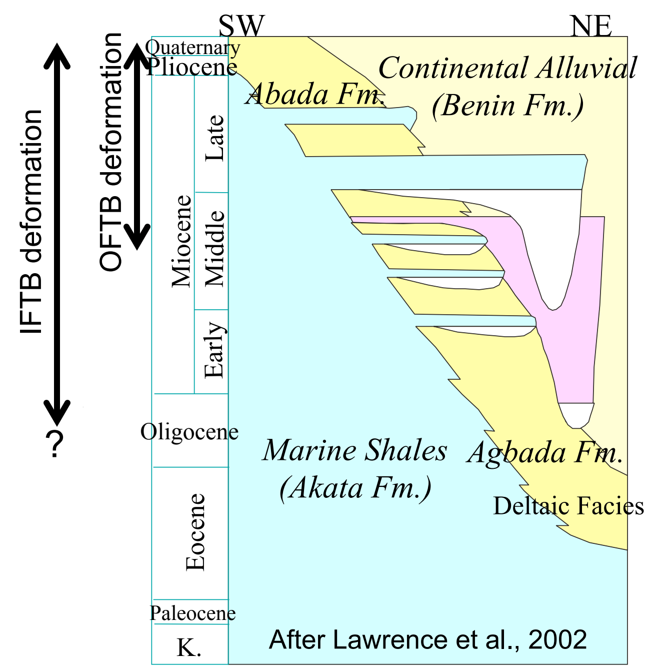




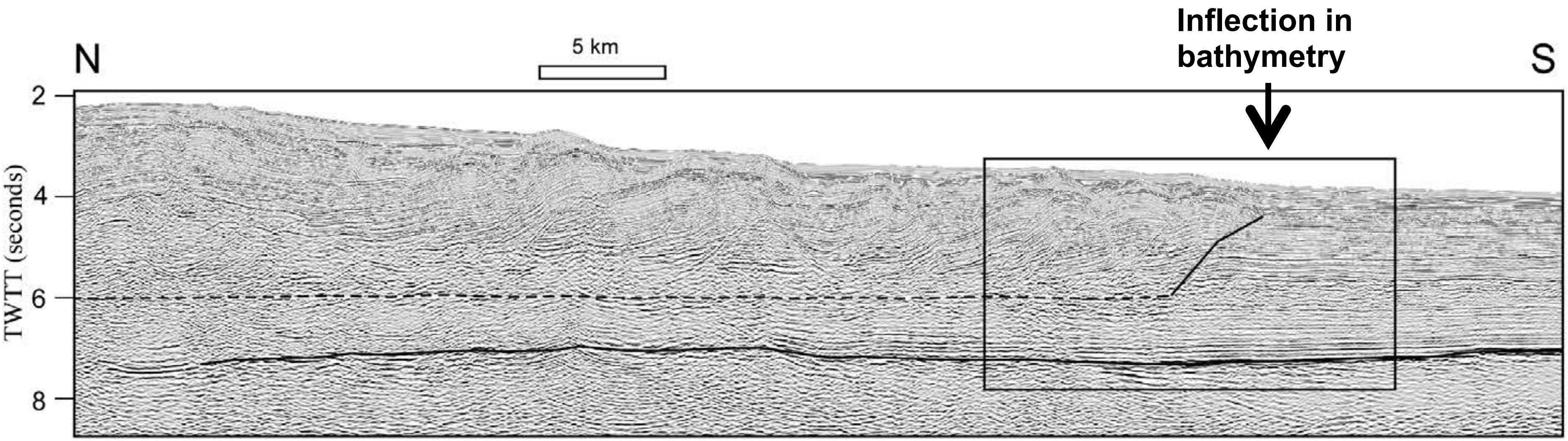
Regional Geologic Setting



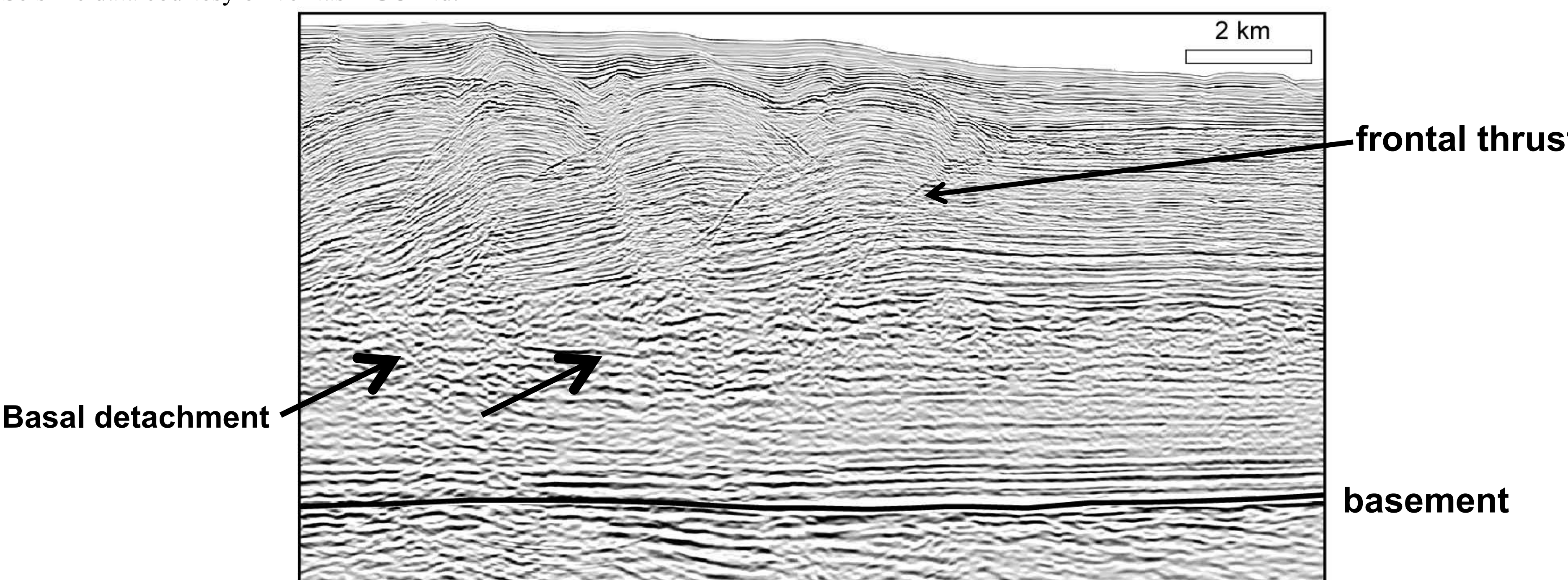




Niger Delta toe

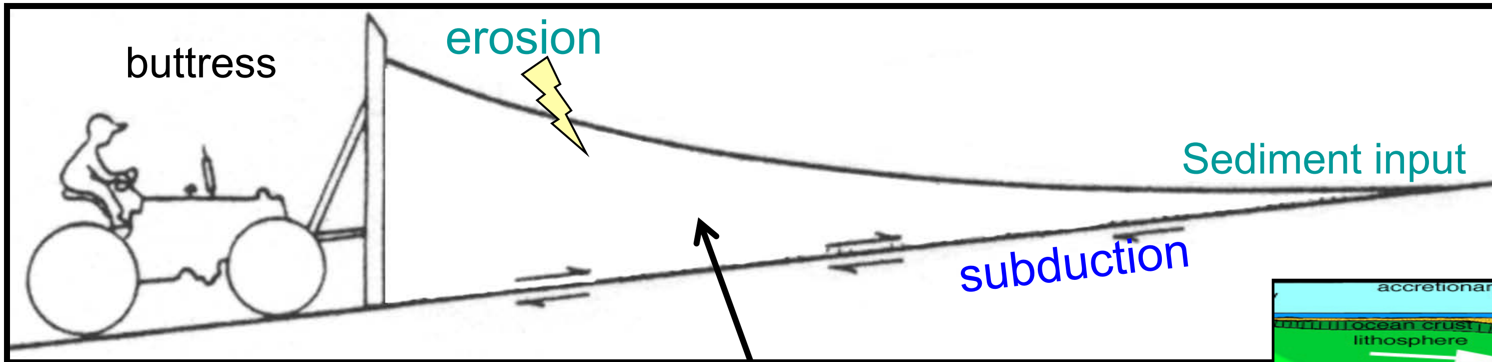


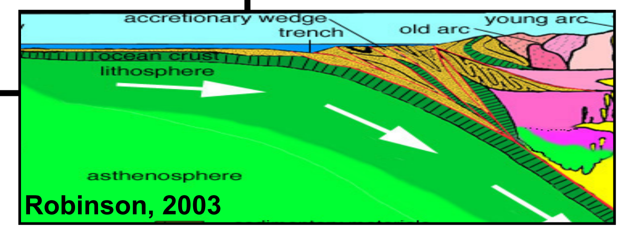
Seismic data courtesy of Veritas DGC Ltd.



Critical taper wedge mechanics

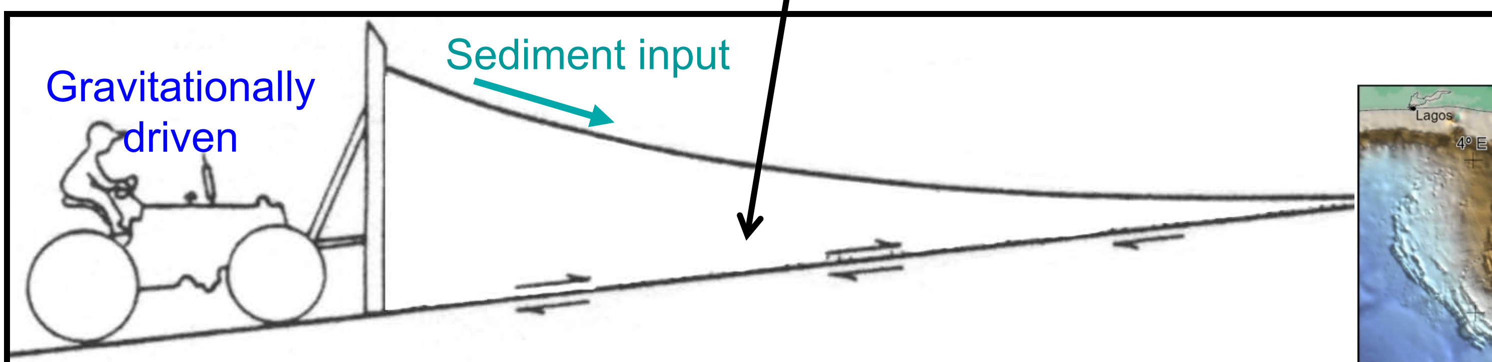
Convergent margins

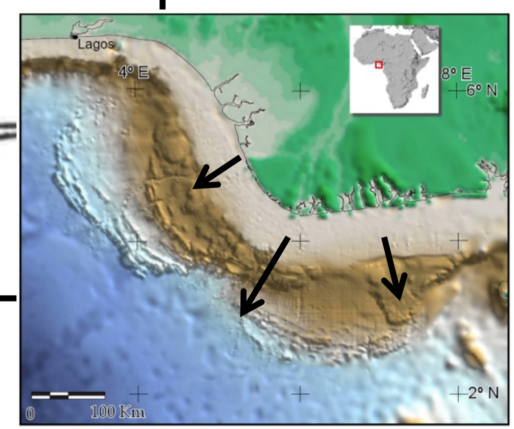




Internally deforming wedge
Whose shape is dictated by its internal strength and basal detachment strength

Passive margins

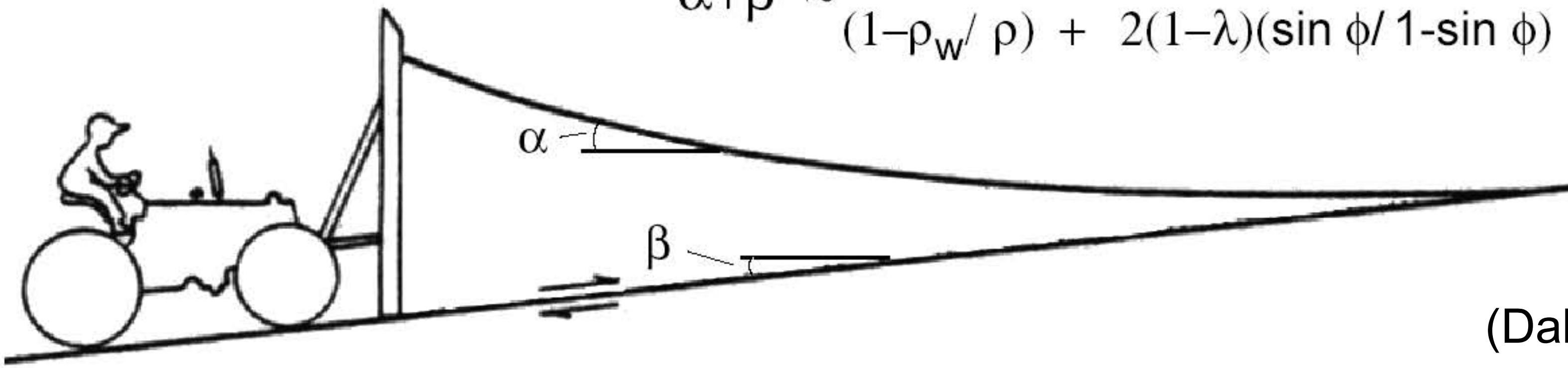




Chapple (1978) – plastic wedge
Davis, et al (1983) – Coulomb wedge
Dahlen, et al. (1984) – Cohesive Coulomb wedge theory

Critical taper wedge equation

$$\alpha+\beta \approx \frac{(1-\rho_w/\rho)\beta + (1-\lambda_b)\mu_b - S_b/\rho g H}{(1-\rho_w/\rho) + 2(1-\lambda)(\sin\phi/1-\sin\phi) + C/\rho g H}$$



(Dahlen, 1990)

λ and $\boldsymbol{\lambda_b}$ - Hubbert-Rubey (1959) pore fluid ratio

ρ – bulk density of the wedge

μ and $\boldsymbol{\mu_b}$– coefficients of friction

$\mathbf{S_0}$ – Cohesive strength

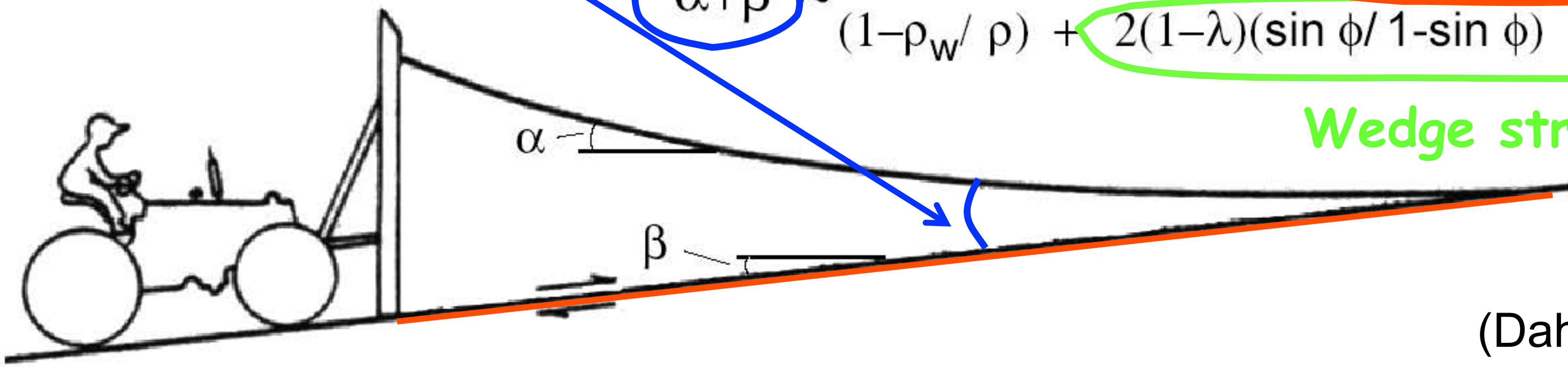
Critical taper wedge equation

Basal strength

Wedge taper

$$\alpha+\beta \approx \frac{(1-\rho_w/\rho)\beta + (1-\lambda_b)\mu_b - S_b/\rho g H}{(1-\rho_w/\rho) + 2(1-\lambda)(\sin\phi/1-\sin\phi) + C/\rho g H}$$

Wedge strength



(Dahlen, 1990)

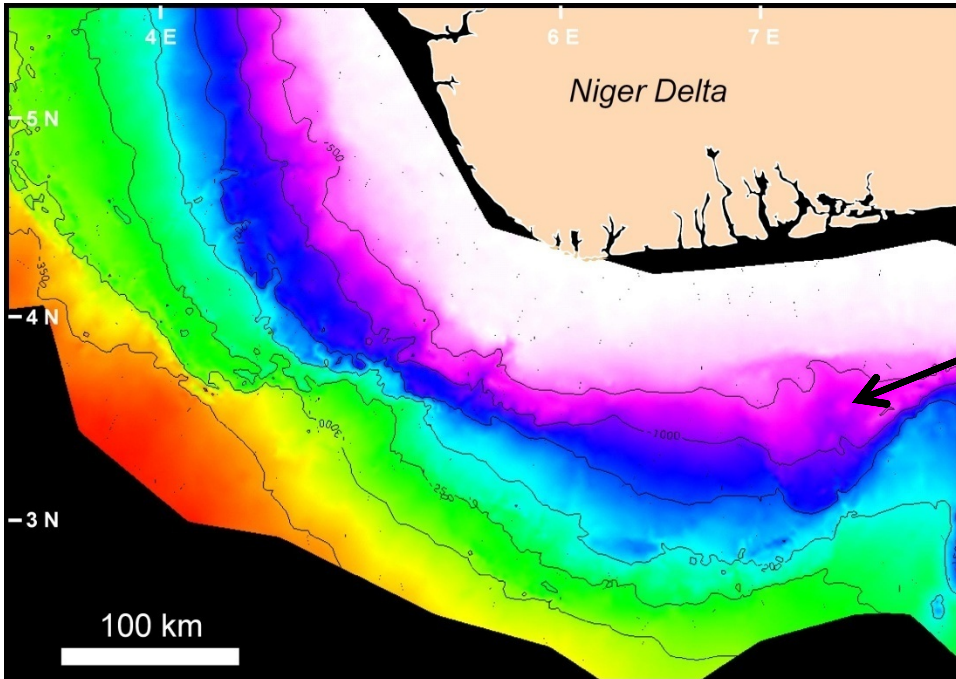
λ and **λ_b** - Hubbert-Rubey (1959) pore fluid ratio

ρ – bulk density of the wedge

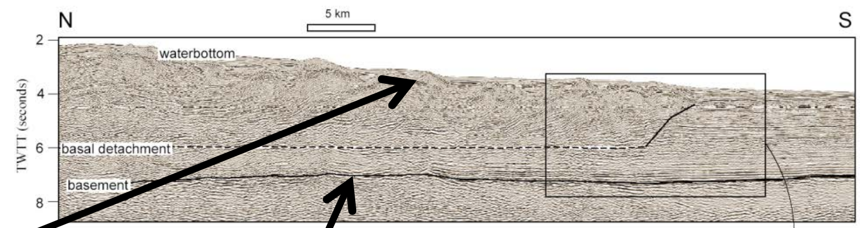
μ and **μ_b**– coefficients of friction

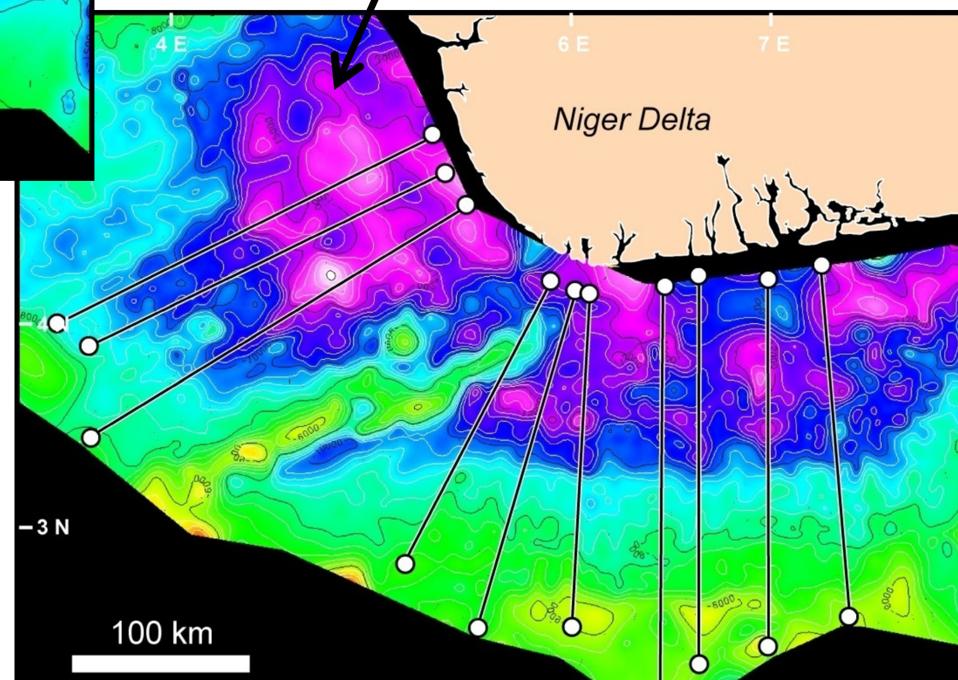
S_0 – Cohesive strength

Niger Delta Bathymetry/Basement

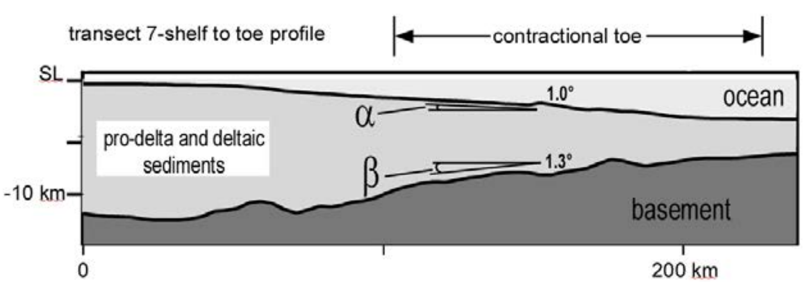


Bathymetry (upper free surface)

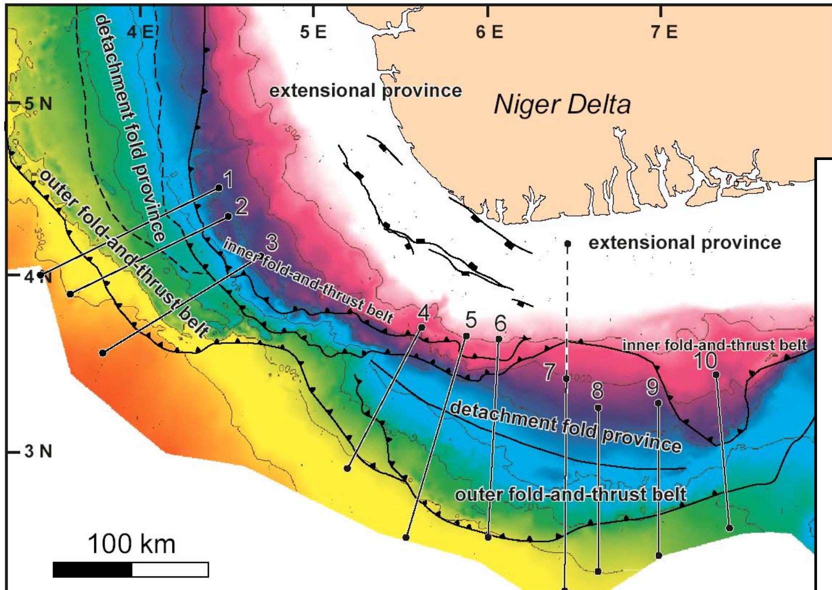


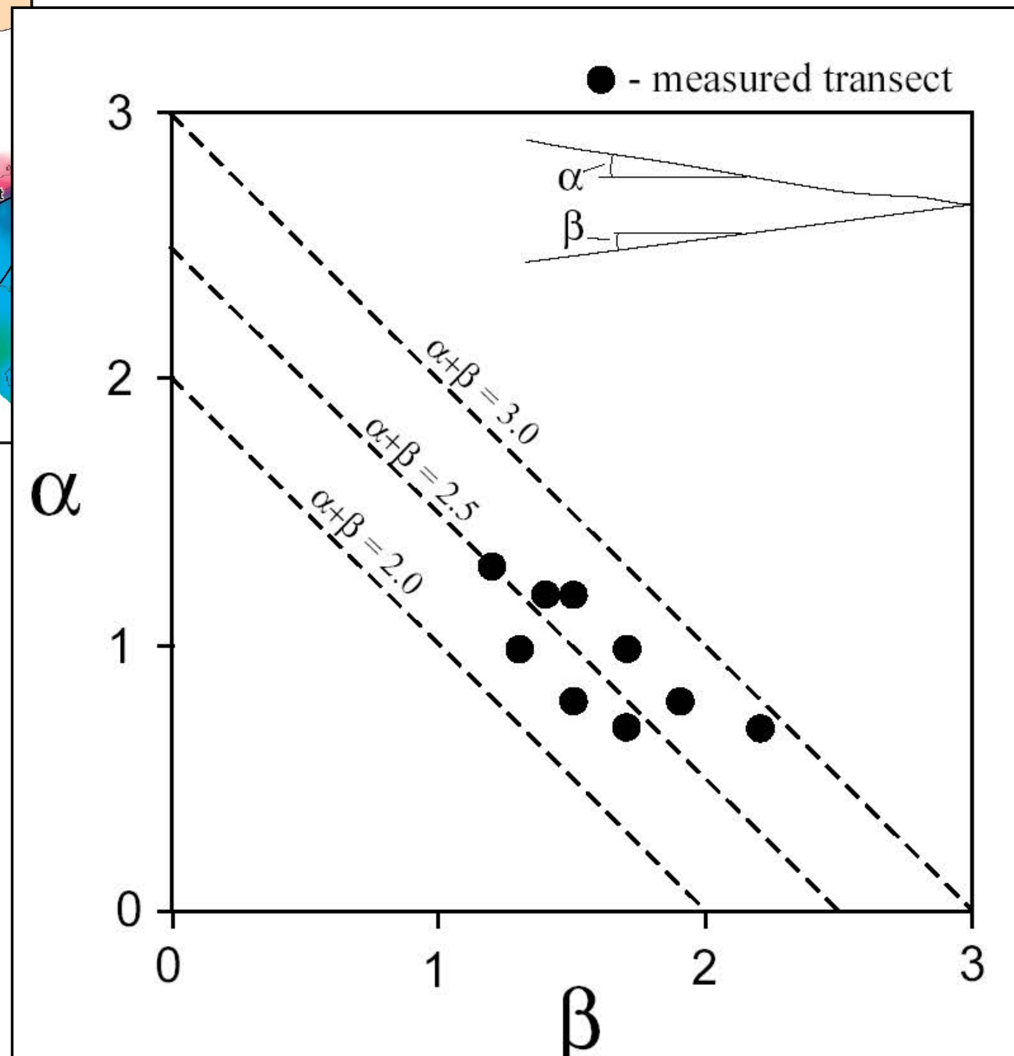


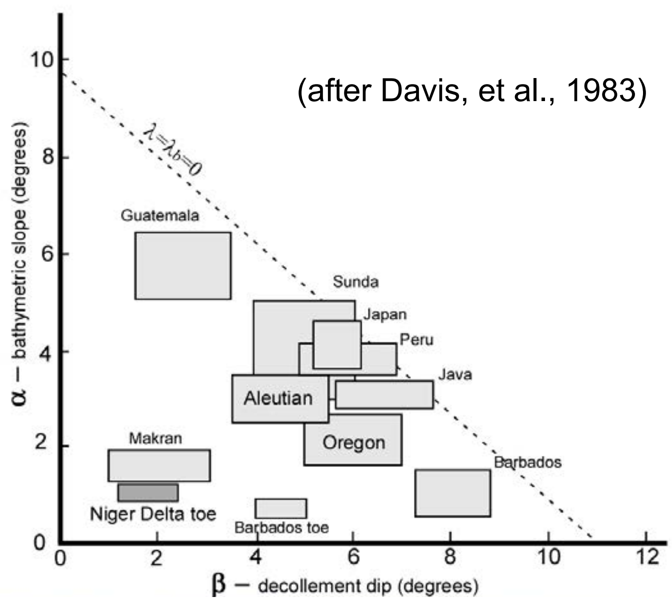
Basement (as shape proxy for basal detachment)



Measured wedge taper

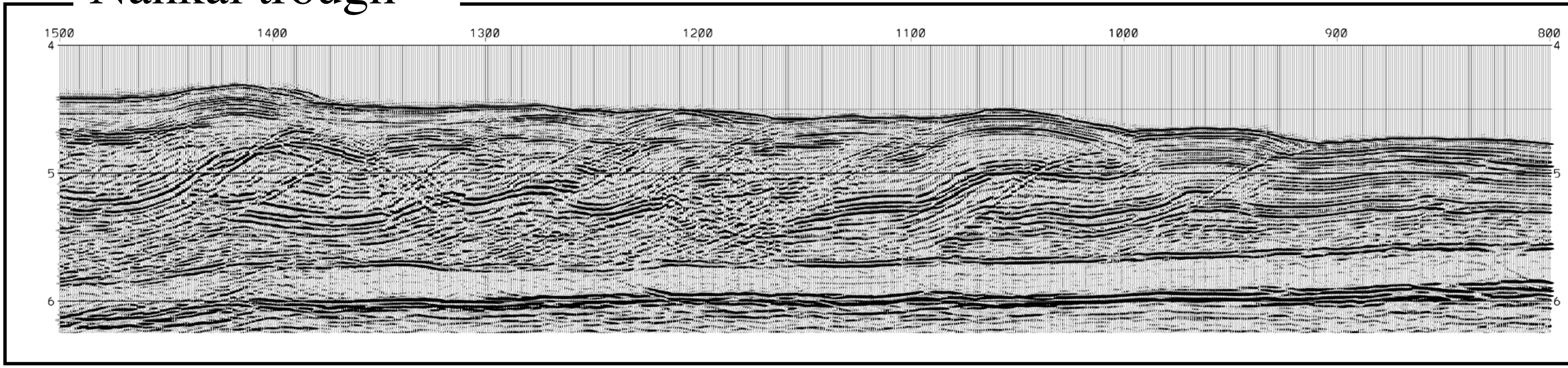




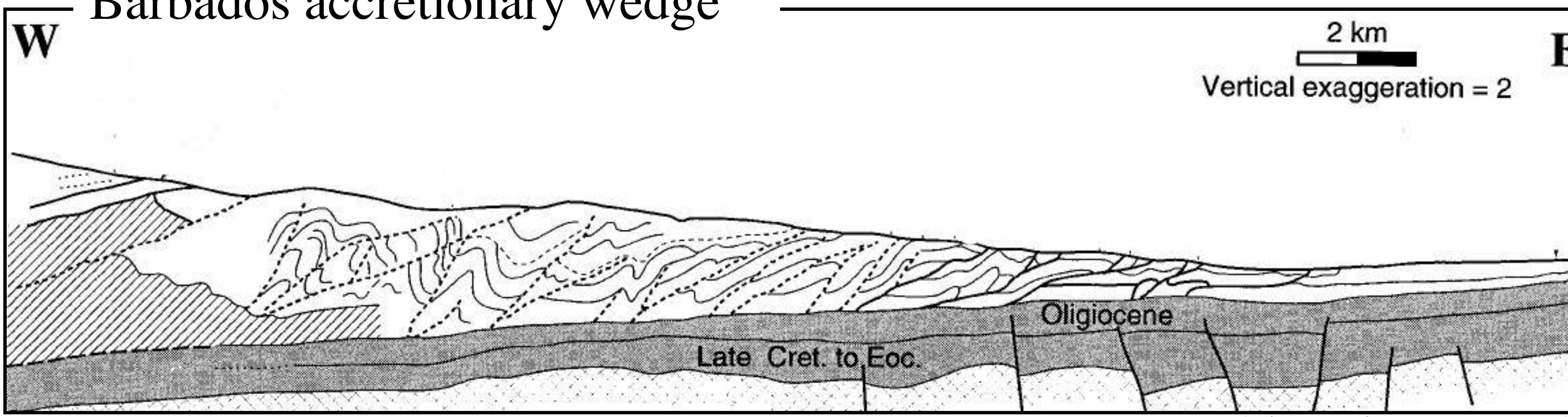


Low-taper wedges

Nankai trough



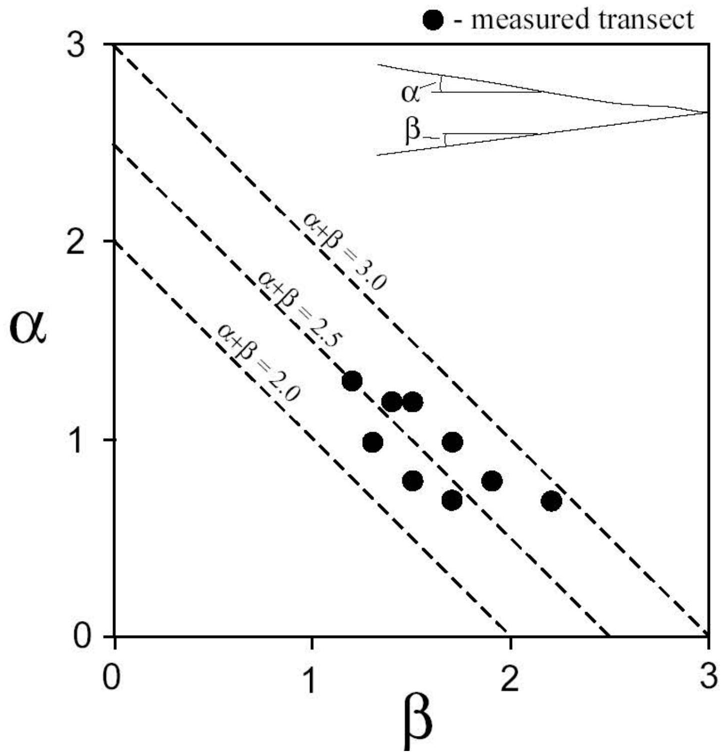
Barbados accretionary wedge



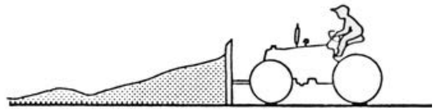
(Fitts and Brown, 1999)

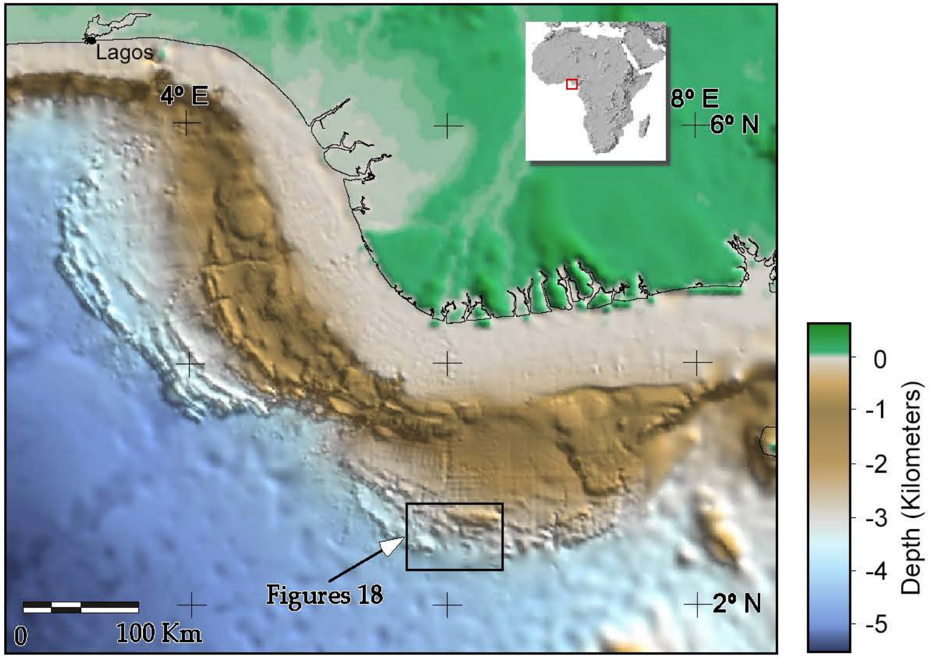
Is the toe of the Niger Delta at Critical Taper?

1. Negative slope of α and β plot



2. Propagation of the fold-and-thrust belt

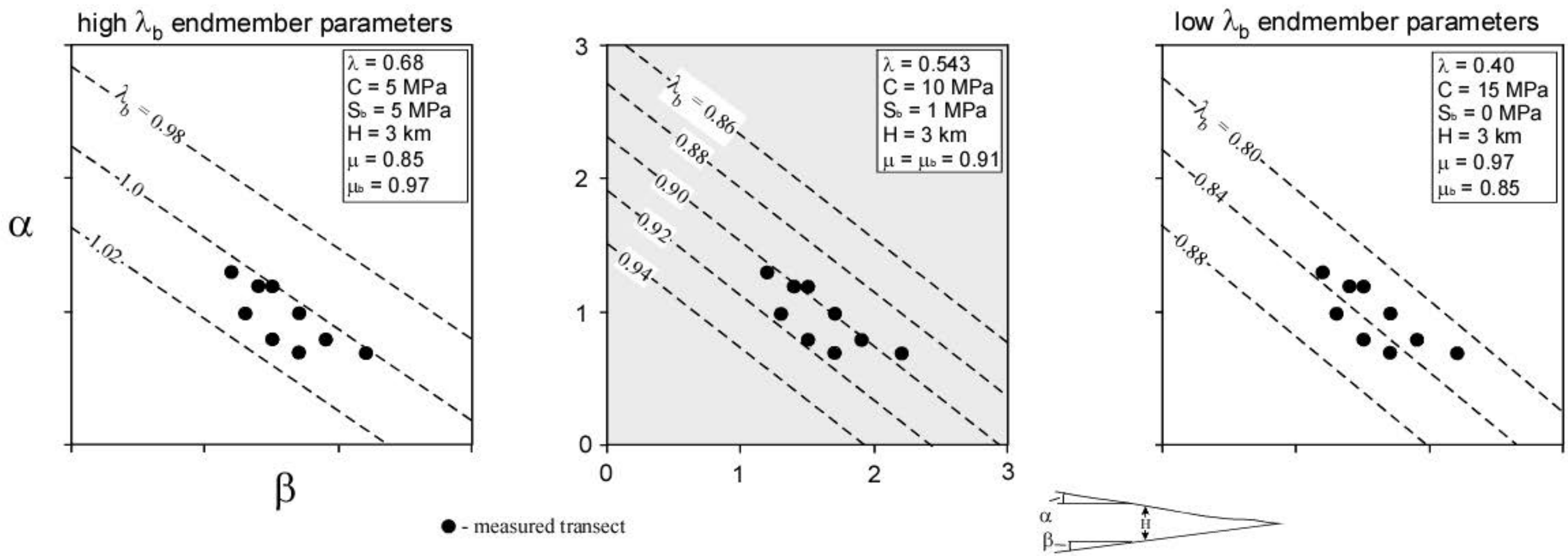




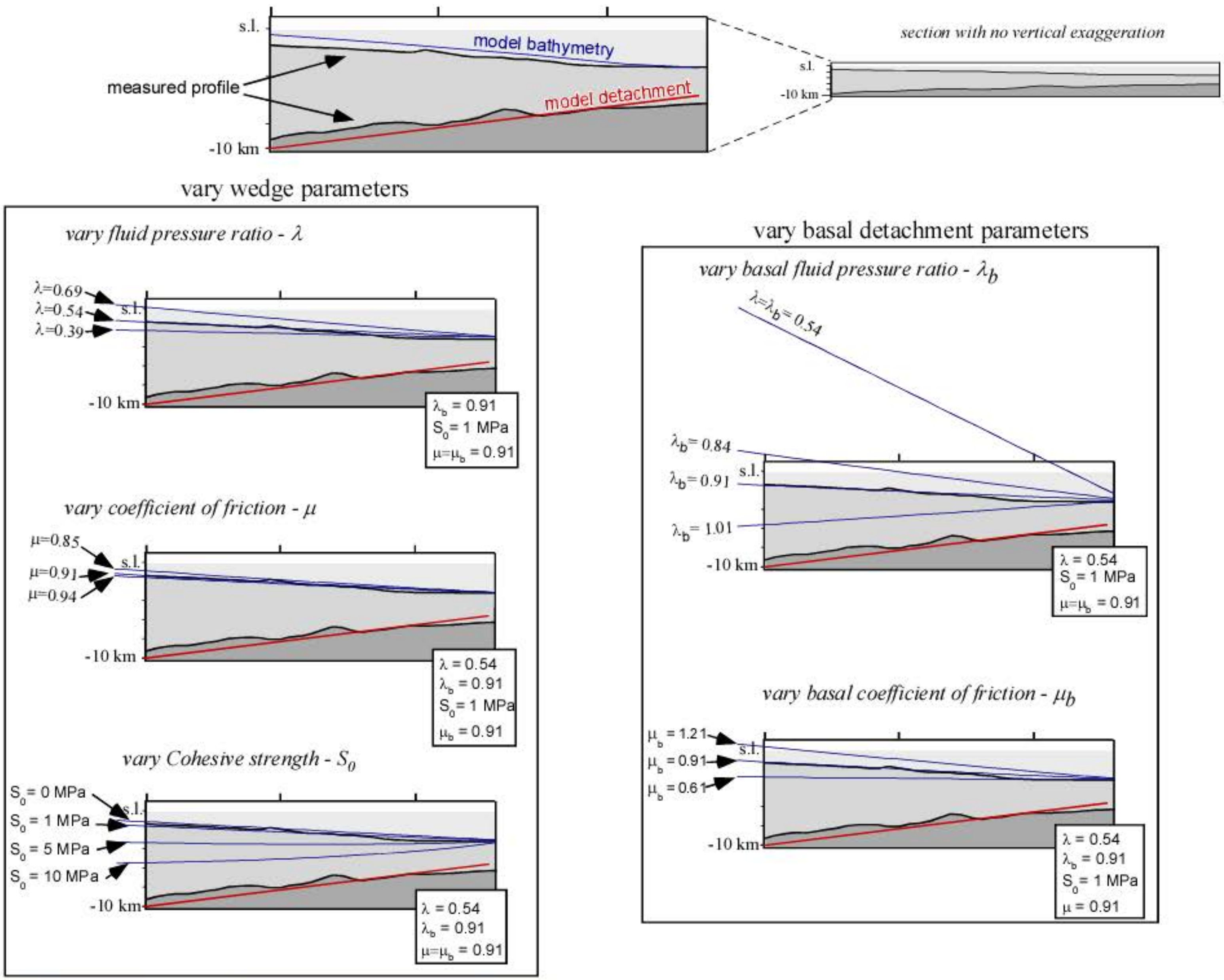
Wedge model parameters

Parameter	Value	Method of determination
Surface slope - α	0.7 - 1.3°	Measured from 10 regional transects of seismic-derived waterbottom map
Detachment dip - β	1.2 - 2.2°	measured from 10 regional transects of seismic-derived basement map
Density - ρ,	2400 kg/m^3	Deepwater well density logs (approximate)
Fluid-pressure ratio - λ	0.54 ± .15	Pressure data from 13 deepwater wells
Basal step up angle - δ_b	22°	Measured from seismic data
Internal coefficient of friction - μ	0.91± .06	Calculated from basal step-up angle
Basal coefficient of friction - μ_b	0.91 ± .3	Similar to wedge material strength and Byerlee's Law (Byerlee, 1978)
Wedge cohesion – C Basal Cohesion – S_b	5-15 MPa 0-5 MPa	(Hoshino, et al., 1972)

Model basal fluid pressure

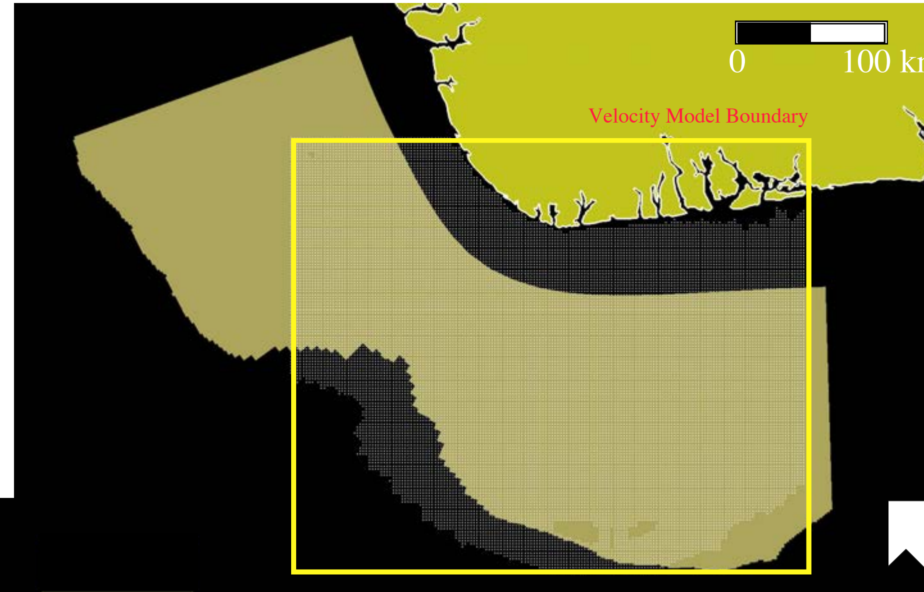


Model bathymetry

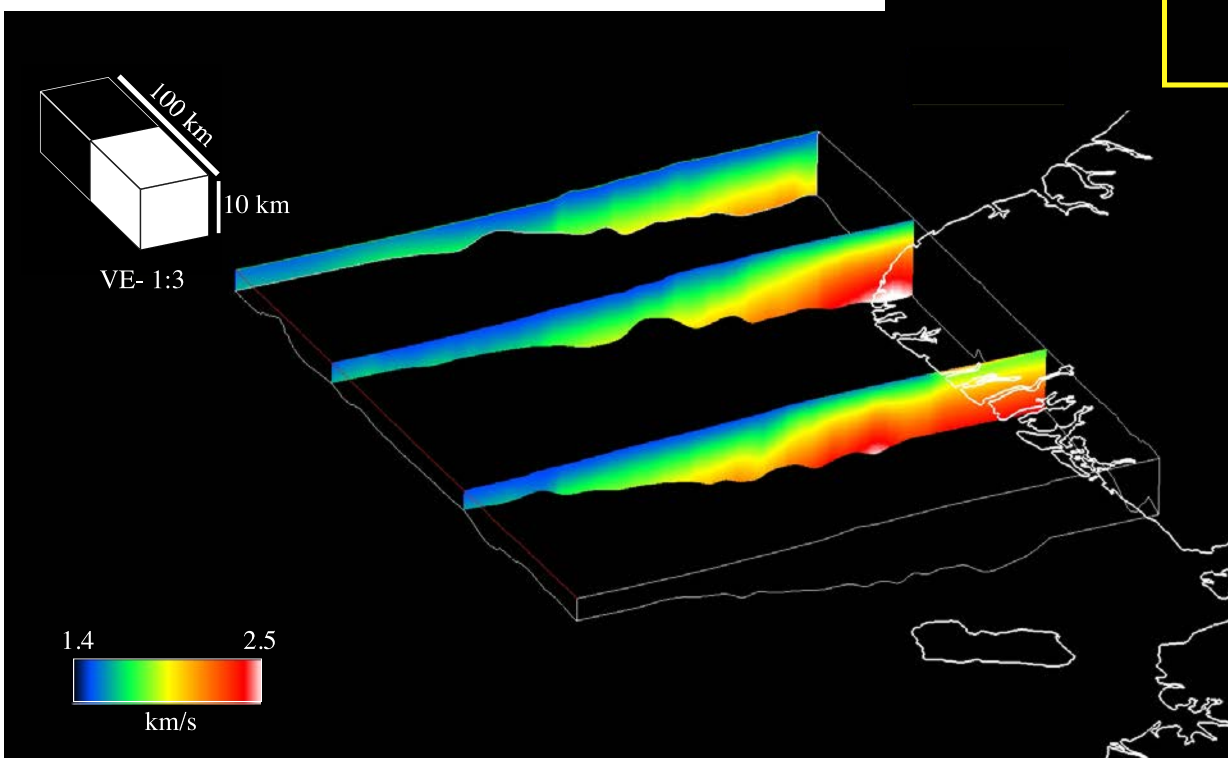


Pseudo 3d modeling

Mechanical parameters: ρ from regional Vp model



Viewing direction

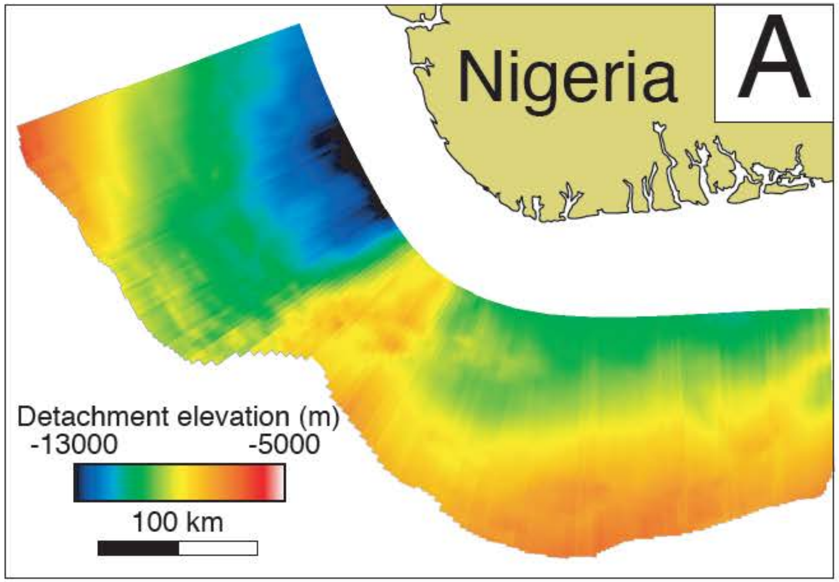


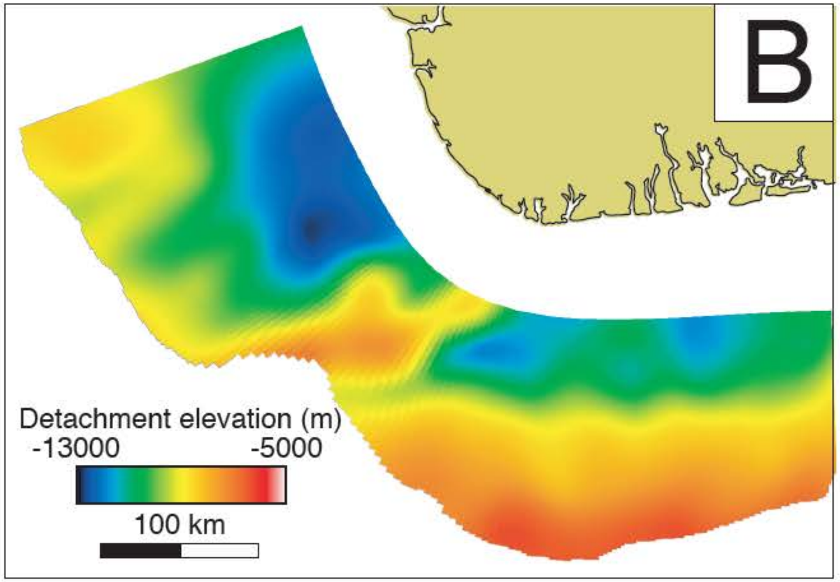
Model basal detachment geometry: prediction

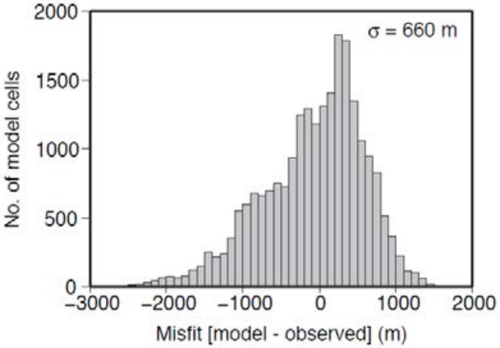
Use the bathymetry (α) to solve for the detachment geometry (β)

Model Prediction

Observation



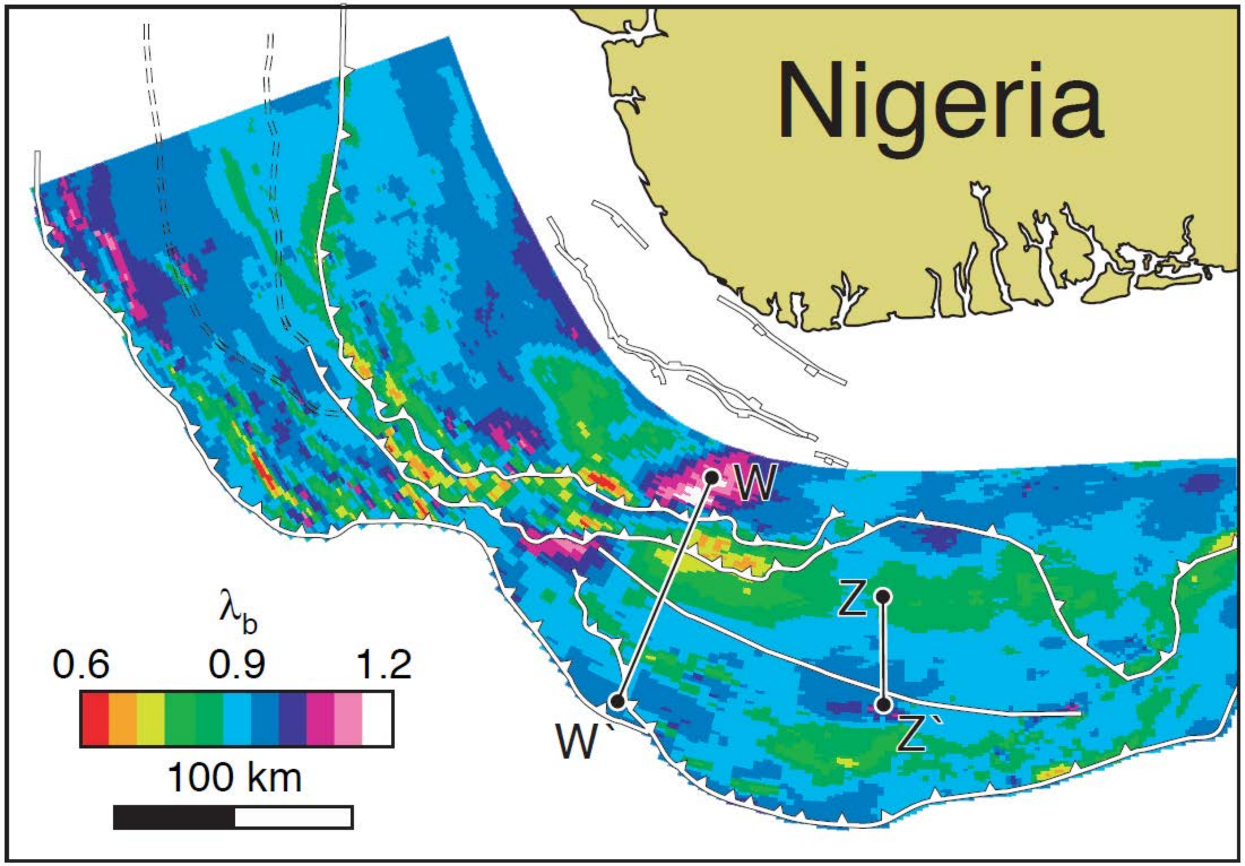




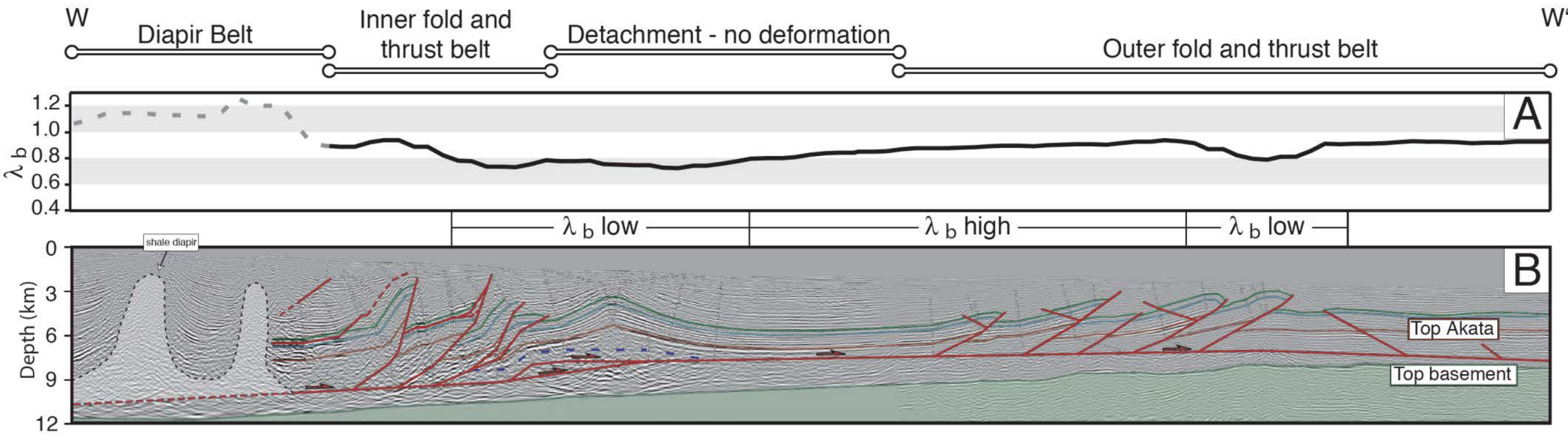
Structural Geology & Tectonics Group

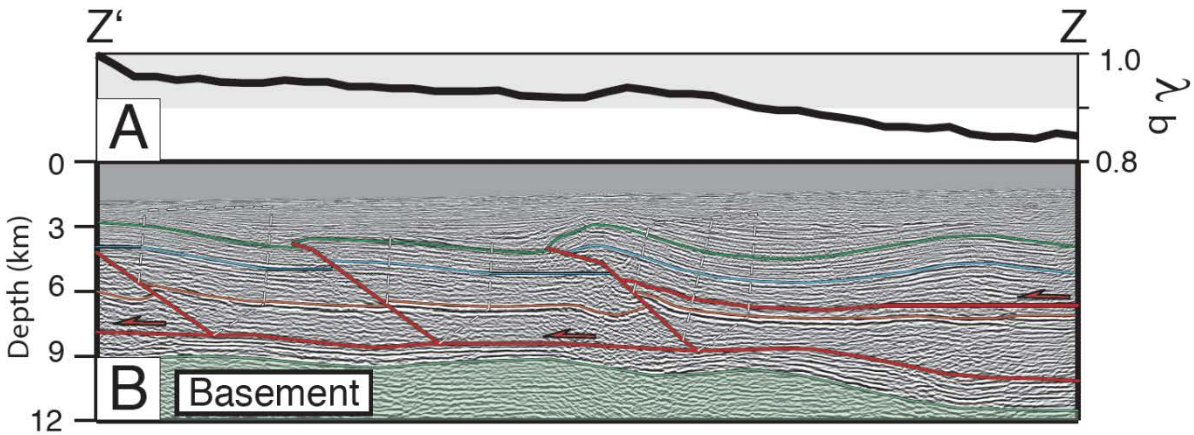
Model based mechanical parameters: λ_b

Using the surface bathymetry and basement dips, we can invert for mechanical parameters



Predicted λ_b for interpreted transects





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Coupled Fluid-mechanical models

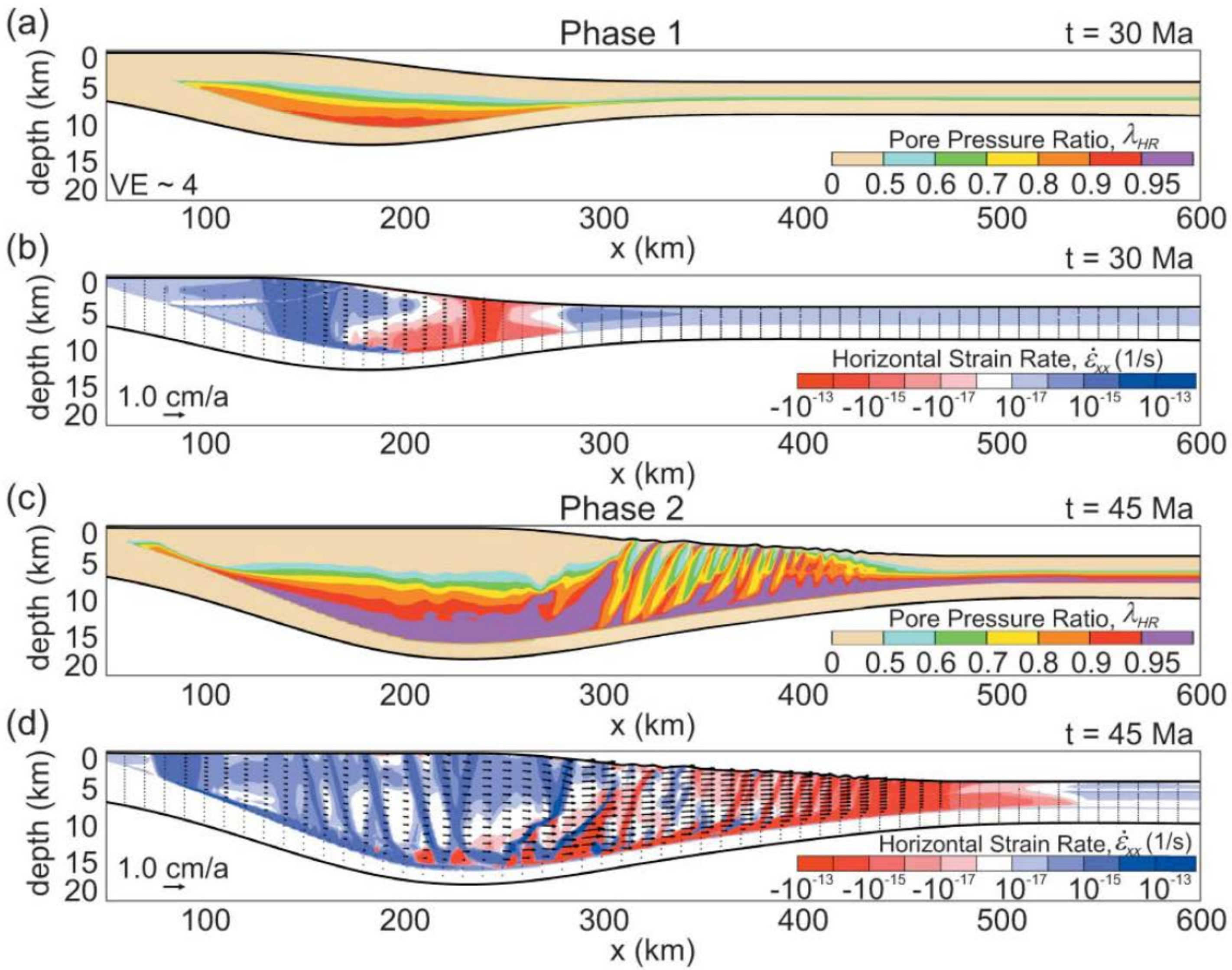


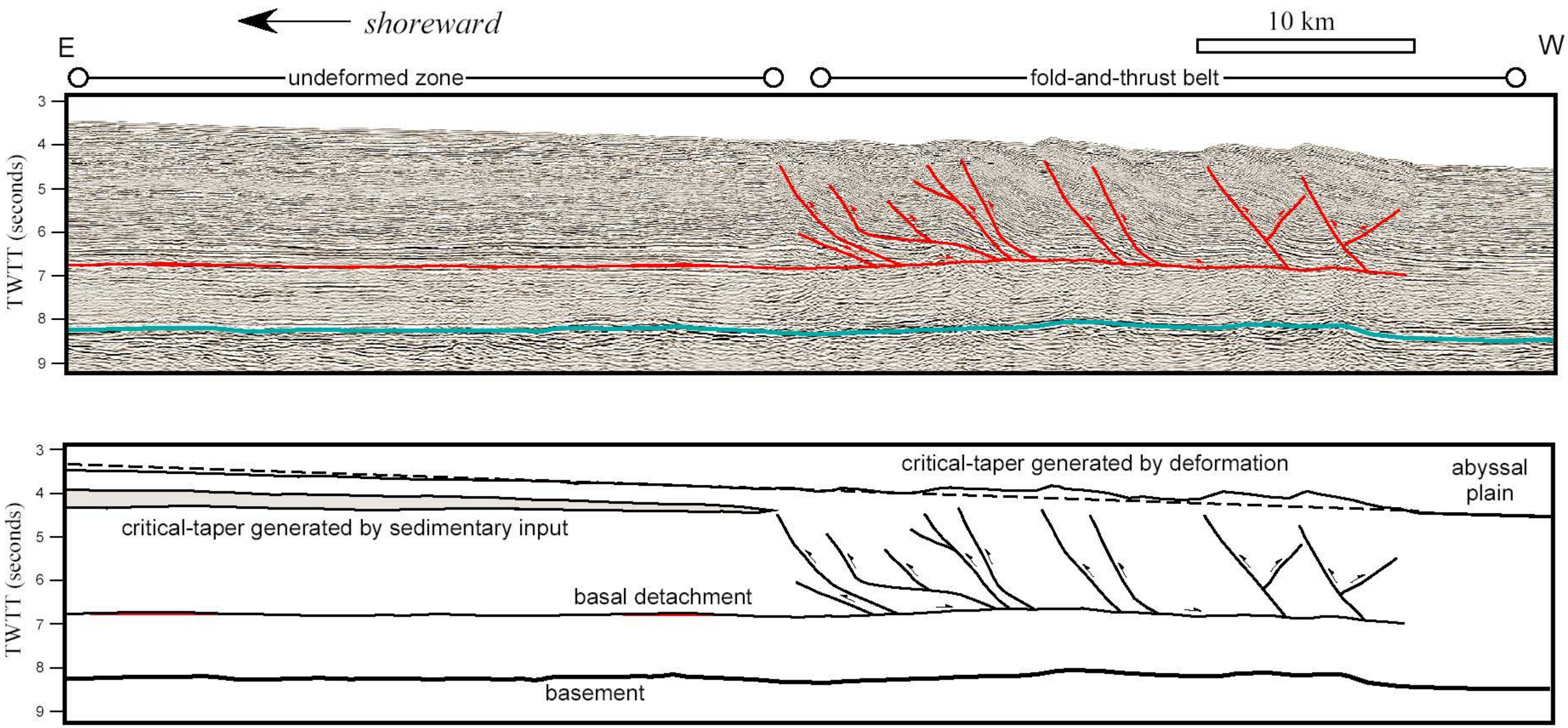
Fig. 6. Hubbert–Rubey pore pressure ratio at **(a)** $t = 30$ Ma and **(c)** $t = 45$ Ma. Horizontal component of the strain rate, $\dot{\varepsilon}_{xx}$, and flow velocities at **(b)** $t = 30$ Ma and **(d)** $t = 45$ Ma. The vertical exaggeration (VE) is *c.* 4.

Ings and Beaumont, 2010

Structural implications of low taper & high basal fluid pressures

- Regional
  - Deformation continues very far offshore
  - Large zones of little compressive deformation
  - No preference between fore and back-thrusts
- Prospect-scale
  - Weak Akata shales result in detachment folds and shear fault-bend folds

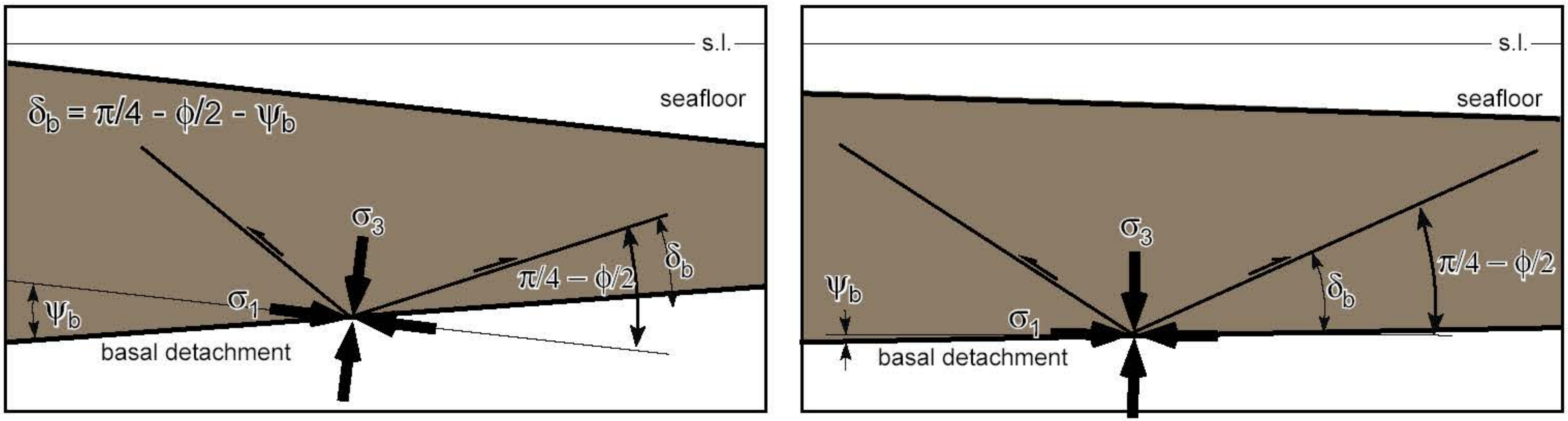
Undeformed zone

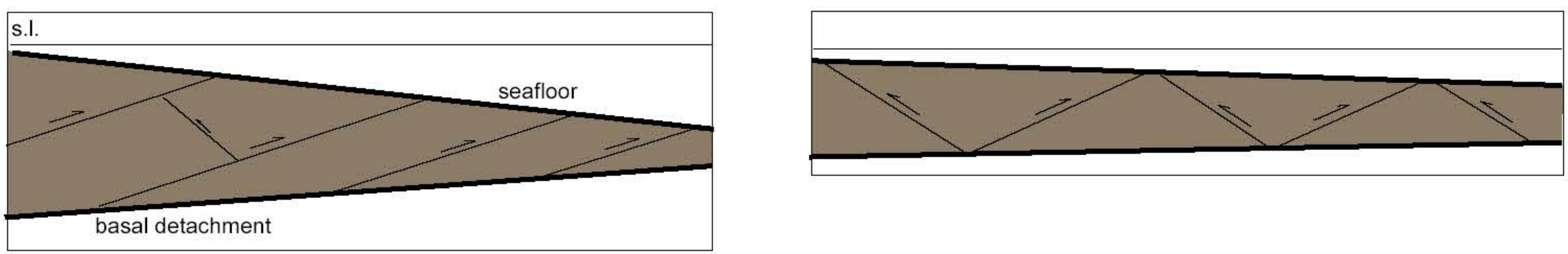


Thrust vergence and wedge taper

moderate taper wedge ($\alpha+\beta$ = 10°)

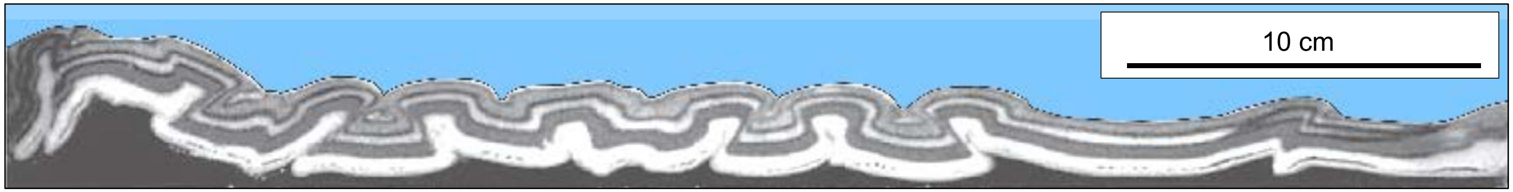
low taper wedge ($\alpha+\beta$ = 3°)





INSIGHTS FROM ANALOG MODELING [COSTA & VENDEVILLE, 2002]

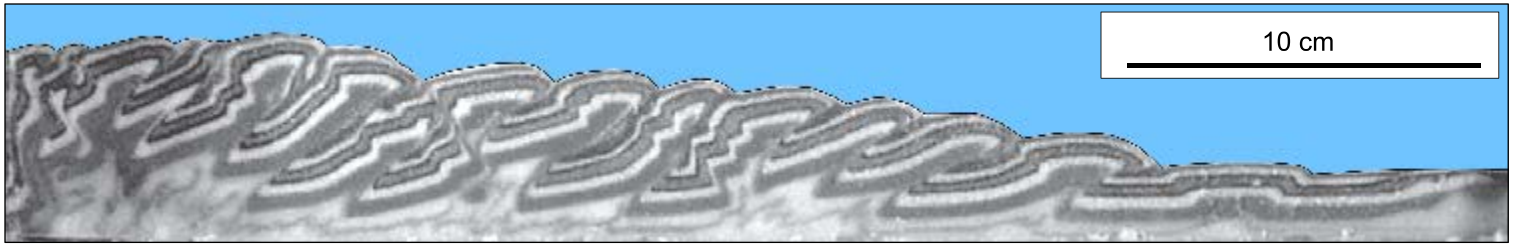
Brittle sand cover over weak, viscous décollement (silicone polymer)



Costa and Vendeville [2002]

- Bivergent directed thrust and fold anticlines separated by broad synclines
- Coeval to nearly coeval activation of contractional structures
- General structural thickening of the décollement unit at deep thrusts locations

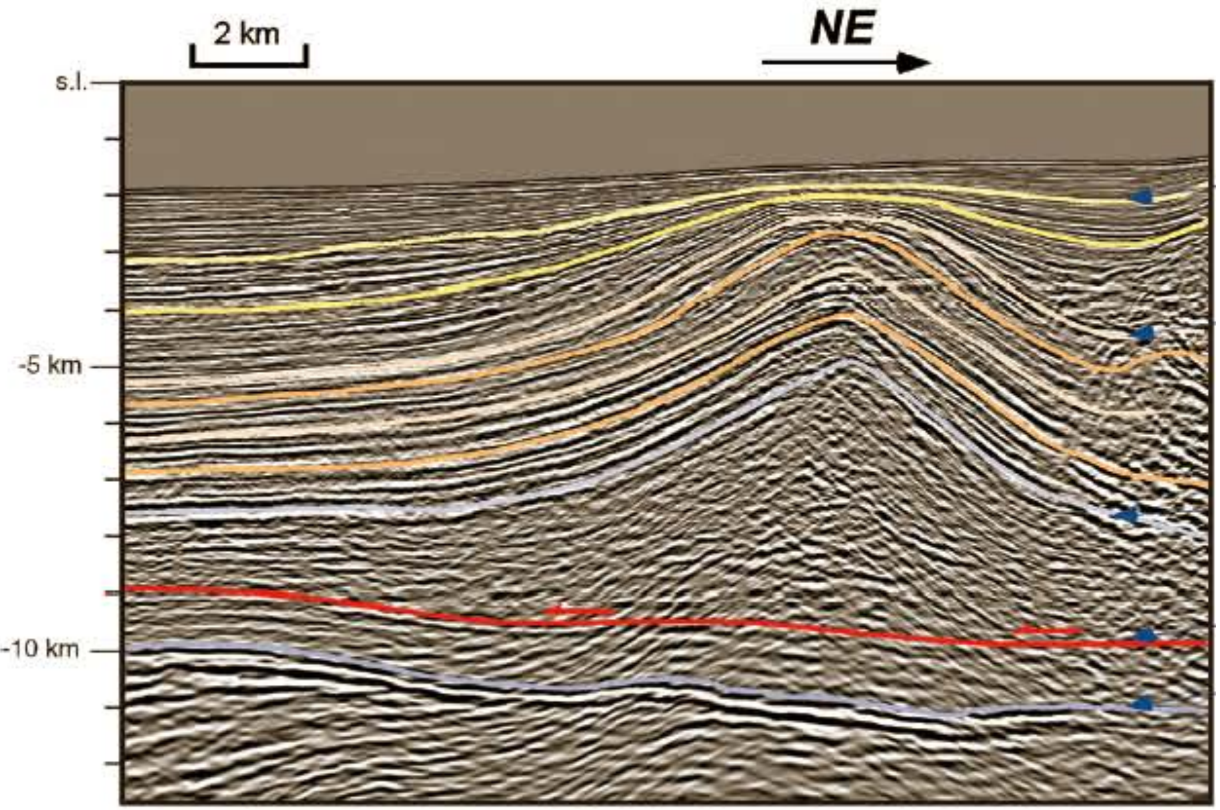
Brittle sand cover over strong, frictional décollement (glass microbeads)



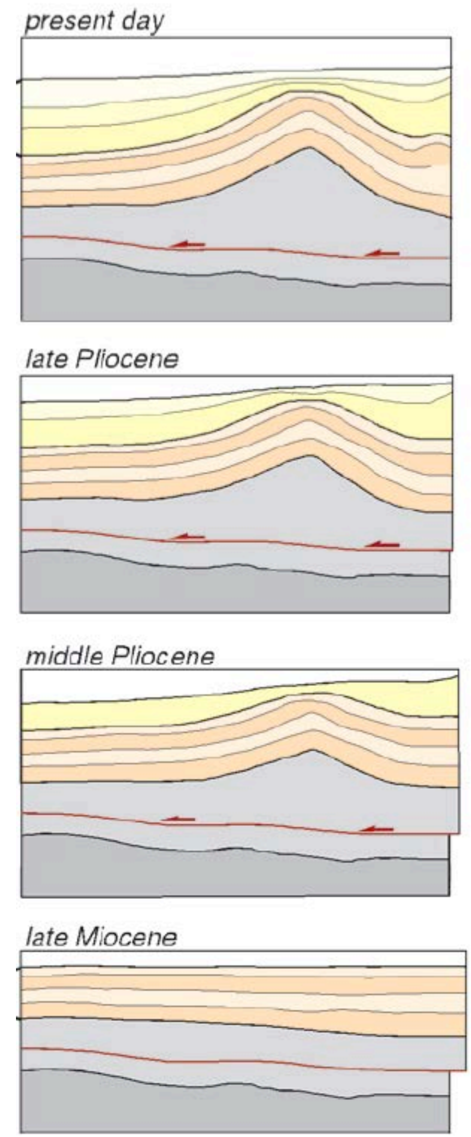
Costa and Vendeville [2002]

- Deformation mainly accommodated by slip along break–forward propagation mode
- Closely space thrust ramps and folded hanging–walls
- Continuous individual thrust–fault planes (up to the depth of detachment)

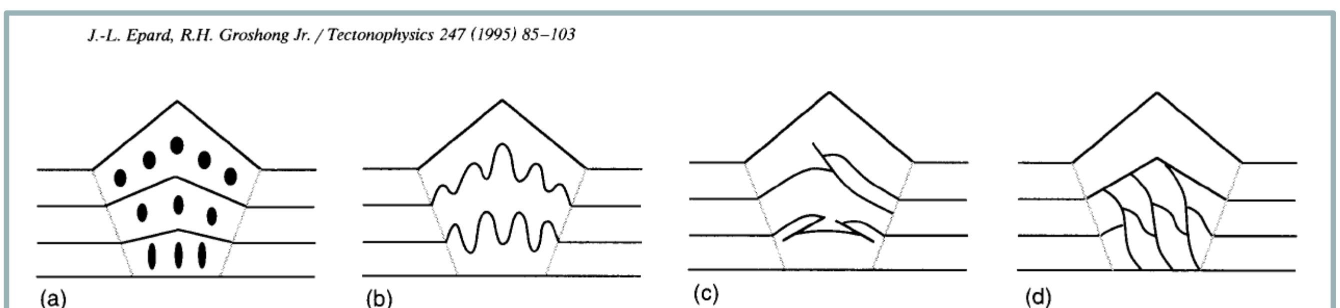
Detachment fold



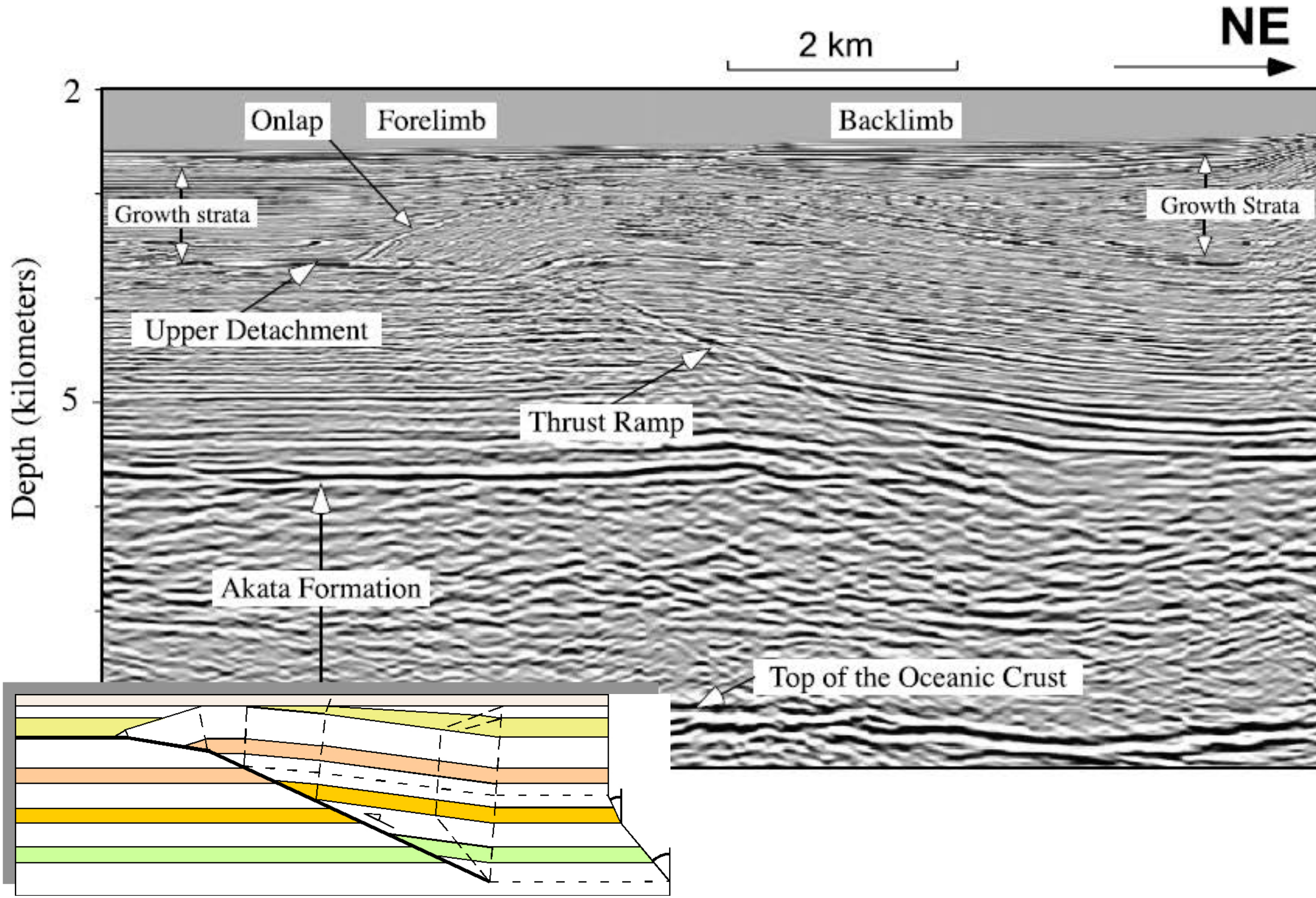
Growth by limb-rotation



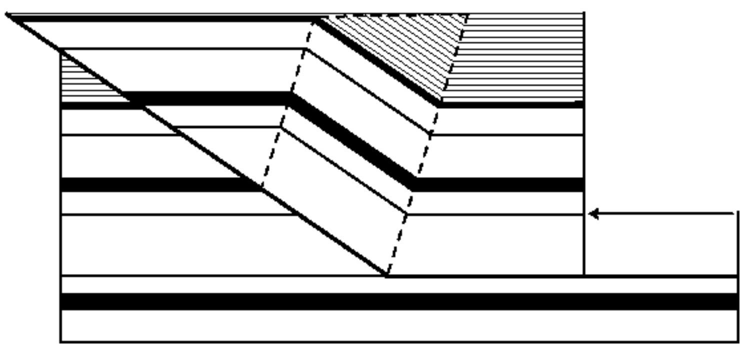
Weaker rocks between deltaic section and basal detachment



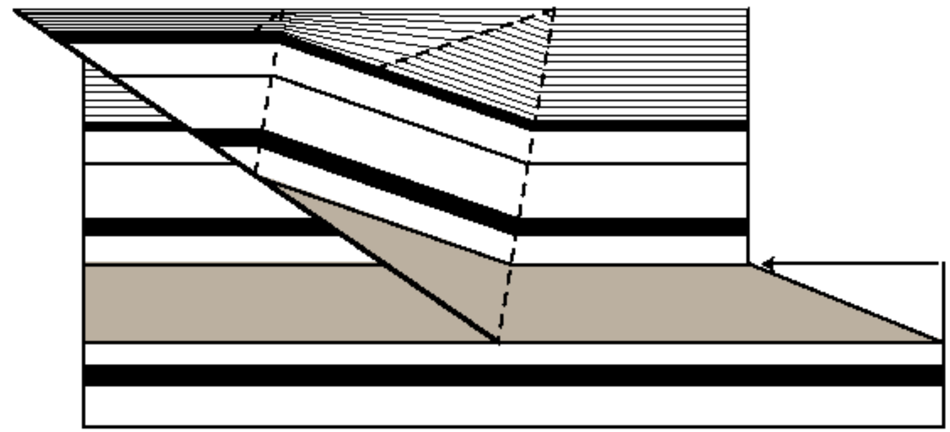
Toe-thrust geometry



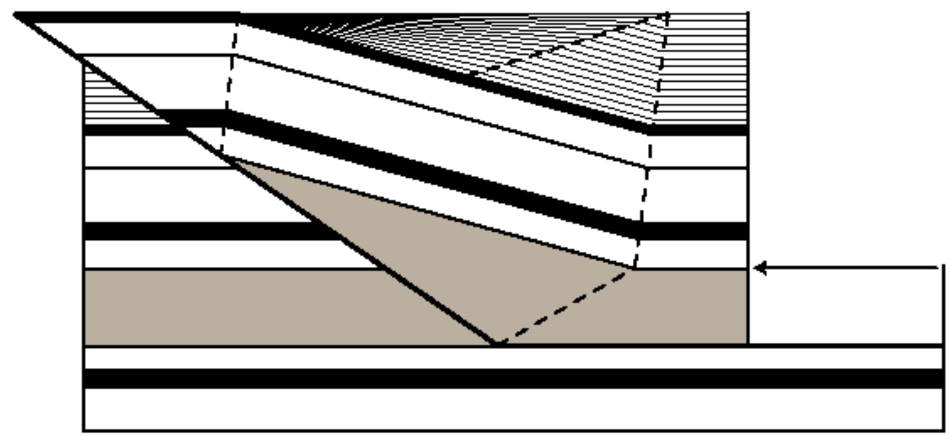
Shear fault-bend folding



Classic fault-bend folding



simple-shear fault-bend fold



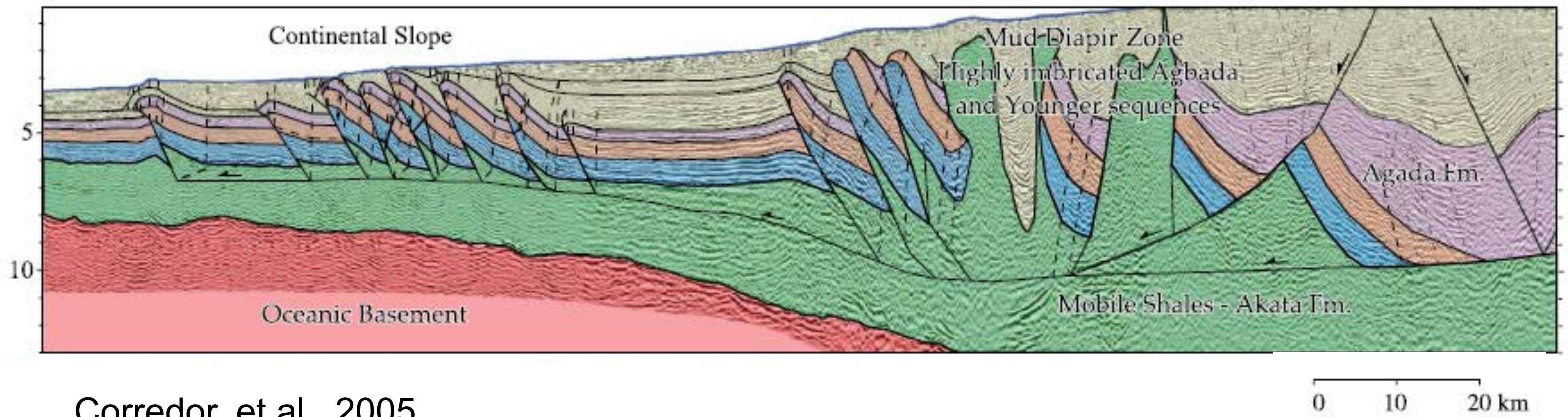
pure-shear fault-bend fold

Suppe et al., 2004

Possible sources of elevated basal fluid pressure

- Undercompaction
- Horizontal compaction
- Hydrocarbon maturation (e.g. Frost 1996, Cobbold,)

Shale Diapirism?

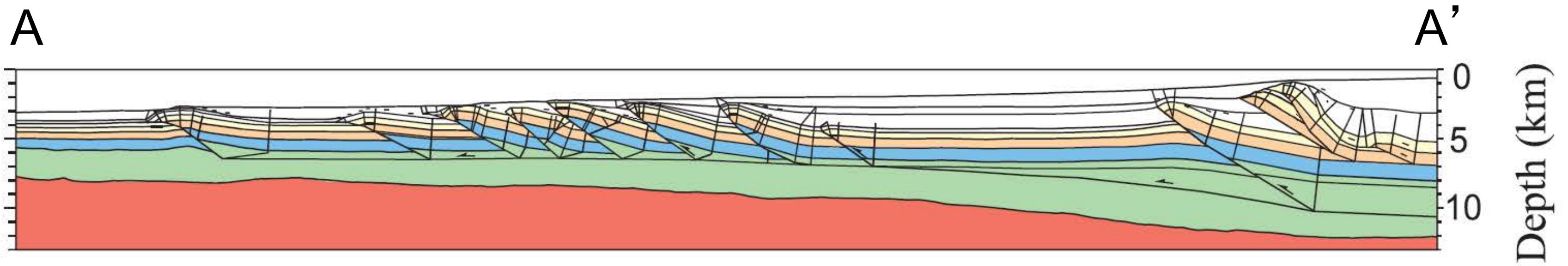


Corredor, et al., 2005

With better seismic data, we see fewer “diapirs”

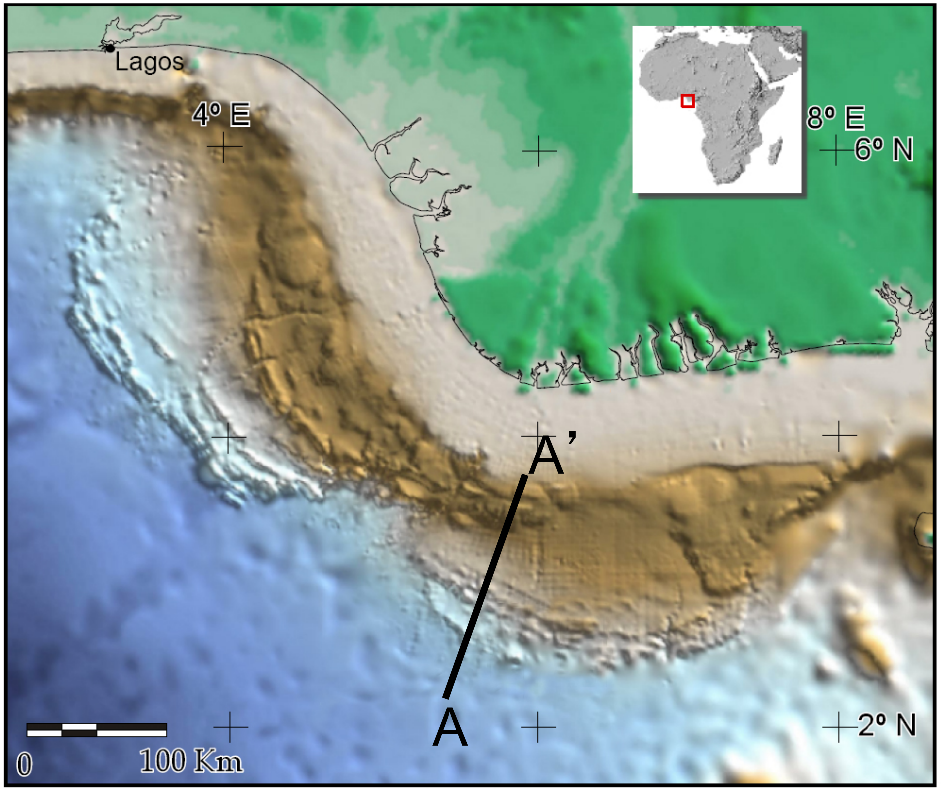
- steeply dipping anisotropic beds
- top of overpressured zones tend to be transparent in seismic data
- large dip contrasts (angular unconformities) are not imaged well

What about the inner fold-and-thrust belt?



<u>Inner fold-and-thrust belt</u>

- Much more complicated deformation
    - older, deeper, polyphase
- Larger, more variable wedge taper
- Much more robust petroleum system



Conclusions

- Basal detachment at the toe of the Niger Delta is very weak
- Probably due to elevated pore pressure

  $\lambda_b \approx 0.91$ compared to λ=0.59 measured in deltaic section
- Hypothesis is robust in 3D and in more sophisticated modeling
- Low taper that results from weak detachment facilitates distal thrusting, zones with little or no deformation, and back-thrusting
- Weakness of Akata formation results in detachment folds and shear fault-bend folds
- Subregional variations in physical properties have strong implications for the petroleum system and prospectivity