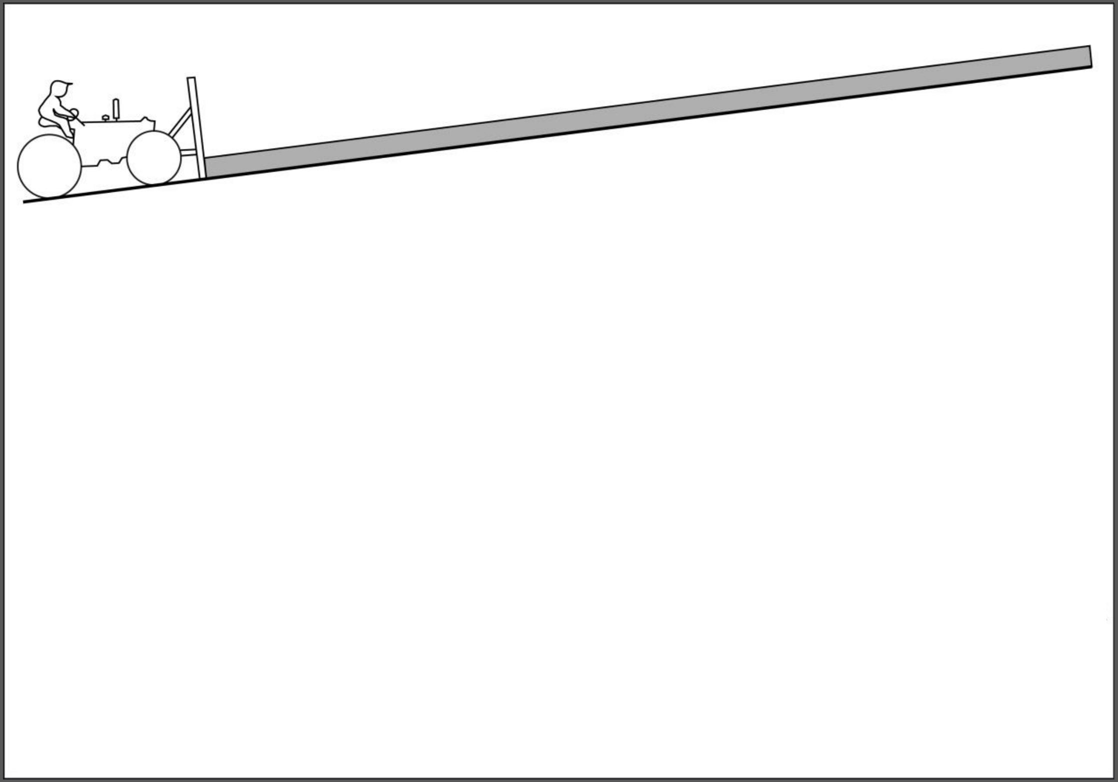
The Coulomb Critical Taper theory applied to gravitational instabilities

Aurélien Lacoste

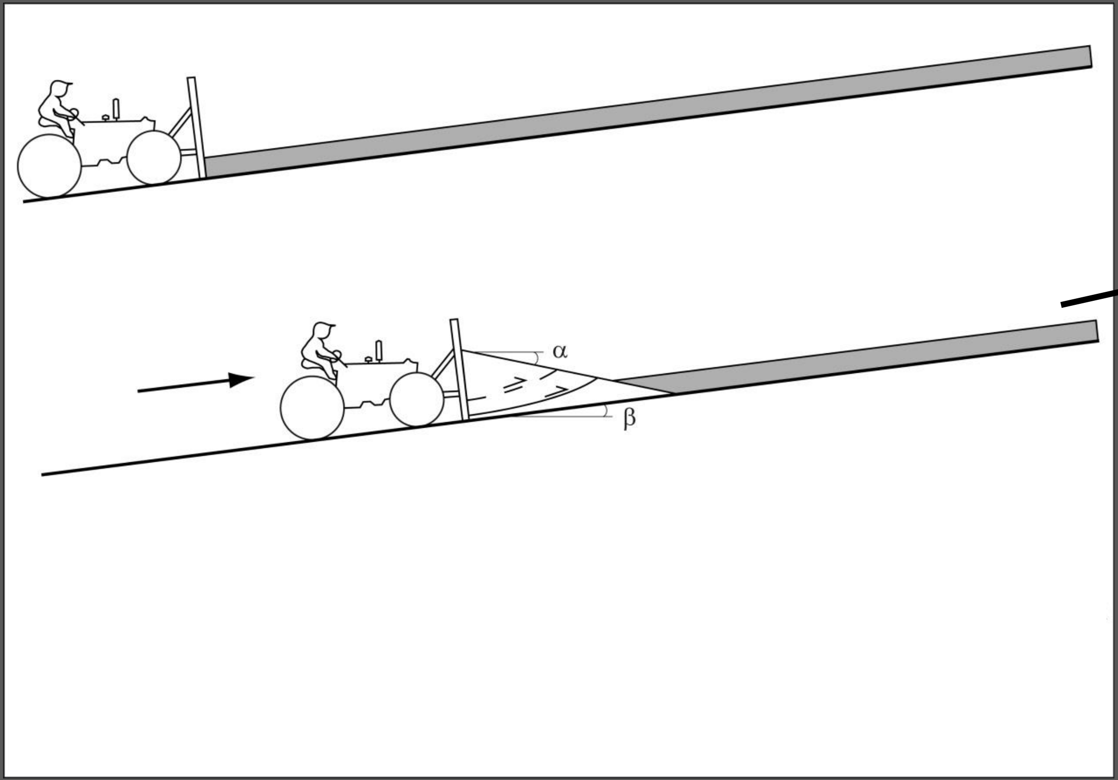
Régis Mourgues
Cynthia Garibaldi

1. The Critical Coulomb wedge theory



Modified after Dahlen (1990)

1. The Critical Coulomb wedge theory

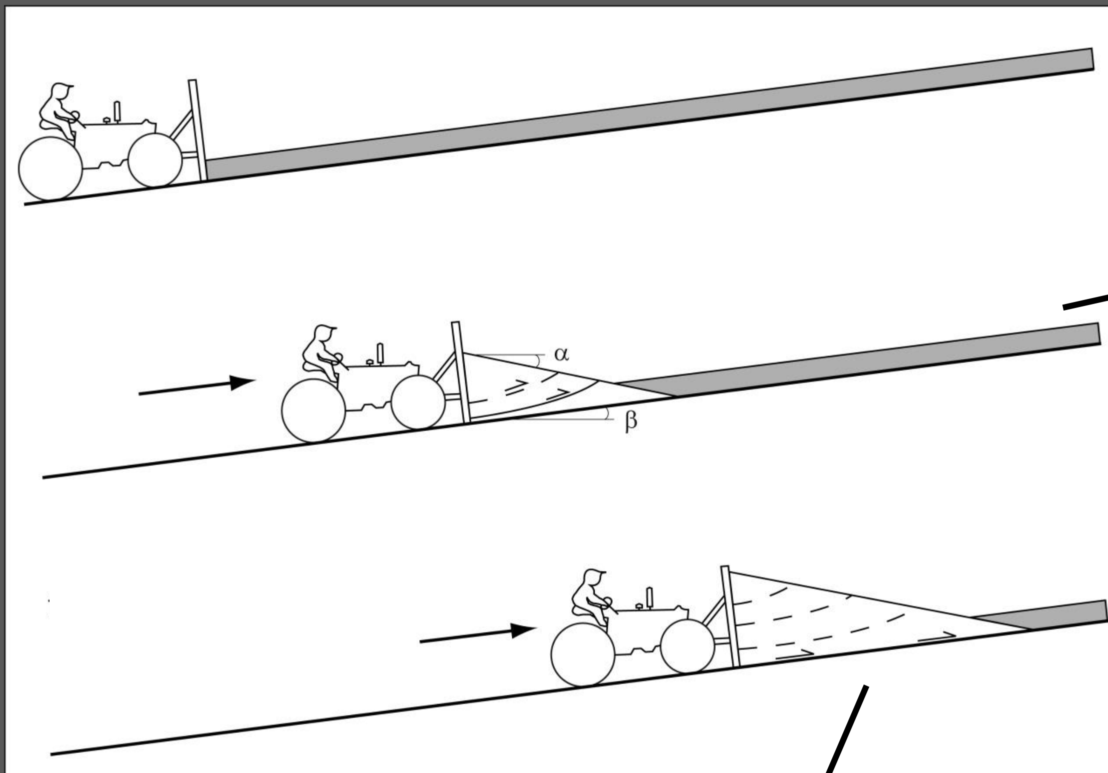


Modified after Dahlen (1990)

Wedge growth
Thrusting

Steepening until the critical taper is attained

1. The Critical Coulomb wedge theory



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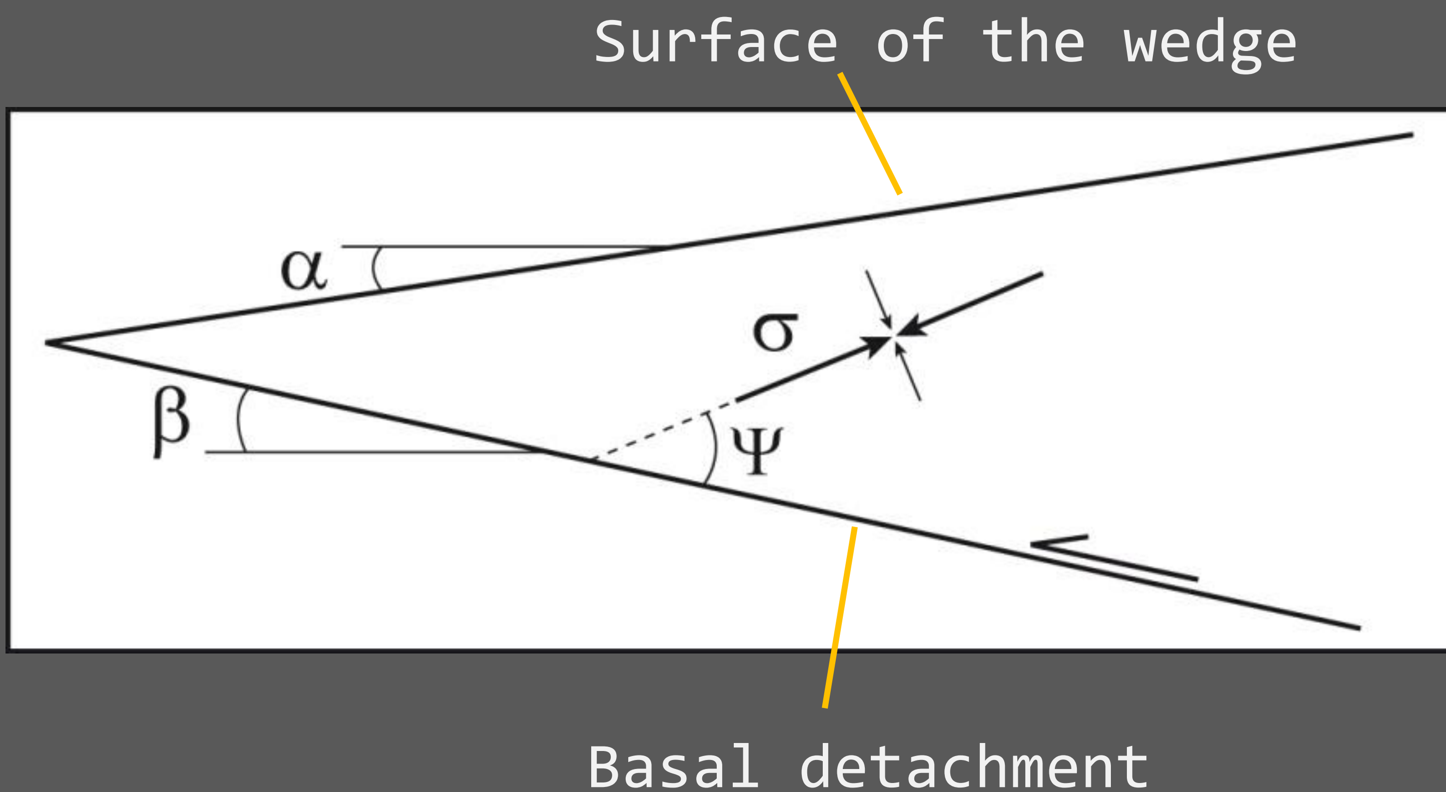
Wedge growth
Thrusting

Steepening until the critical taper is attained

Sliding along the basal detachment

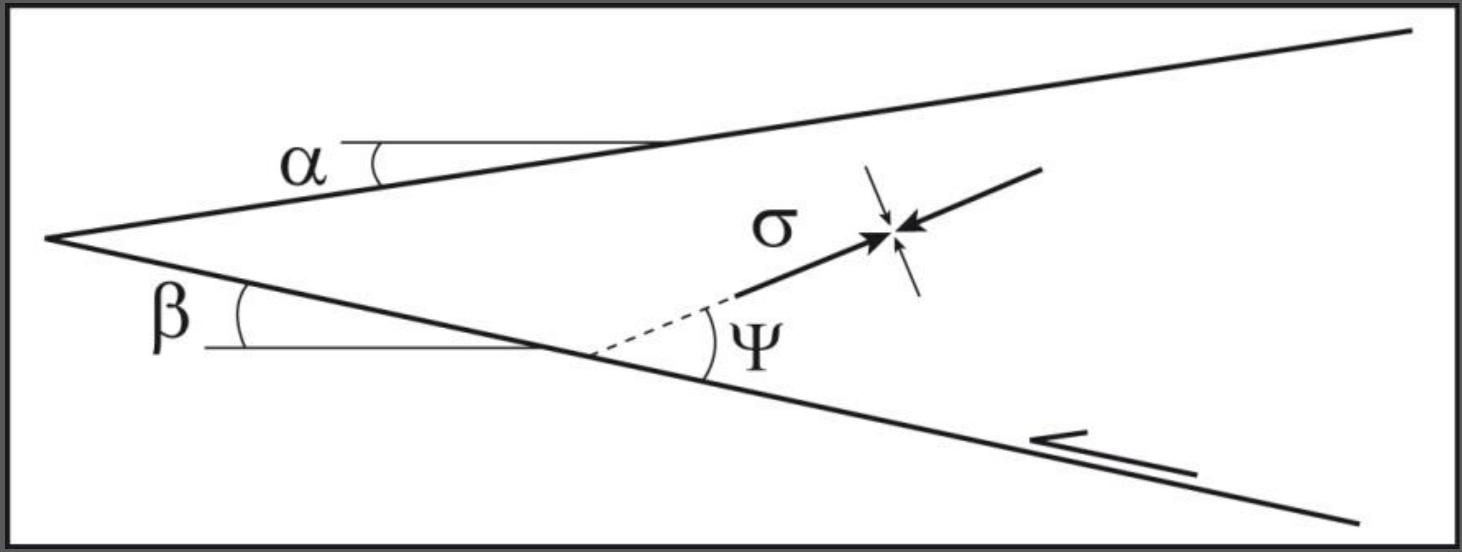
1. The Critical Coulomb wedge theory

General solution (Davis et al., 1983)



1. The Critical Coulomb wedge theory

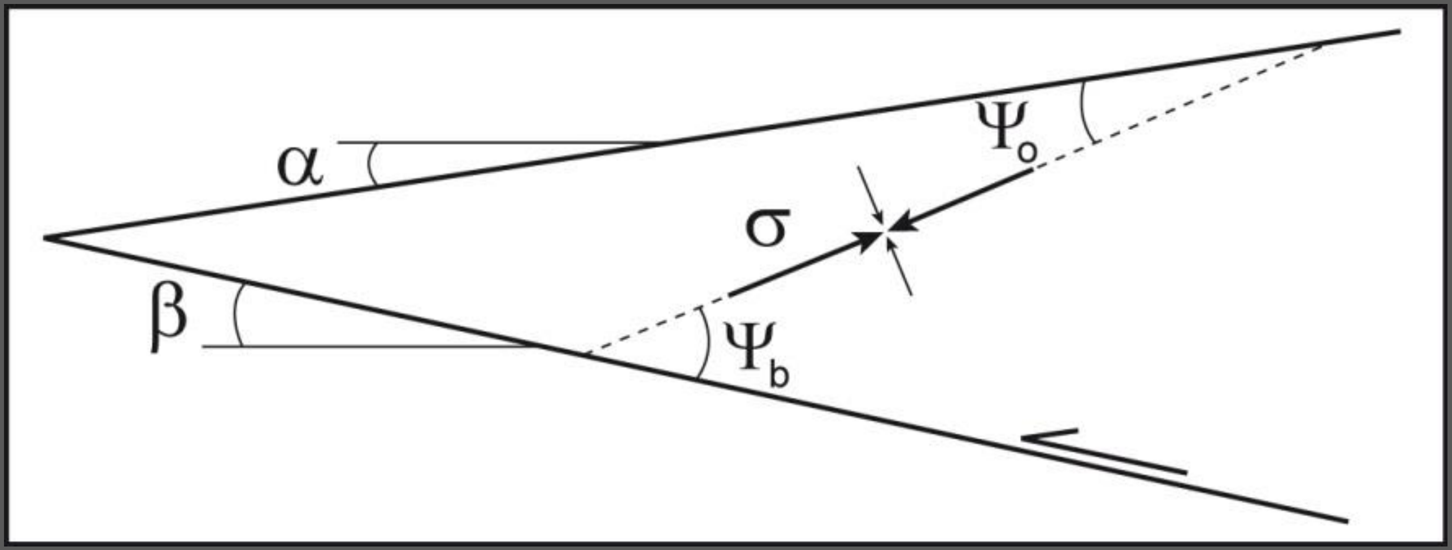
General solution *(Davis et al., 1983)*



$$\alpha + \beta \sim \rho, \lambda, \phi, \Psi, H$$

1. The Critical Coulomb wedge theory

Case of a noncohesive wedge *(Dahlen, 1984)*



Exact solution: $\alpha + \beta = \Psi_b - \Psi_o$

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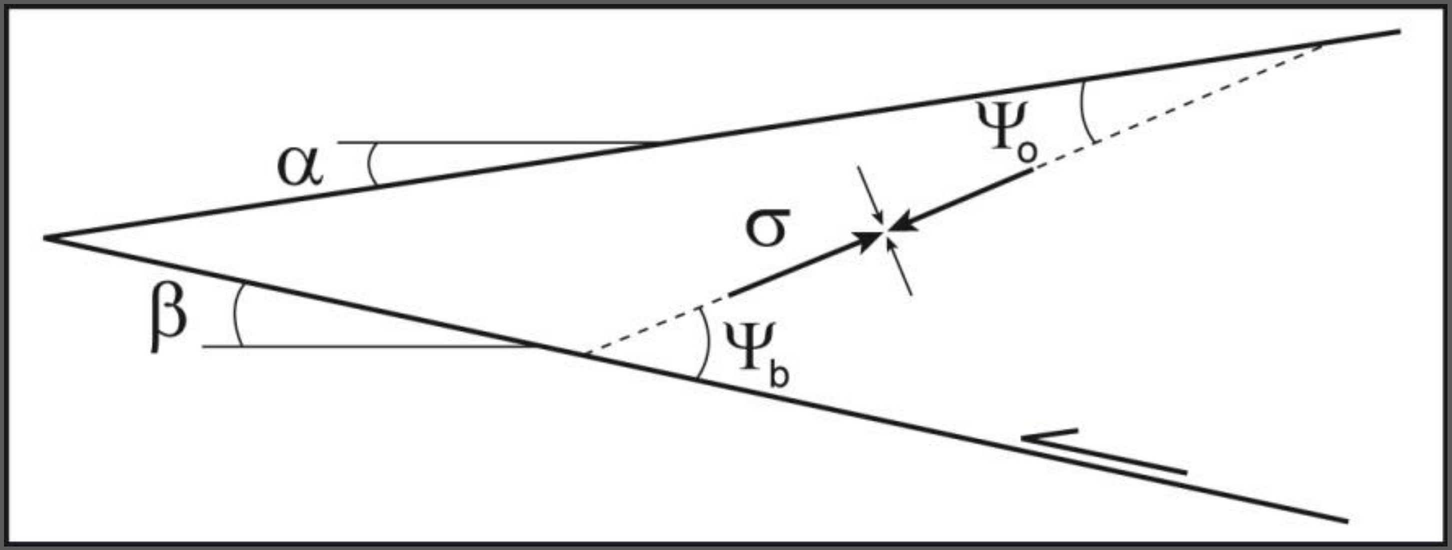


Exact solution: $\alpha + \beta = \Psi_b - \Psi_o$

- Mohr-Coulomb criterion of deformation
- Wedge everywhere on the verge of failure

1. The Critical Coulomb wedge theory

- Mohr-Coulomb criterion of deformation:

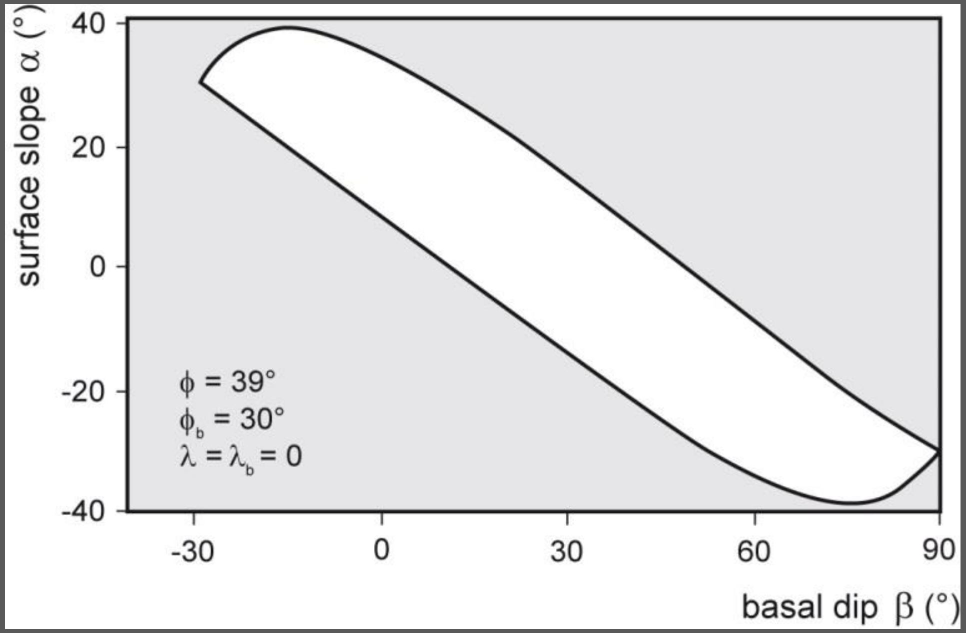
$$\tau = \mu \sigma_n + c$$

- Wedge everywhere on the verge of failure

Stress : deformation

1. The Critical Coulomb wedge theory

Accretionary wedges



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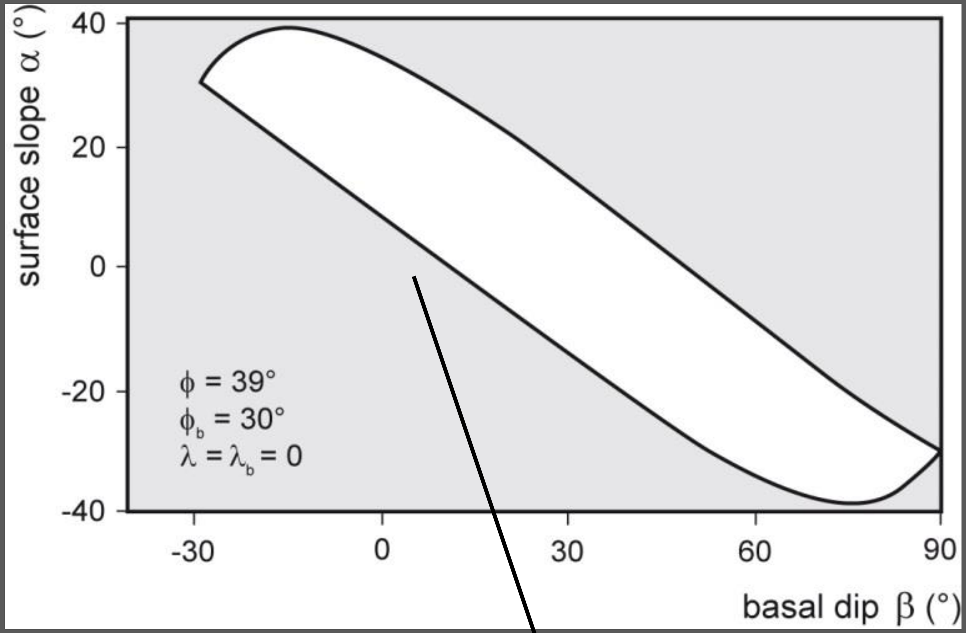
Accretionary wedges



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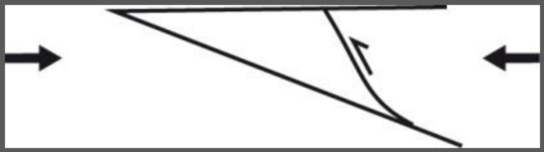
Sub-critical wedges: formation of thrusts



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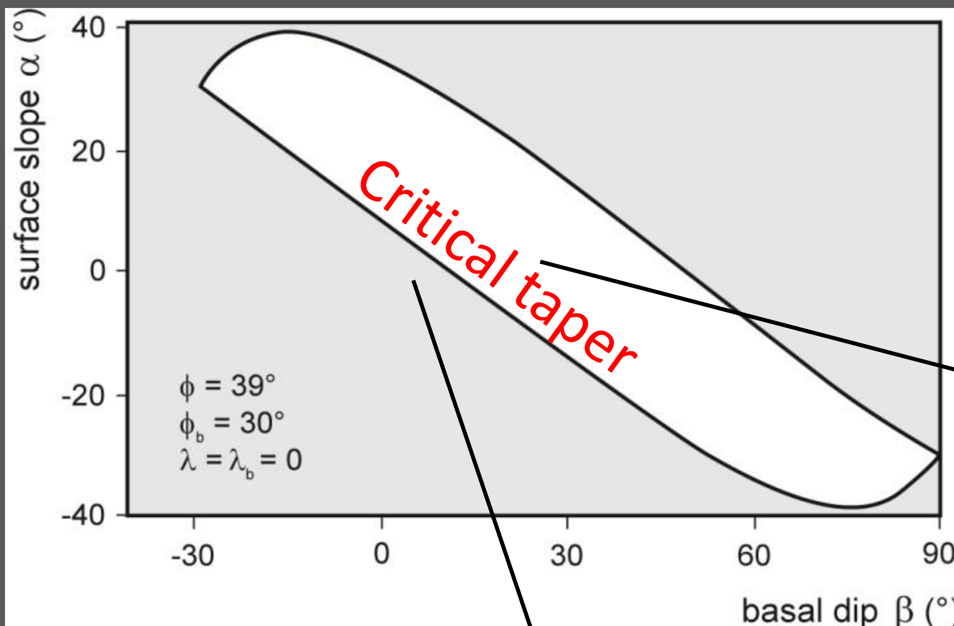
Accretionary wedges



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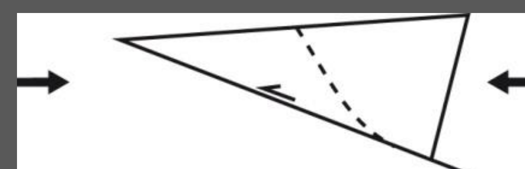
Stable supercritical wedges: sliding on basal detachment



Sub-critical wedges: formation of thrusts

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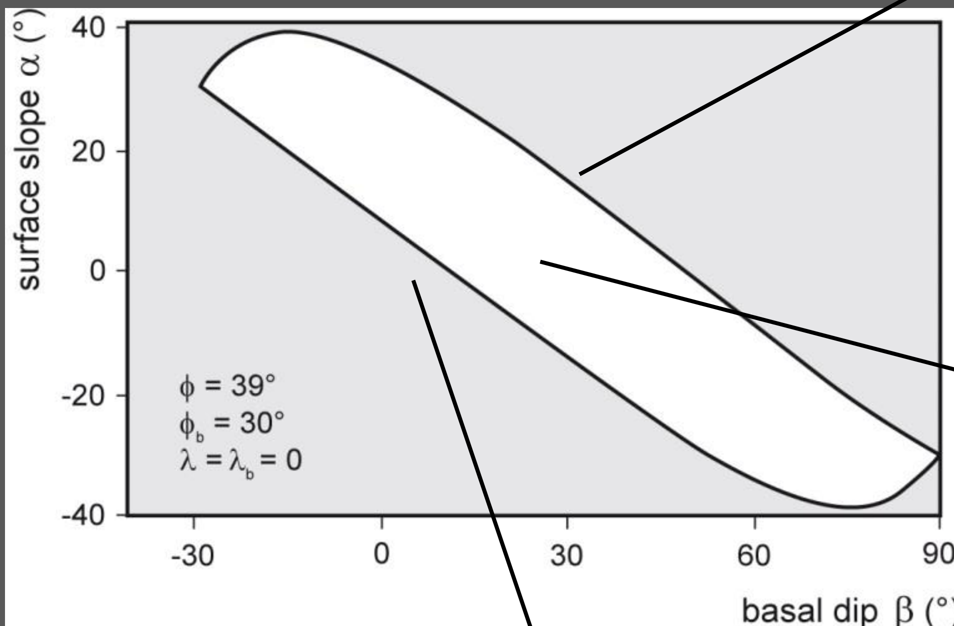
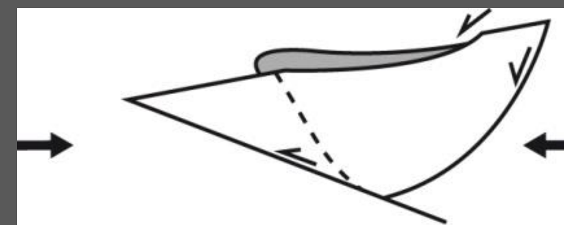
Accretionary wedges



Modified after Dahlen (1984)

Unstable wedges: shallow slumping + normal faulting



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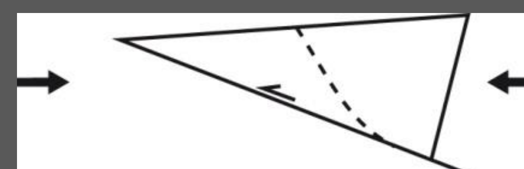

Sub-critical wedges: formation of thrusts

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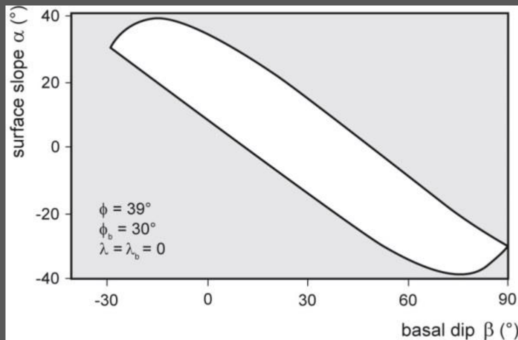
Accretionary wedges



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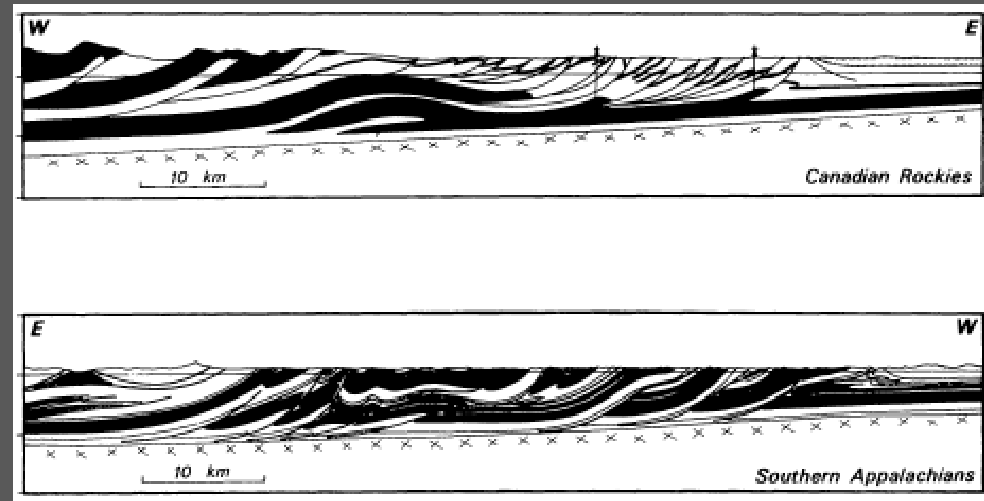
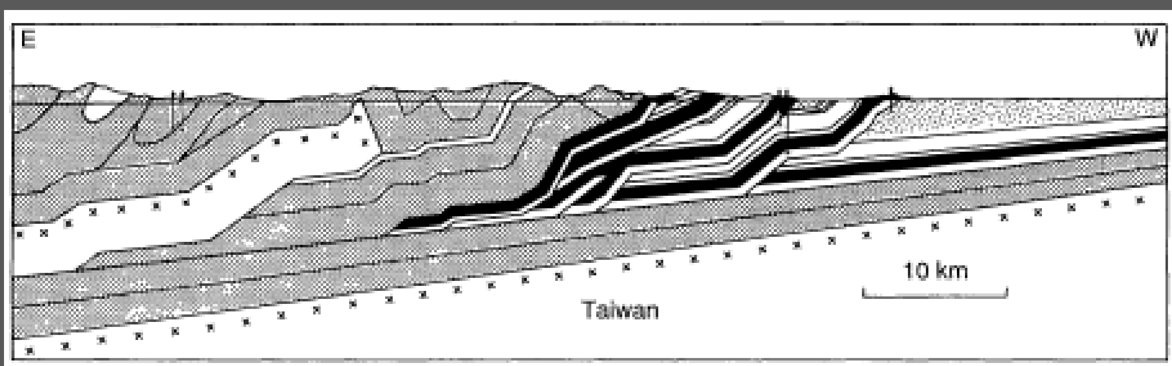
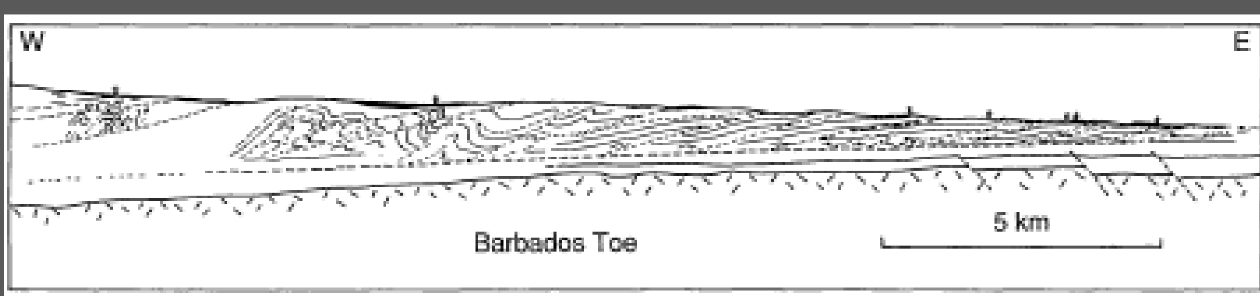
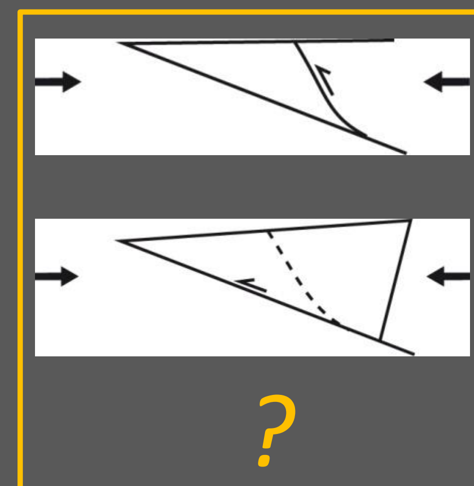


Dahlen (1990)

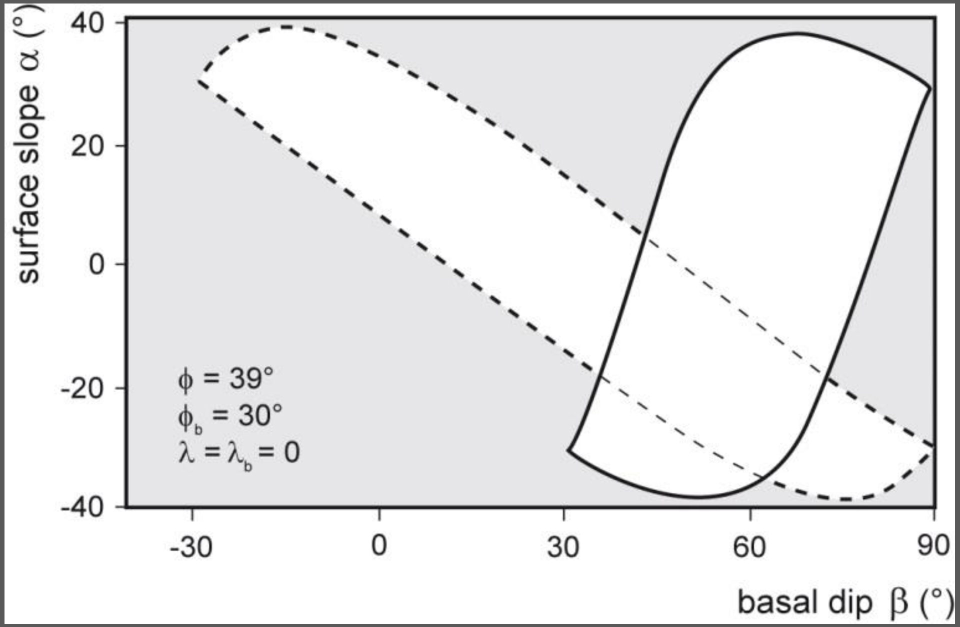






1. The Critical Coulomb wedge theory

Extensional wedges

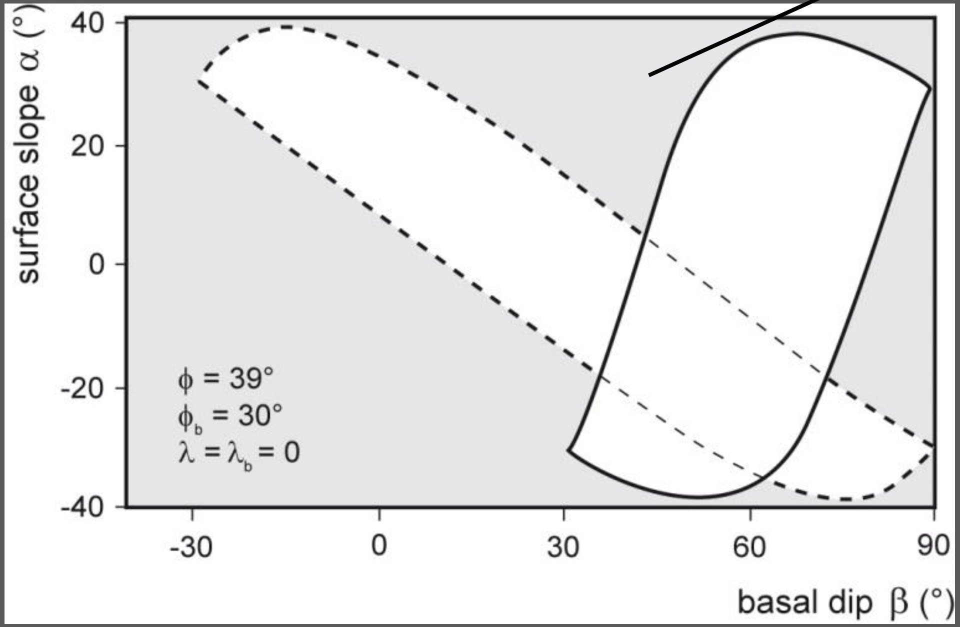


Modified after Xiao et al. (1991)

1. The Critical Coulomb wedge theory

Extensional wedges

Sub-critical wedges:
normal faulting



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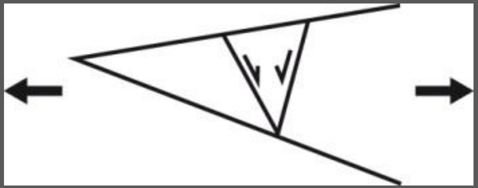

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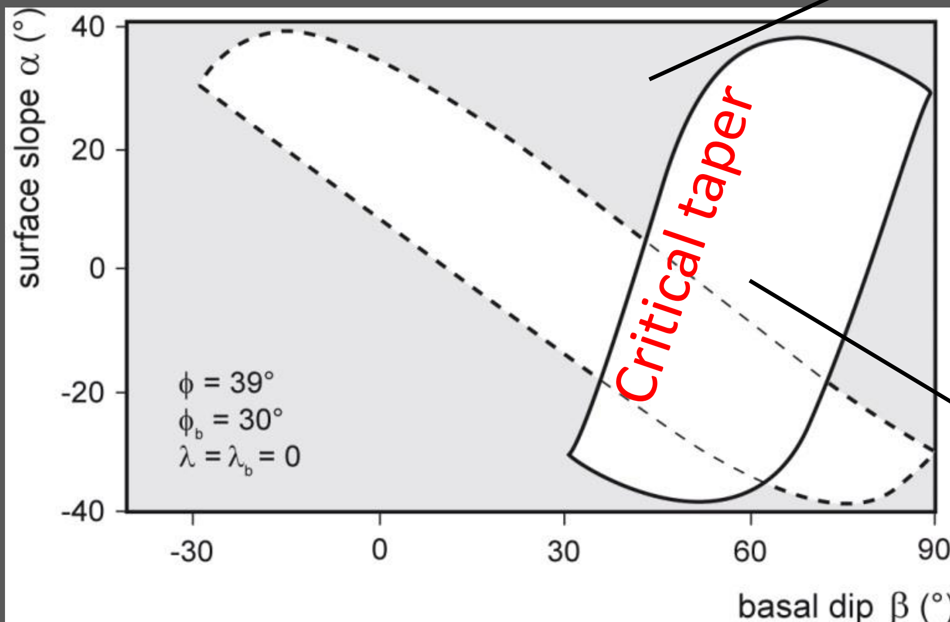

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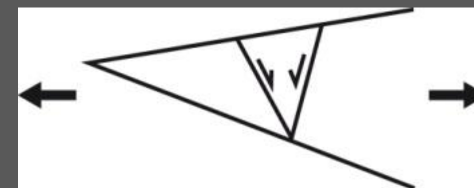
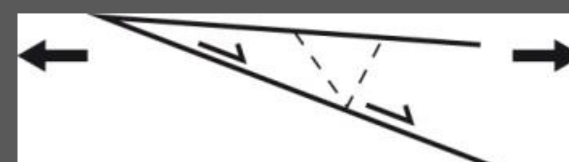


Stable wedges: sliding on basal detachment



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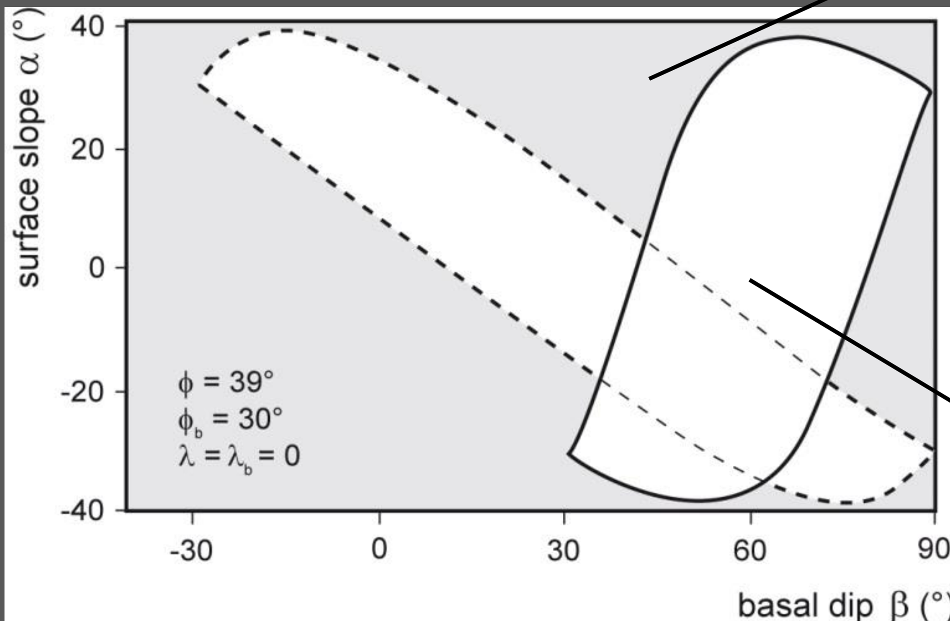
Extensional wedges



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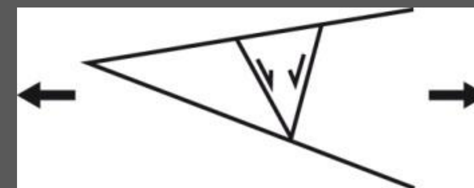
Sub-critical wedges: normal faulting

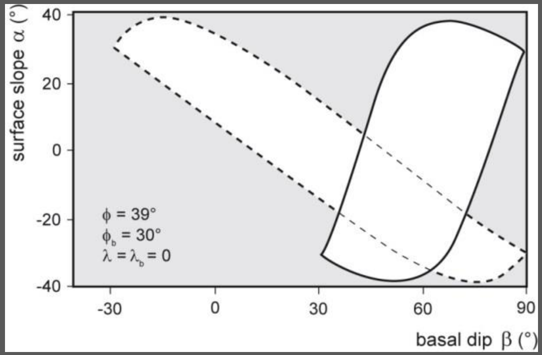


Stable wedges: sliding on basal detachment

- *Active* extensional setting
- Basal shear stress towards the thicker part

1. The Critical Coulomb wedge theory

Extensional wedges



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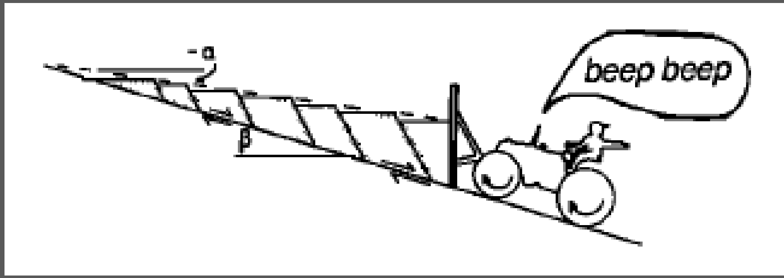

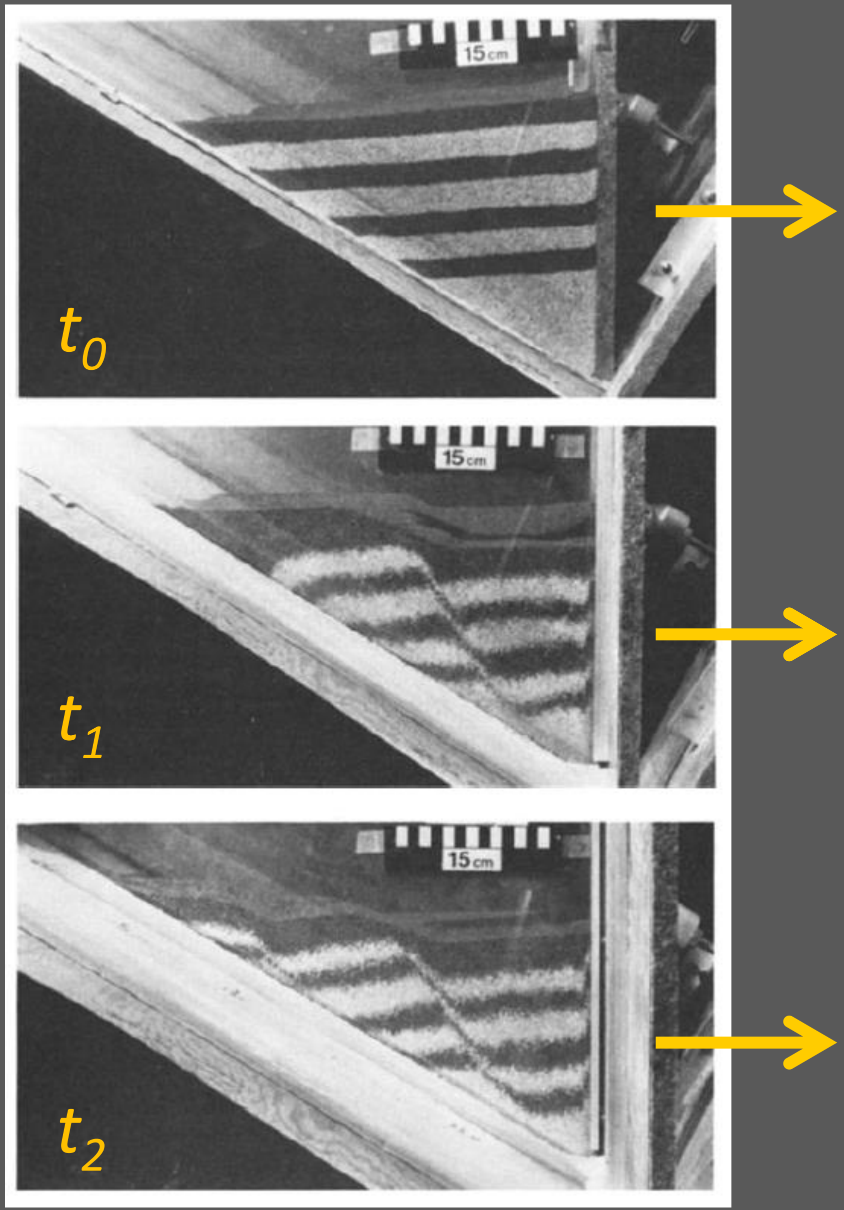

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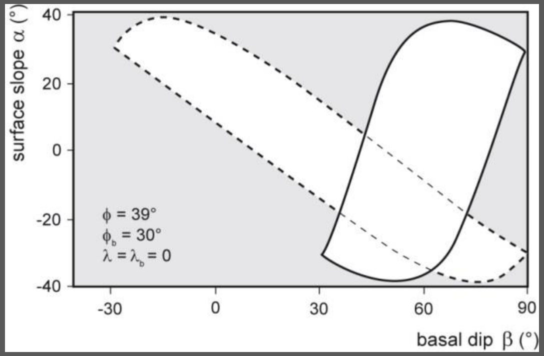
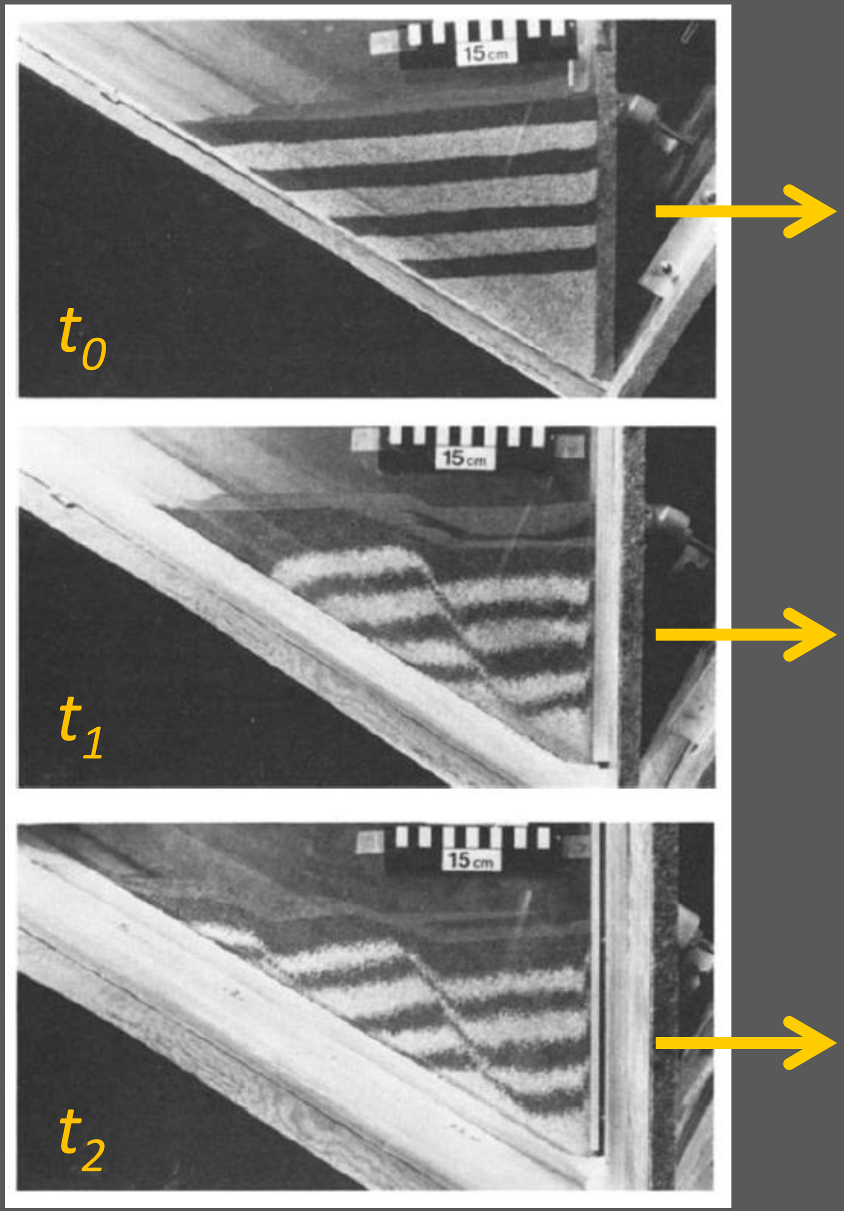
Extensional wedges



Modified after Xiao et al. (1991)

$-\alpha$ increases

β constant



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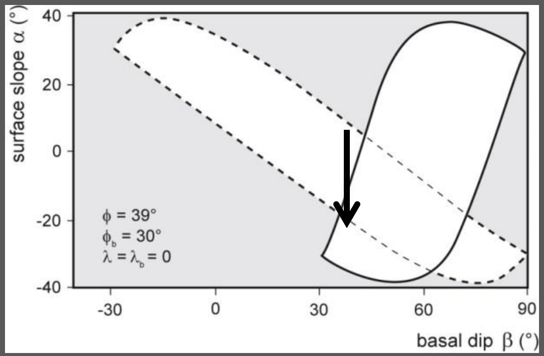
Extensional wedges



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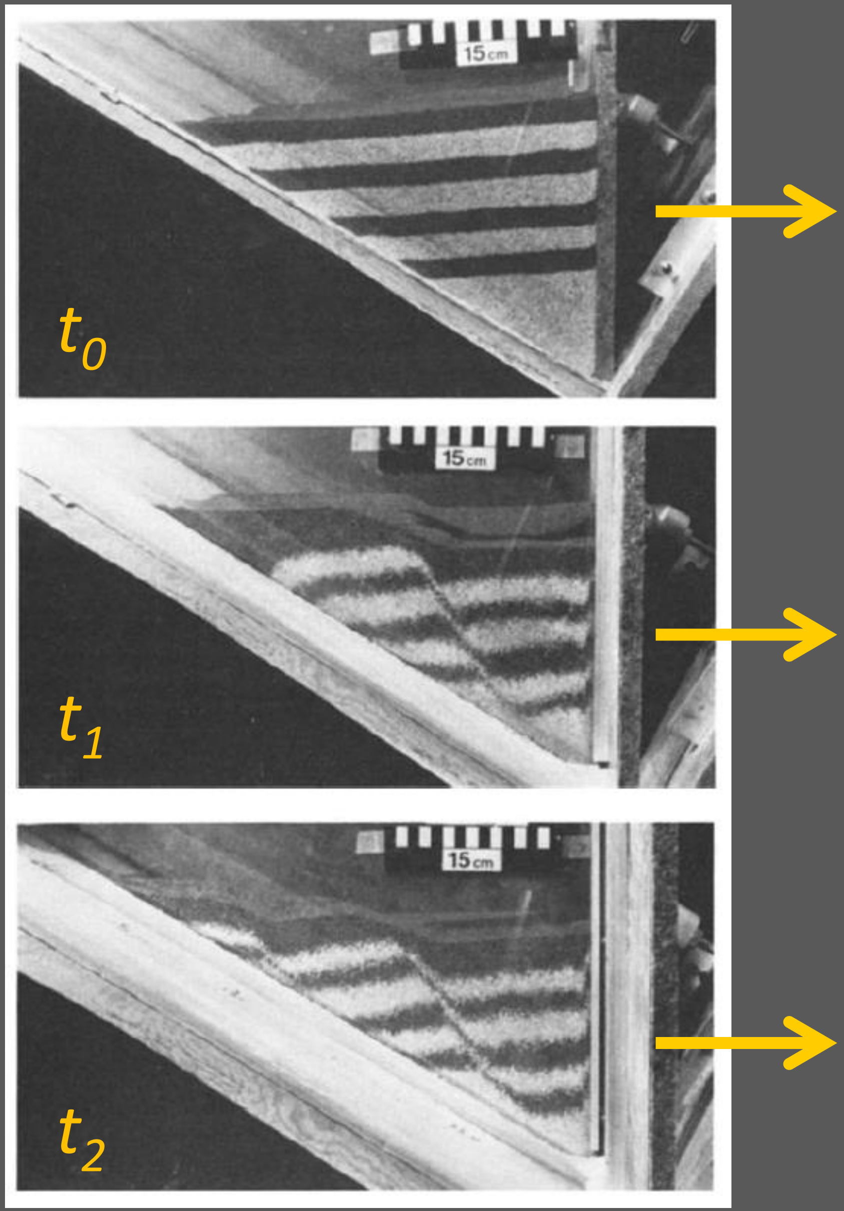
$-\alpha$ *increases*
β *constant*

Faulting until stable configuration



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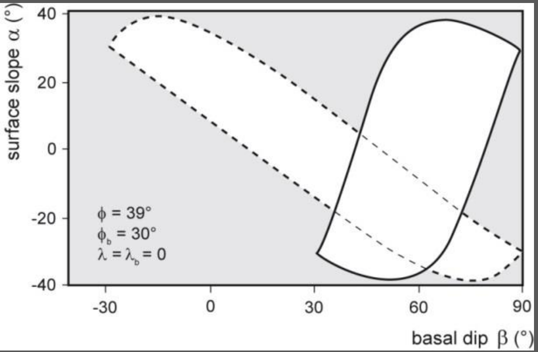
Extensional wedges



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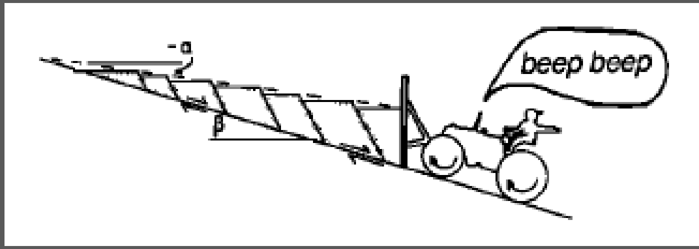
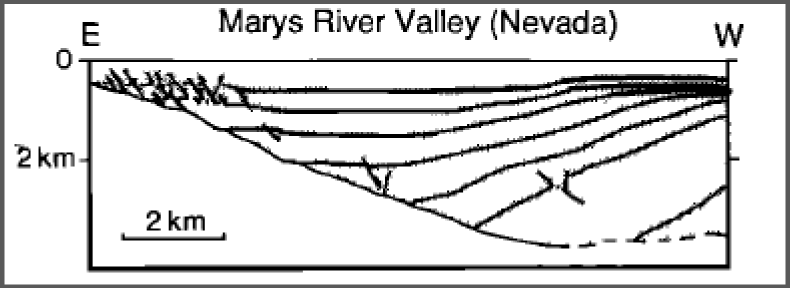
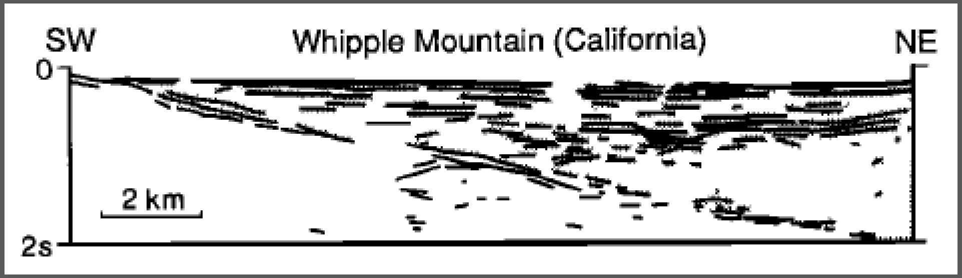
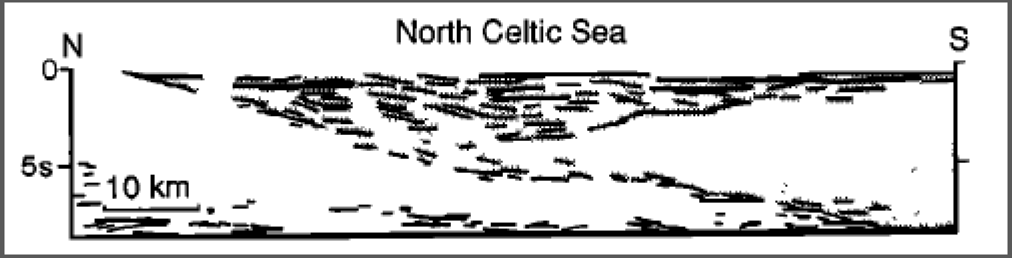
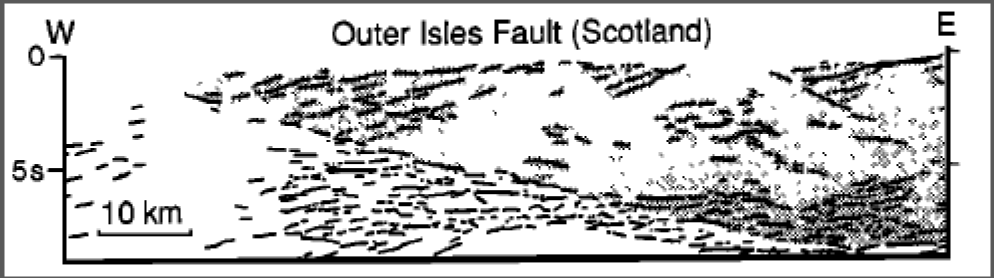


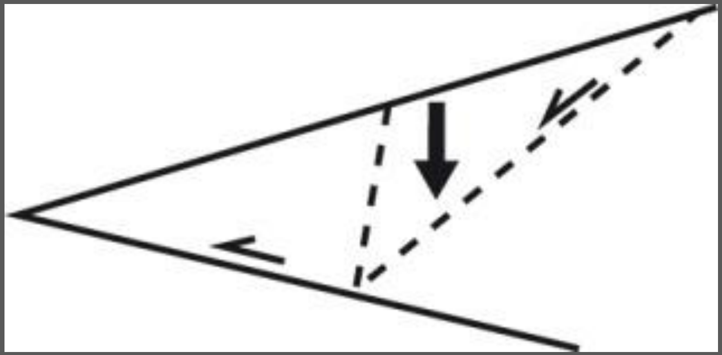








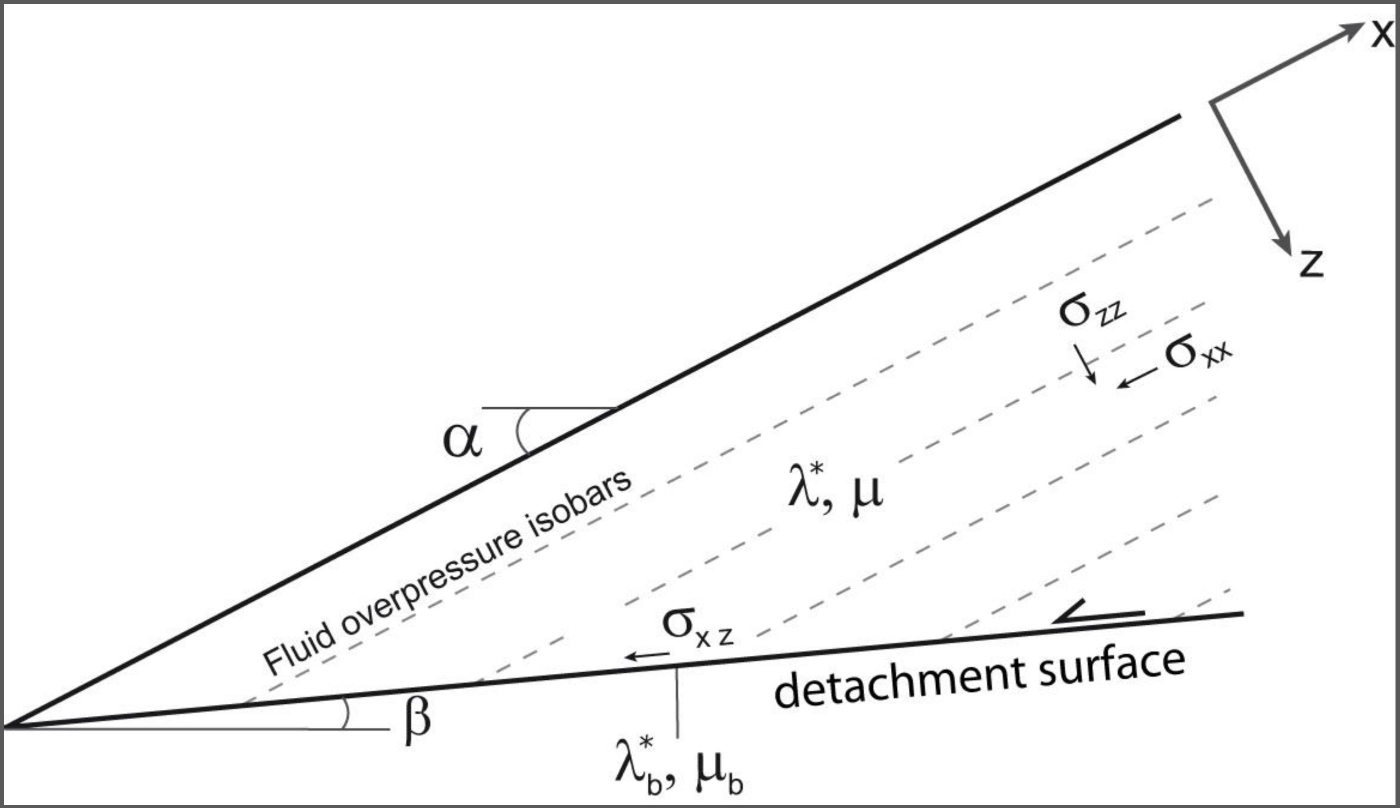
What if there is no external force (other than gravity)?



- Gravitational spreading

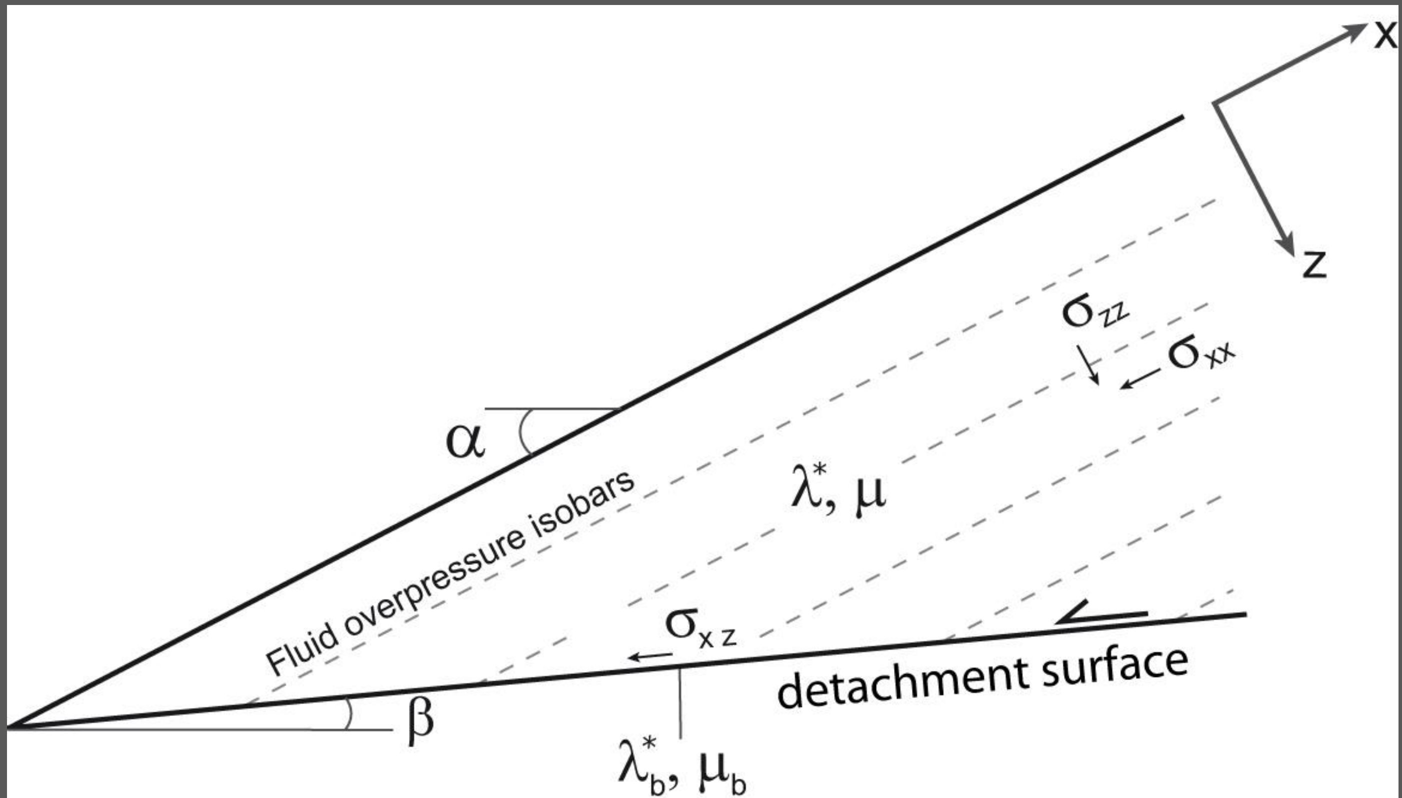
- Basal shear stress towards the thinner part

2. The theory adapted to gravitational instabilities



- Noncohesive material on the verge of failure

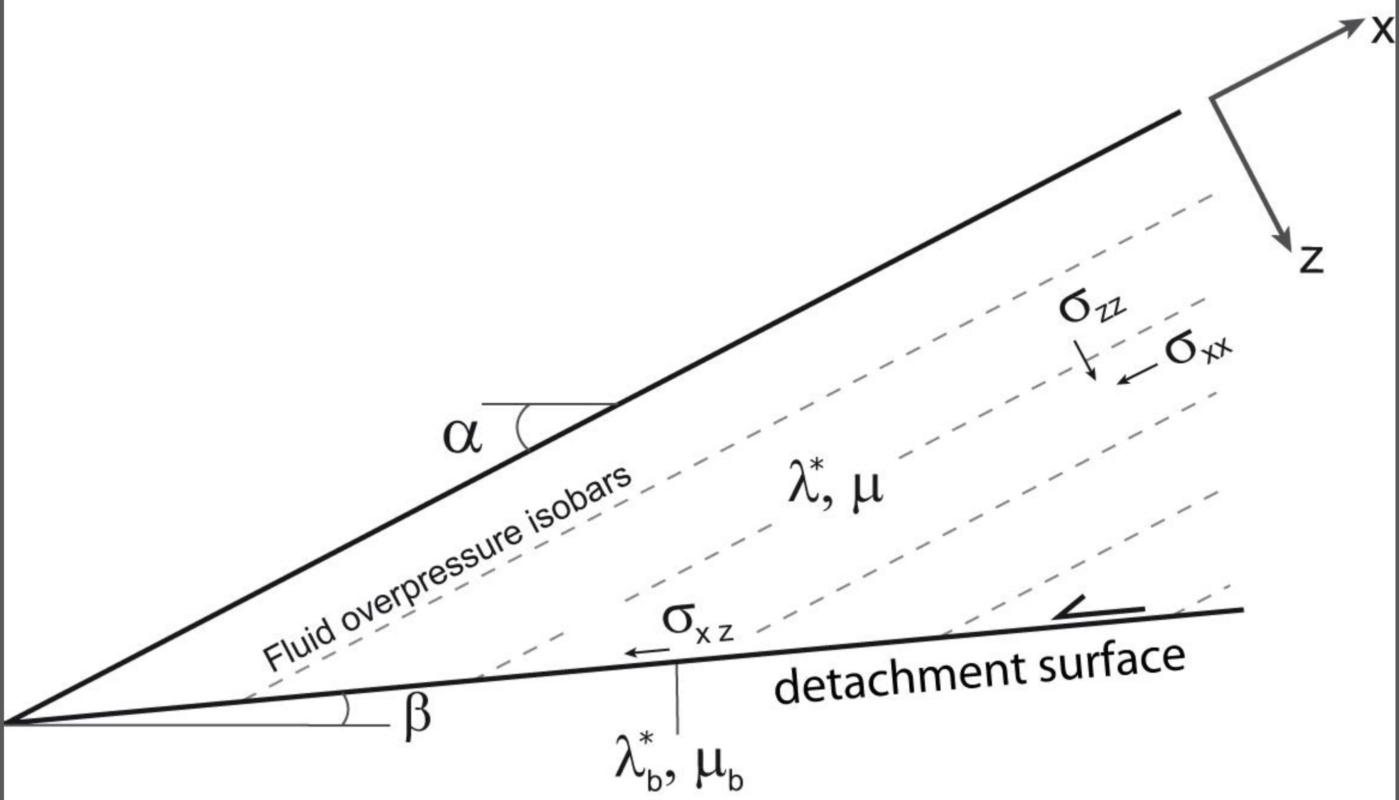
2. The theory adapted to gravitational instabilities



- Noncohesive material on the verge of failure

- System subjected to pore-fluid pressure

2. The theory adapted to gravitational instabilities



- Noncohesive material on the verge of failure

- System subjected to pore-fluid pressure

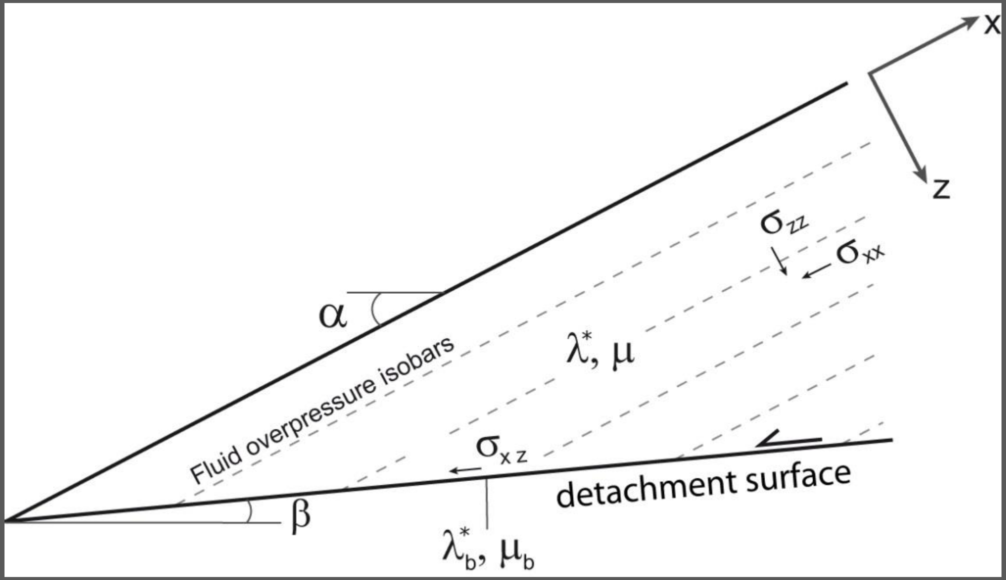
- No downslope buttress

2. The theory adapted to gravitational instabilities

A part of the total stresses is supported by the fluid

→ *Effective stresses*

$$\sigma' = \sigma - P_f$$

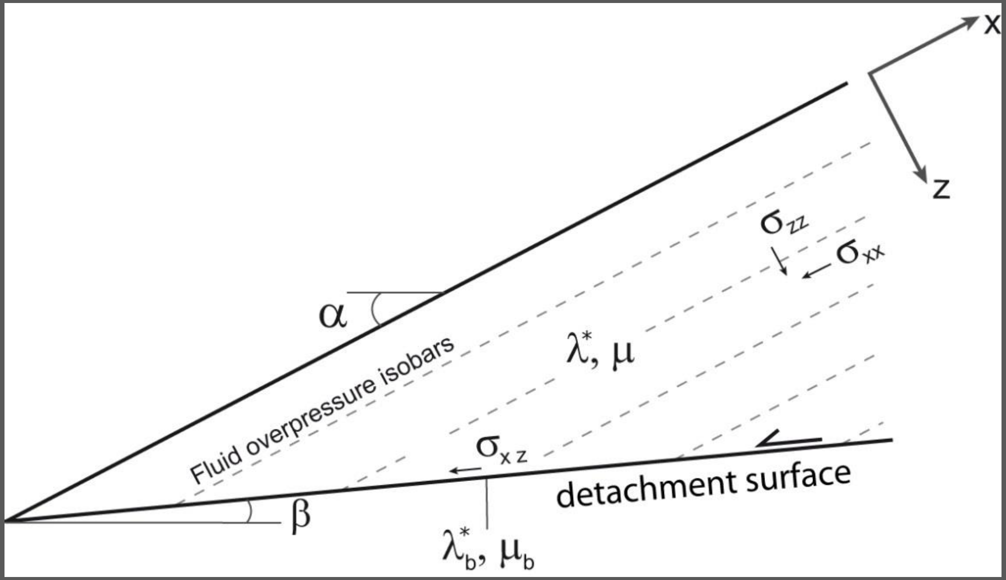


2. The theory adapted to gravitational instabilities

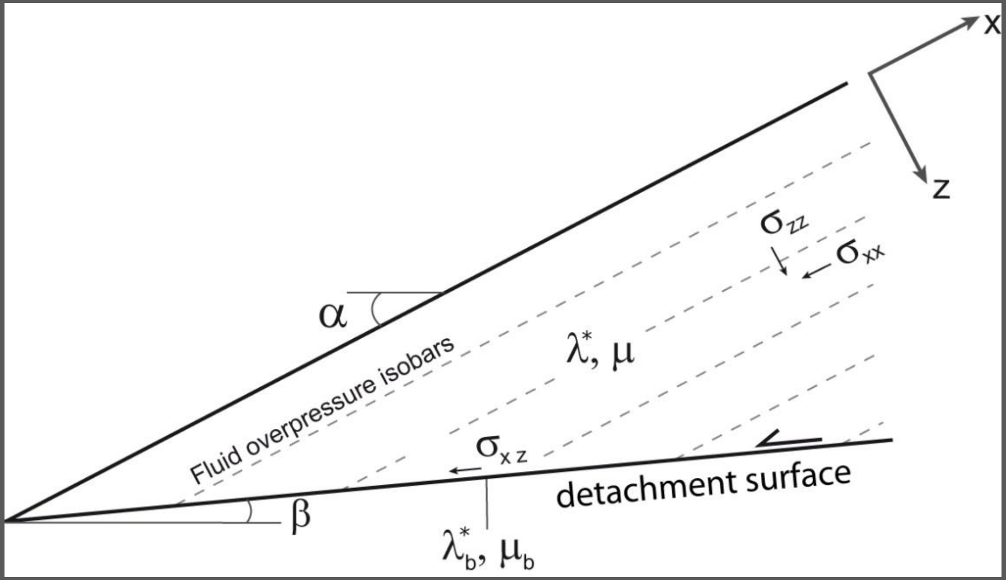
Equations of equilibrium:

$$\sigma'_{zz} = (1-\lambda^*)\rho g z \cos\alpha$$

$$\sigma'_{xz} = \rho g z \sin\alpha$$



2. The theory adapted to gravitational instabilities



Equations of equilibrium:

$$\sigma'_{zz} = (1-\lambda^*)\rho g z \cos\alpha$$

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Fluid overpressure ratio: $\lambda^* = P_{ov}/\rho g z \cos\alpha$

2. The theory adapted to gravitational instabilities

<u>*Equations of equilibrium:*</u>

$$\sigma'_{zz} = (1-\lambda^*)\rho g z \cos\alpha$$

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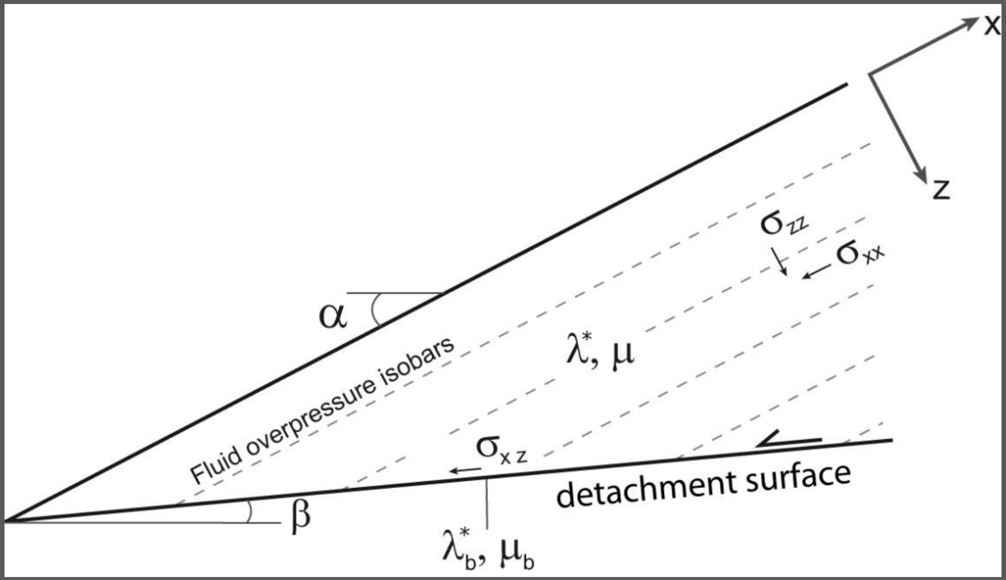
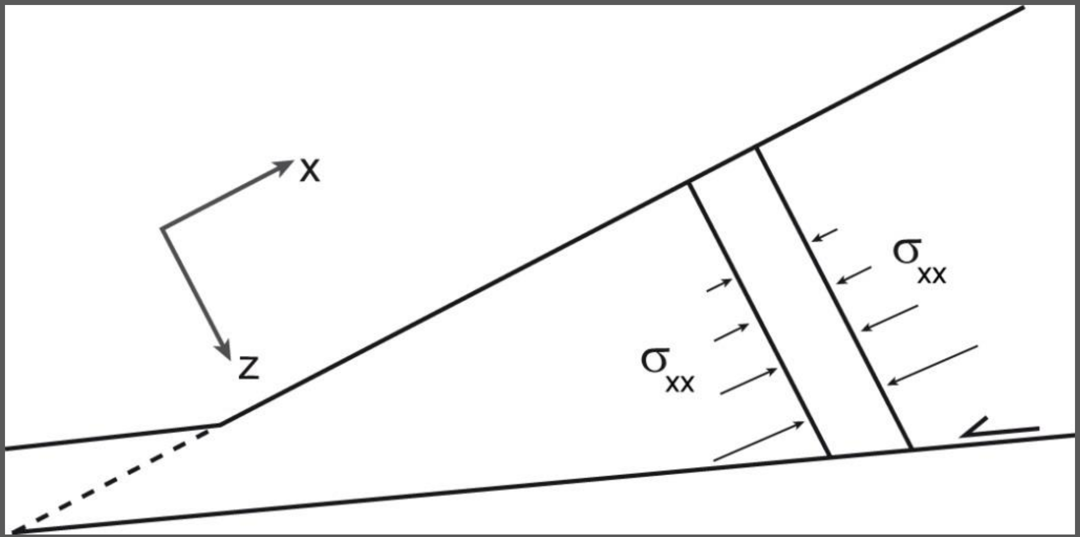


<u>*Fluid overpressure ratio:*</u> $\lambda^* = P_{ov}/\rho g z \cos\alpha$

$\lambda^* = 0$ in hydrostatic equilibrium

2. The theory adapted to gravitational instabilities

Expression of σ'$_{xx}$:

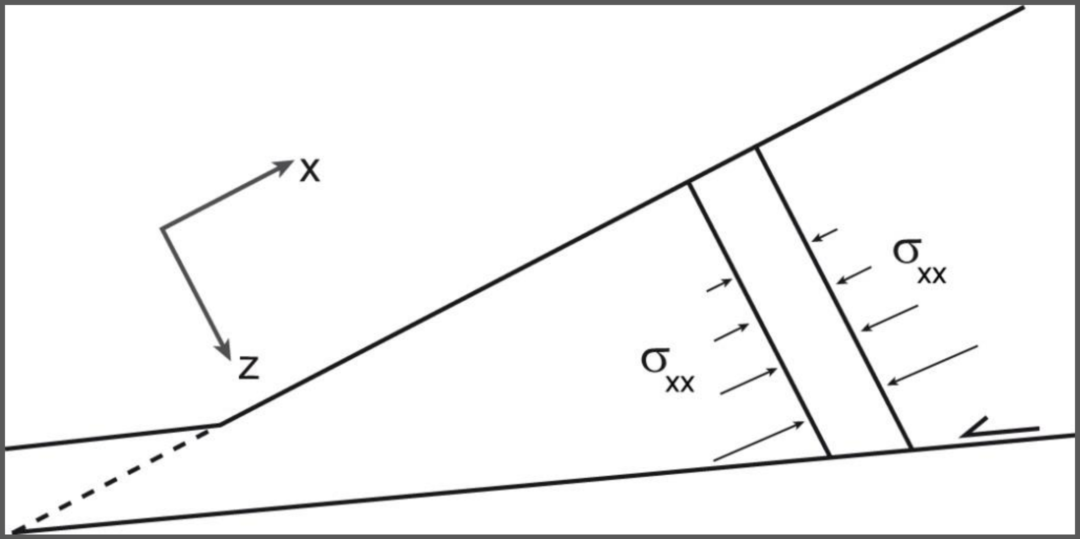


2 values of σ'$_{xx}$

Extensional & Contractional states of stress

2. The theory adapted to gravitational instabilities

Expression of σ'_{xx} :



2 values of σ'_{xx}

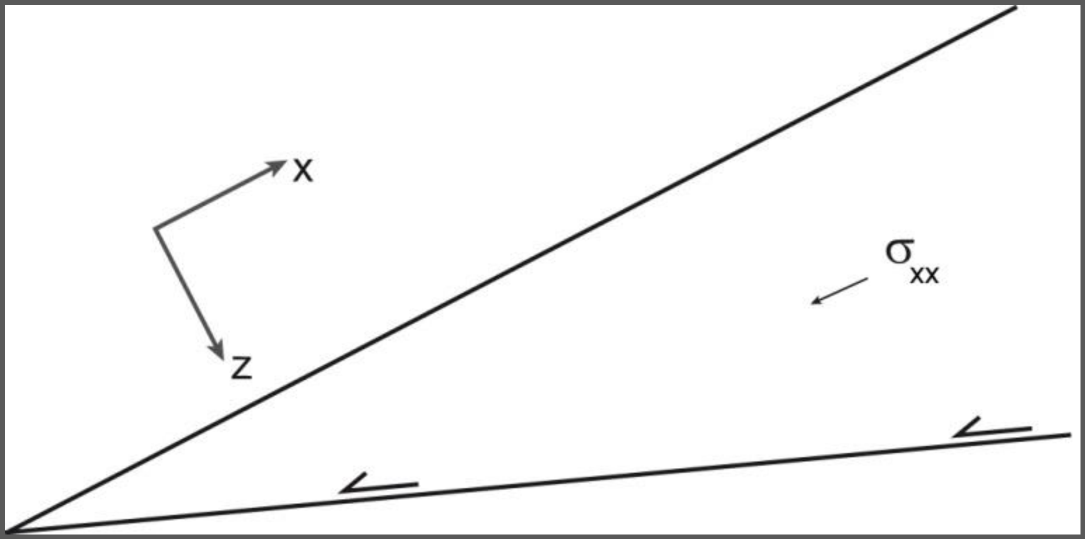
Extensional & Contractional states of stress

Rankine states of equilibrium

2. The theory adapted to gravitational instabilities

Expression of σ'_{xx} :

Without downslope resistance

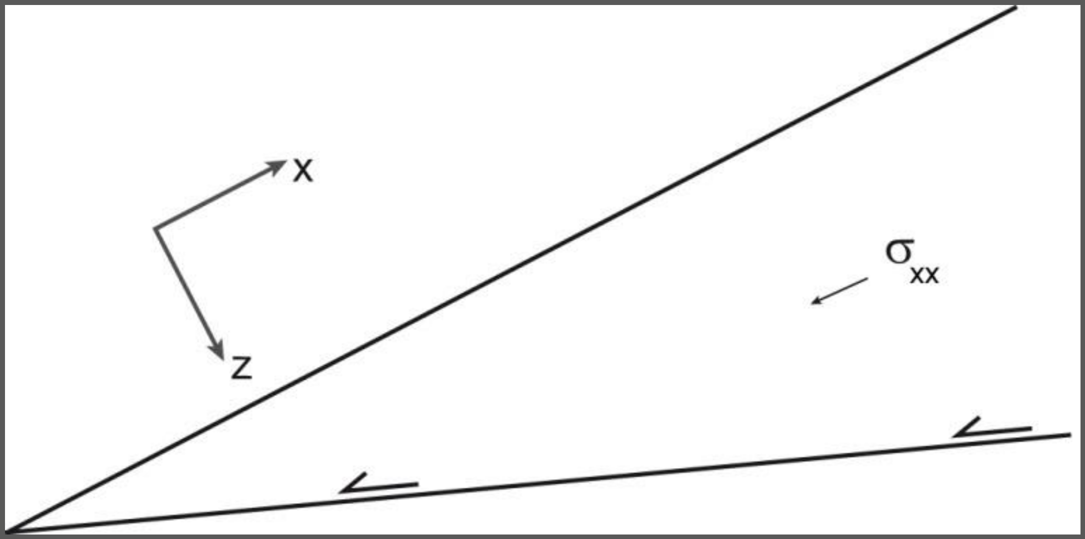


Only extensional state of stress within the wedge

2. The theory adapted to gravitational instabilities

Expression of σ'$_{xx}$:

Without downslope resistance



Only extensional state of stress within the wedge

$$\sigma'_{xx} = (2Y-1)\sigma'_{zz}$$

$$\text{with } Y = \frac{1 - \sin\sqrt{1 - FS^2}}{\cos^2 \phi}$$

2. The theory adapted to gravitational instabilities

The factor of safety FS:

$$\mathrm{FS} = \frac{\tan\alpha}{(1-\lambda^{*})\tan\phi}$$

2. The theory adapted to gravitational instabilities

The factor of safety FS:

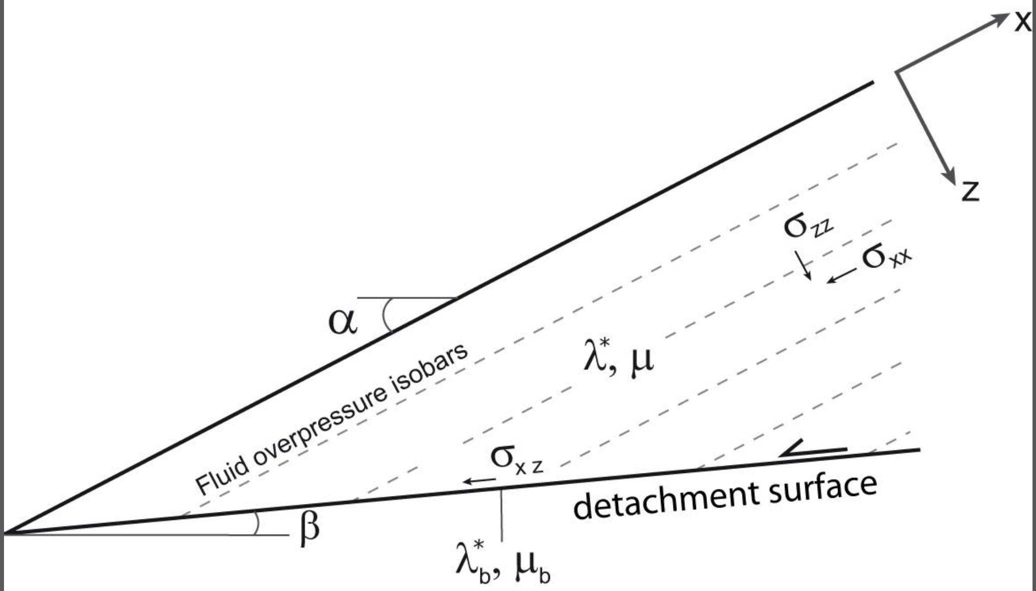
$$FS = \frac{\tan \alpha}{(1 - \lambda^{*}) \tan \phi}$$

- Corrected from the fluid overpressure

- FS>1: unstable slope, shallow landsliding

2. The theory adapted to gravitational instabilities

The effective basal friction μ'_b:



Sliding = low friction on the basal detachment:

$$\mu_b(1-\lambda^*_b) < \mu(1-\lambda^*)$$

2. The theory adapted to gravitational instabilities

The effective basal friction μ'_b:

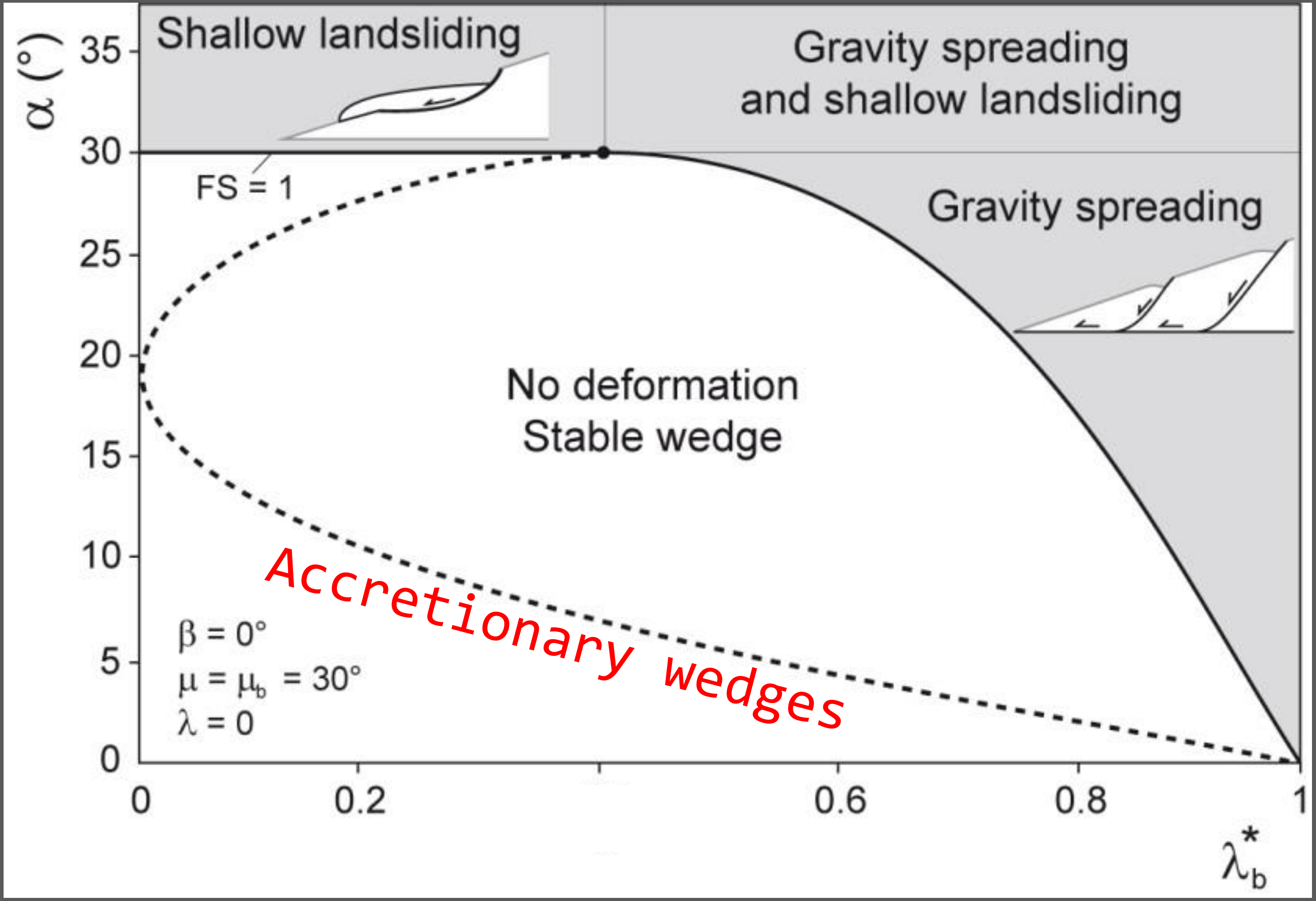
Sliding = low friction on the basal detachment:

$$\mu_b(1-\lambda^*_b) < \mu(1-\lambda^*)$$

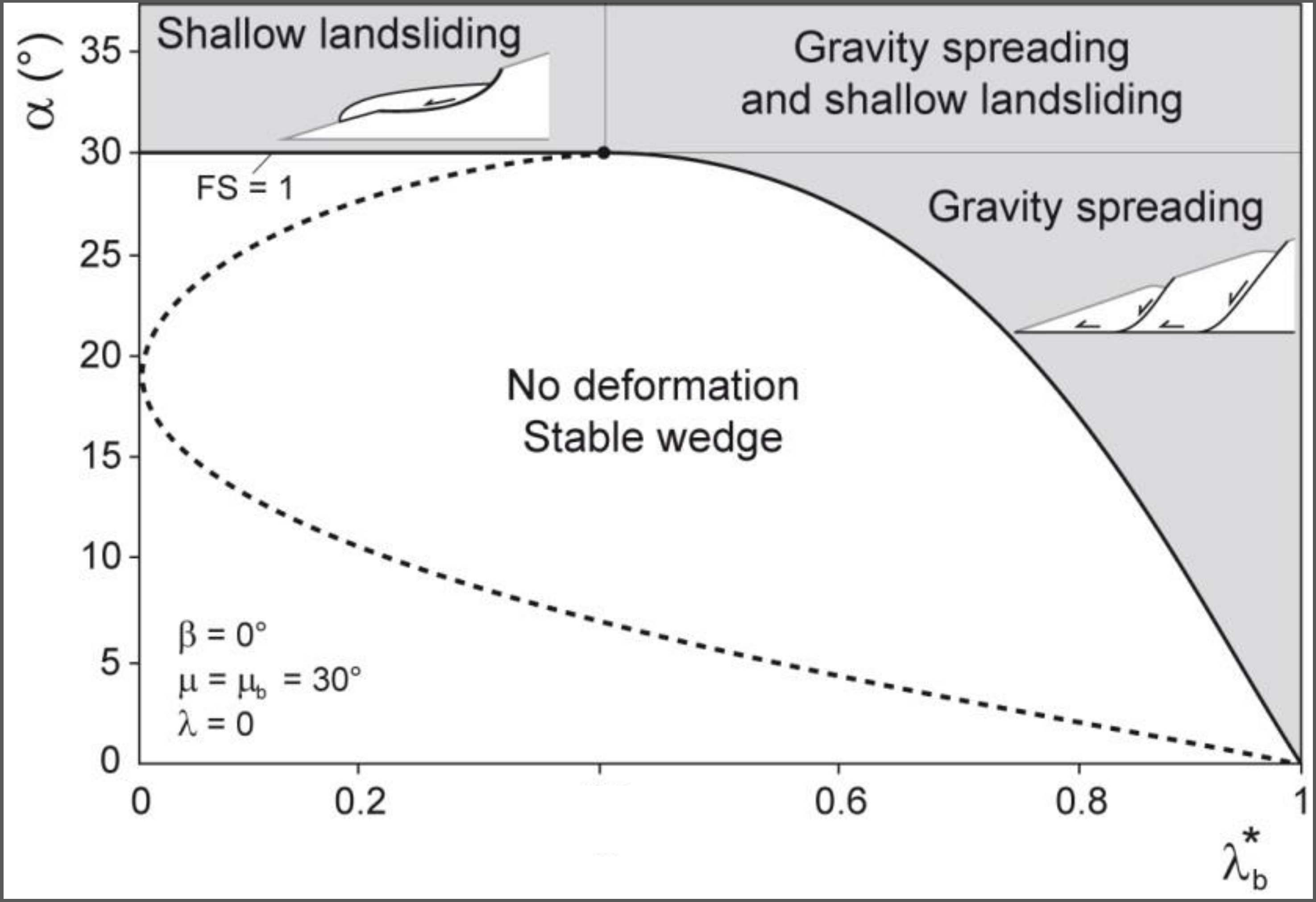
After expressing σ'_{xz} and σ'_{zz} on the detachment:

$$\lambda_b^* = 1 - (1 - \lambda^*)\frac{E_2}{\mu_b E_1}$$

2. The theory adapted to gravitational instabilities

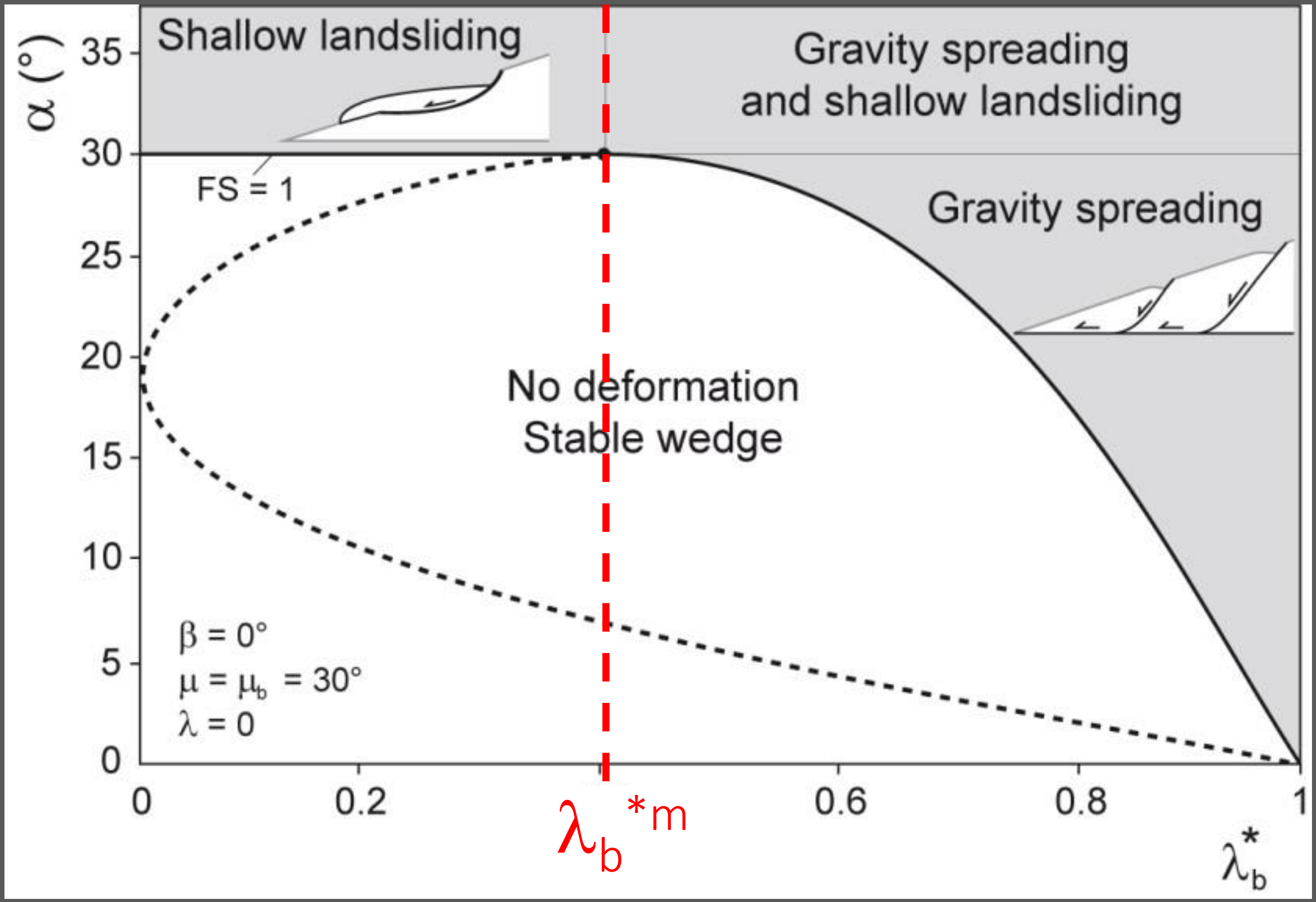


2. The theory adapted to gravitational instabilities



System subjected to gravity only: 3 domains

2. The theory adapted to gravitational instabilities



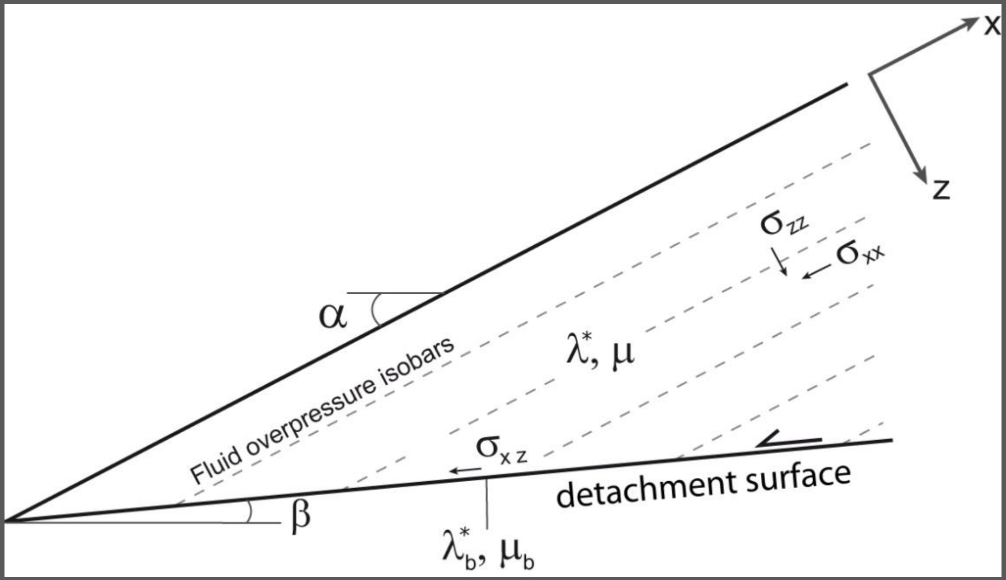
System subjected to gravity only: 3 domains

2. The theory adapted to gravitational instabilities

Alternative expression of μ'_b:

Dahlen's definition:

$$\mu'_b = \mu_b \frac{1-\lambda_b}{1-\lambda}$$



2. The theory adapted to gravitational instabilities

<u>*Alternative expression of μ'_b:*</u>

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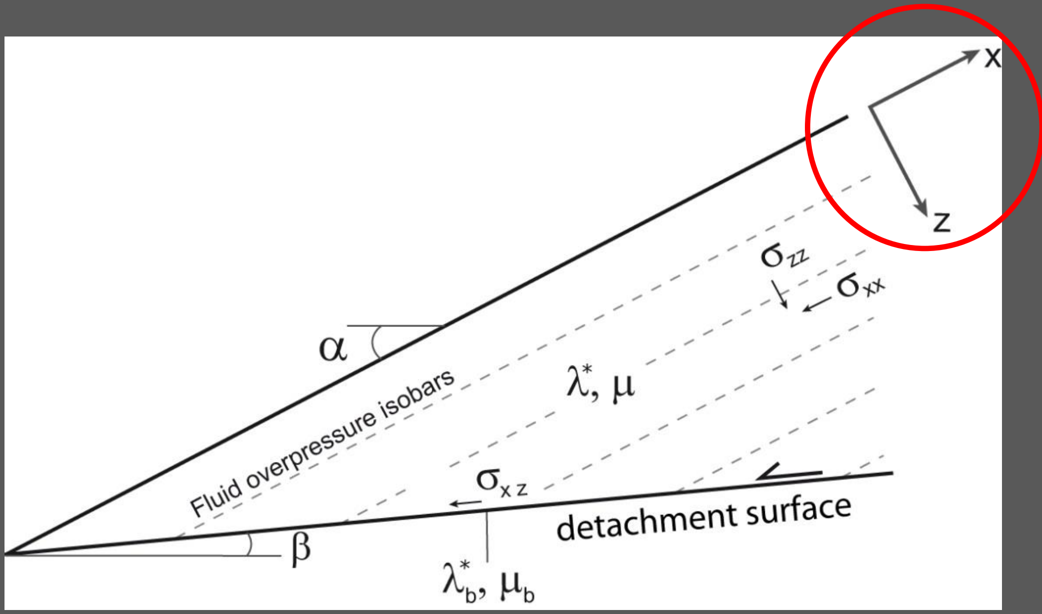


xz coordinate system (surface)

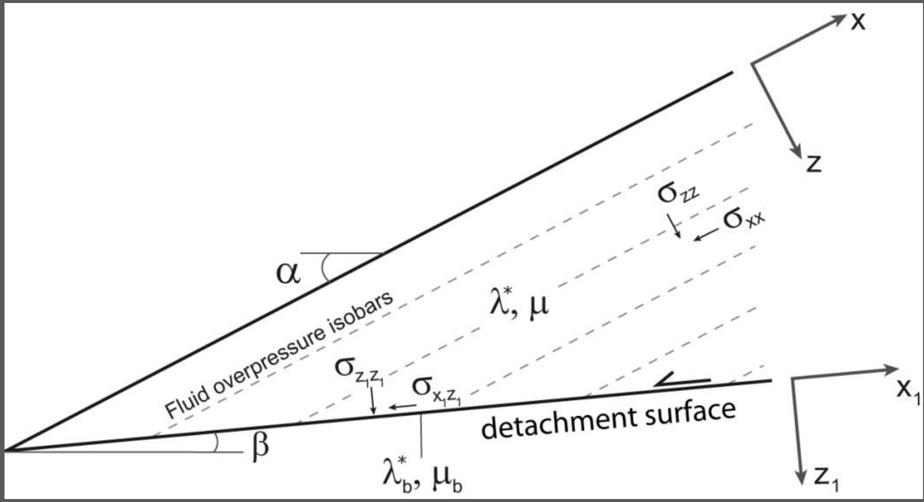
σ_{zz} independent of λ

2. The theory adapted to gravitational instabilities

Alternative expression of μ'_b:

Dahlen’s definition:

xz coordinate system
σ_{zz} independent of λ



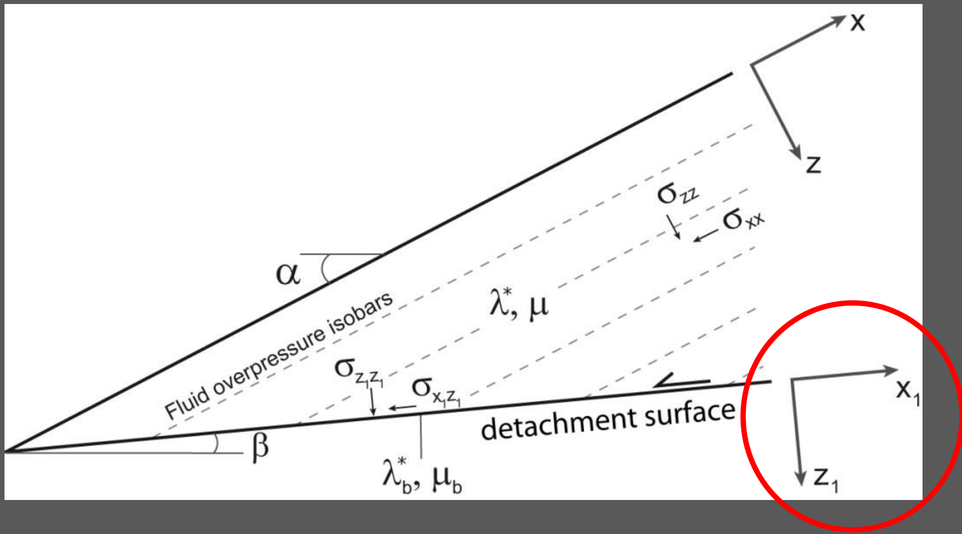
But *μ'_b dependent on $\sigma'_{z_1z_1}$* (varying with λ)

2. The theory adapted to gravitational instabilities

Alternate expression of μ'_b:

Dahlen's definition:

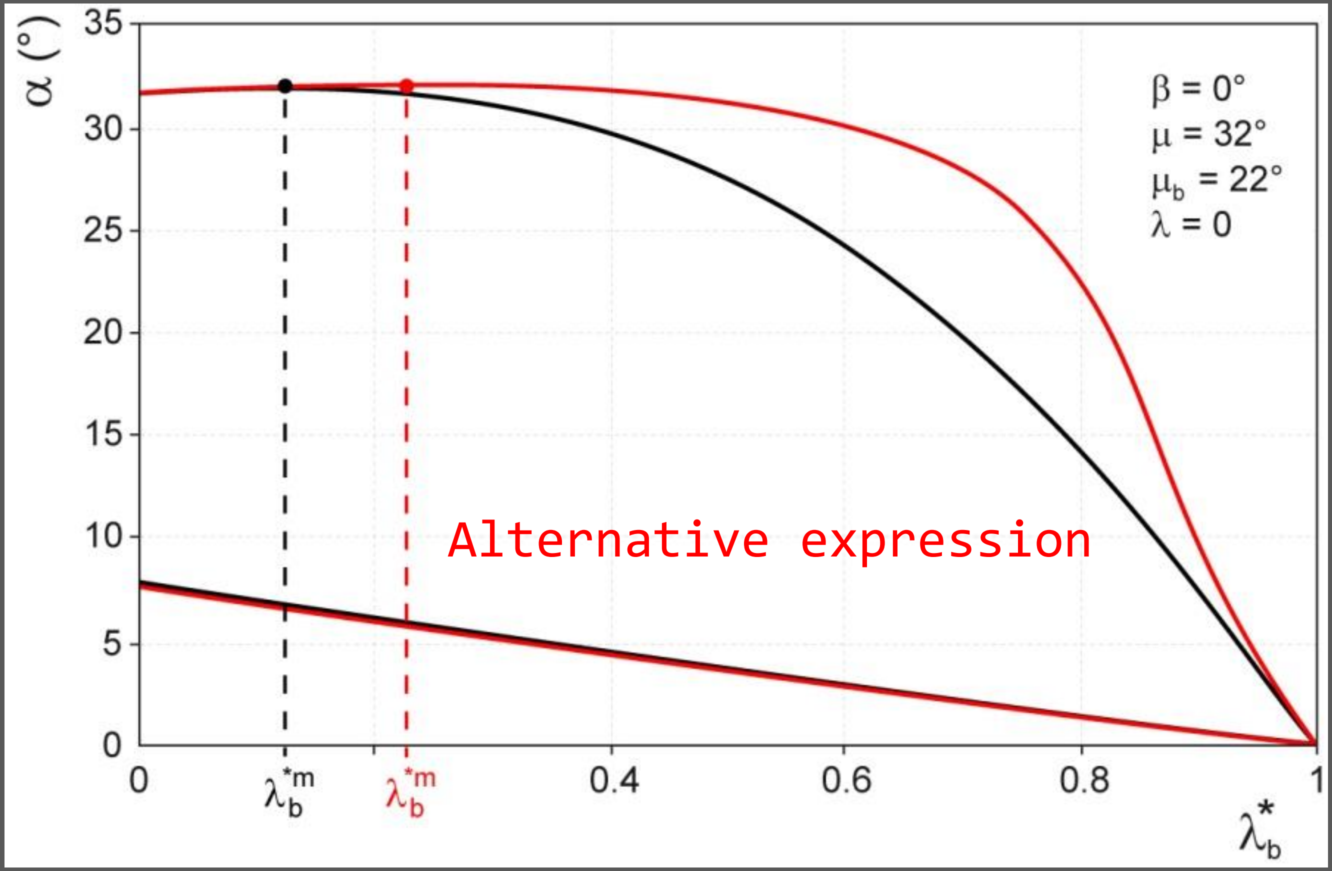
xz coordinate system
σ_{zz} independent of λ



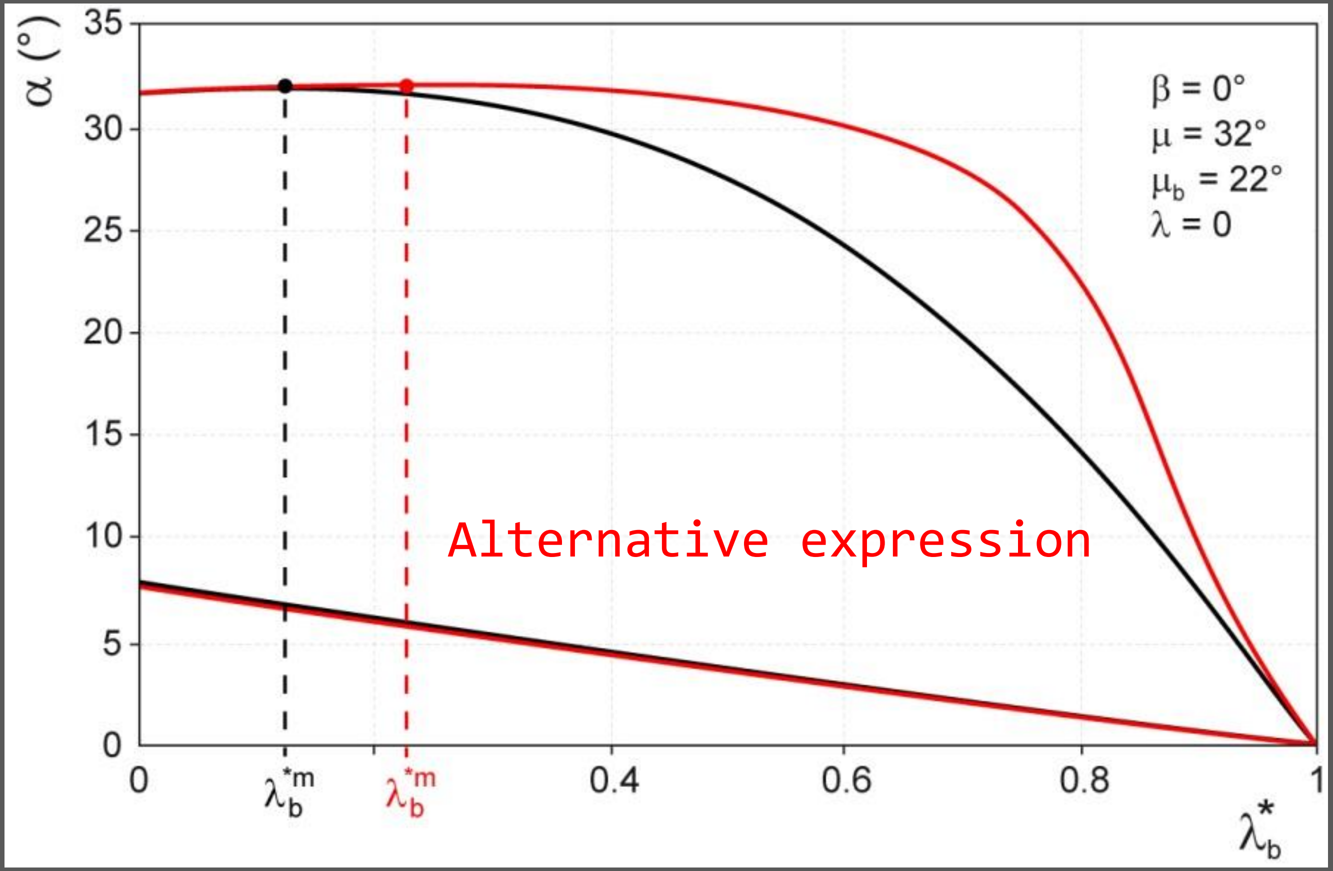
But *μ'_b dependent on $\sigma'_{z'z'}$* (varying with λ)
↓
Definition in the x'z' coordinate system (detachment)

$$\lambda_b^* = E_1 + \lambda^* - \frac{E_2}{\mu_b}$$

2. The theory adapted to gravitational instabilities



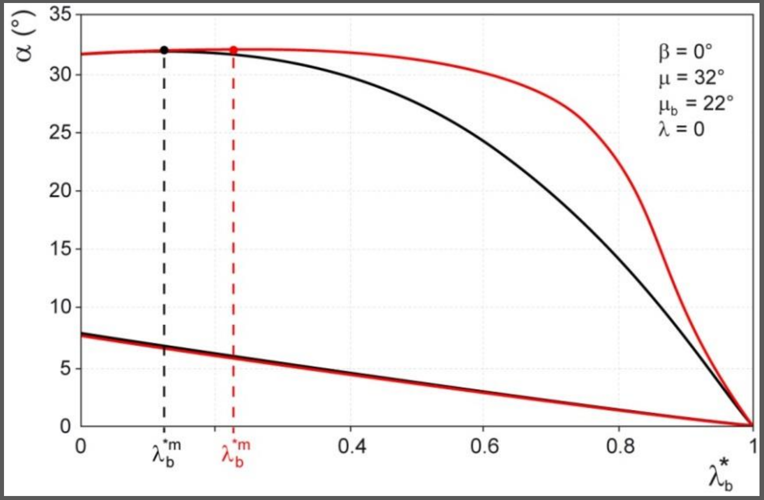
2. The theory adapted to gravitational instabilities



- Negligible differences for compressive wedges

- Higher critical gravitational sliding limit

3. Experimental modelling



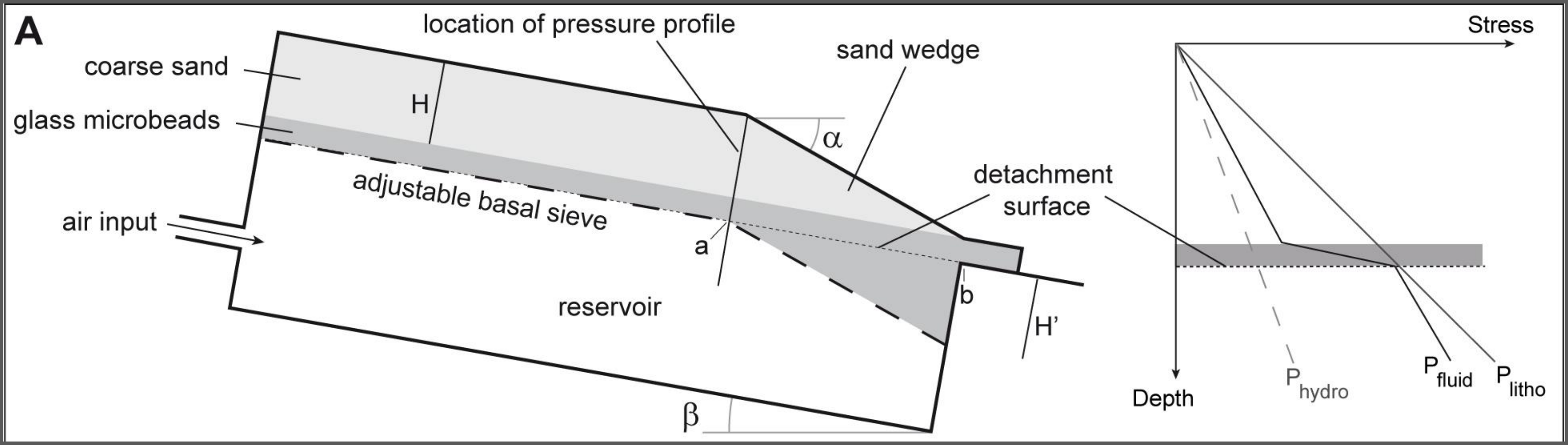
- Experimental verification of the theory

- Previous works:

    Mostly compressive settings
    Fluid pressure not taken into account

3. Experimental modelling

Experimental set-up



Material	Grain size (µm)	Bulk density (kg/m3)	Angle of internal friction (°)	Coefficient of internal friction µ	Permeability (Darcy)	Cohesion (Pa)
Coarse sand (cover)	300	1600	34	0,67	90	0
Glass microbeads (décollement)	200-300	1600	24	0,44	15	0

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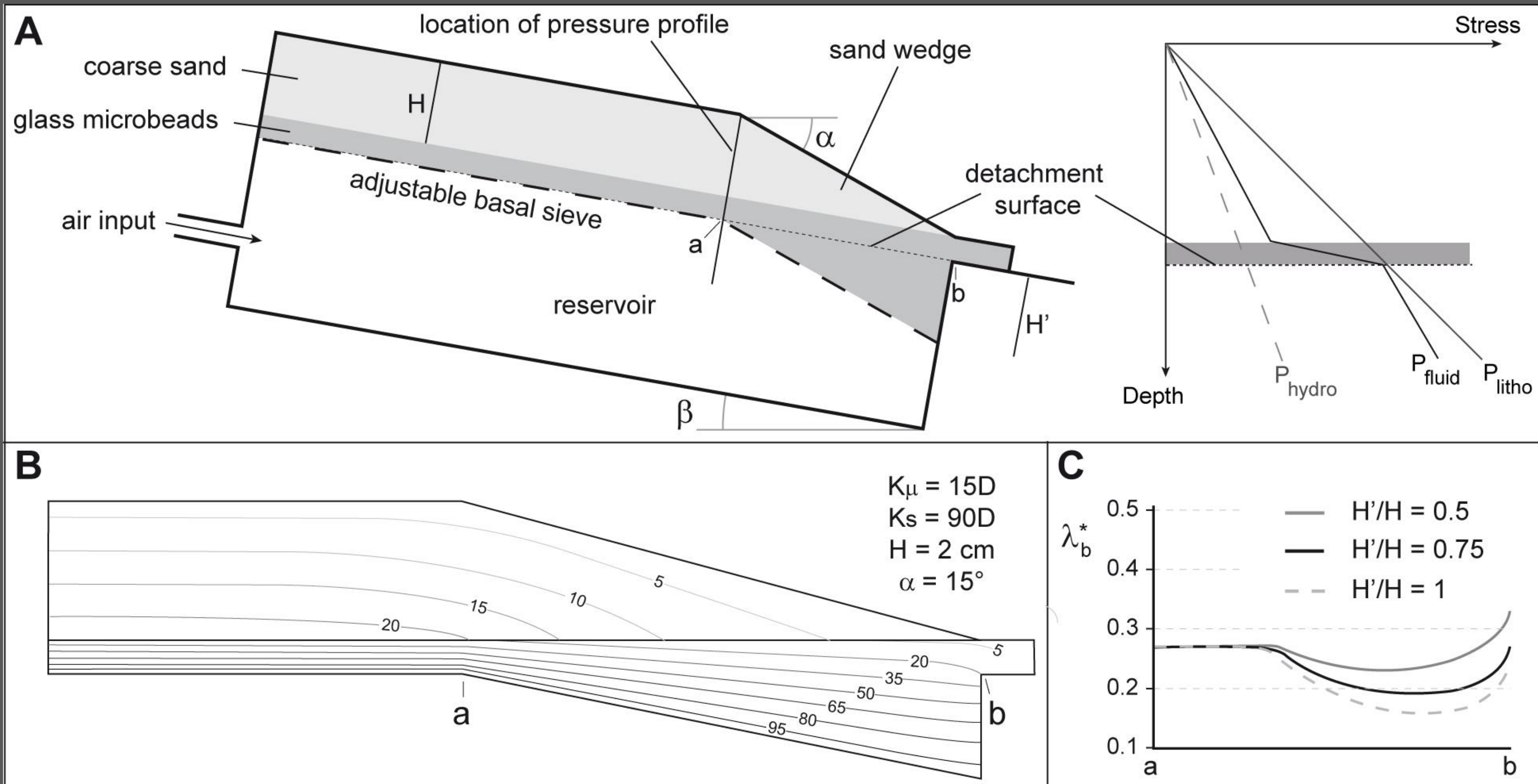

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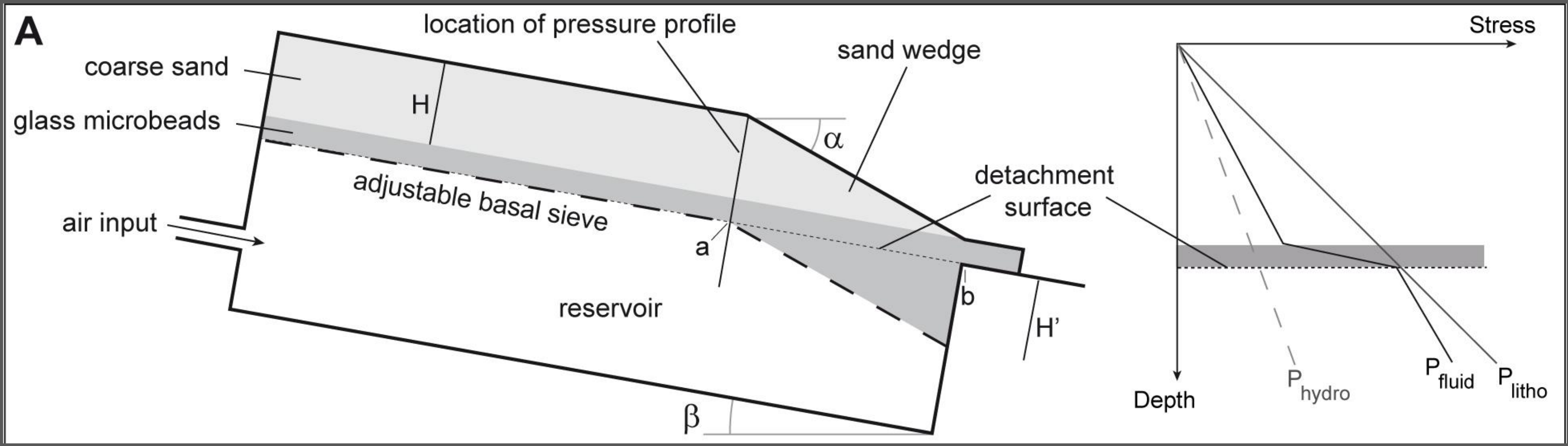


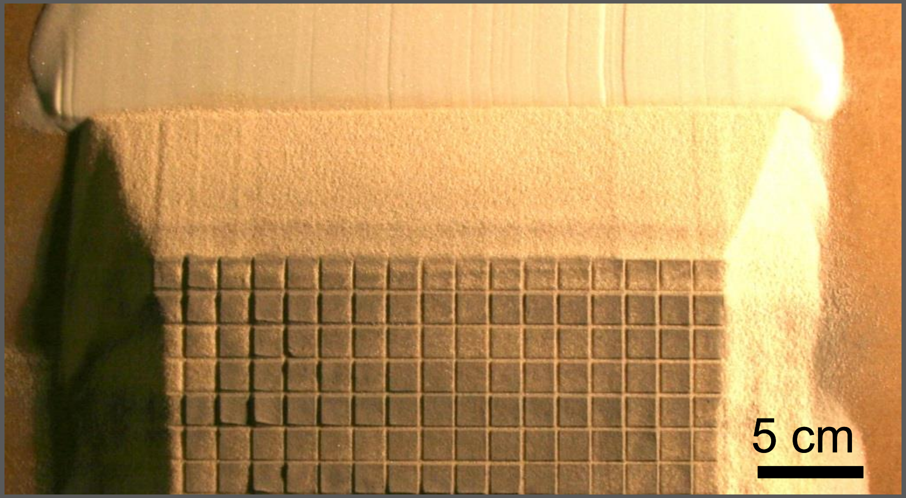
- No downslope buttress

- Adjustable basal and surface slopes

- λ^*_b constant along the detachment

3. Experimental modelling

Experimental procedure

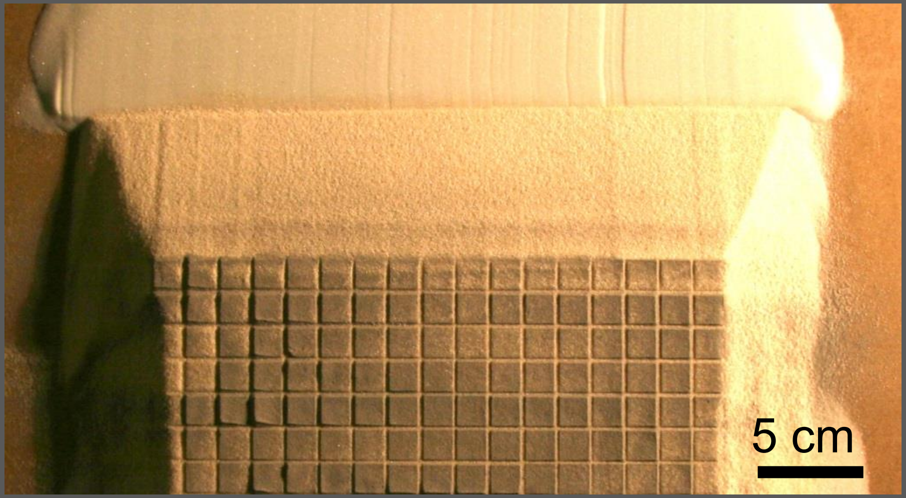


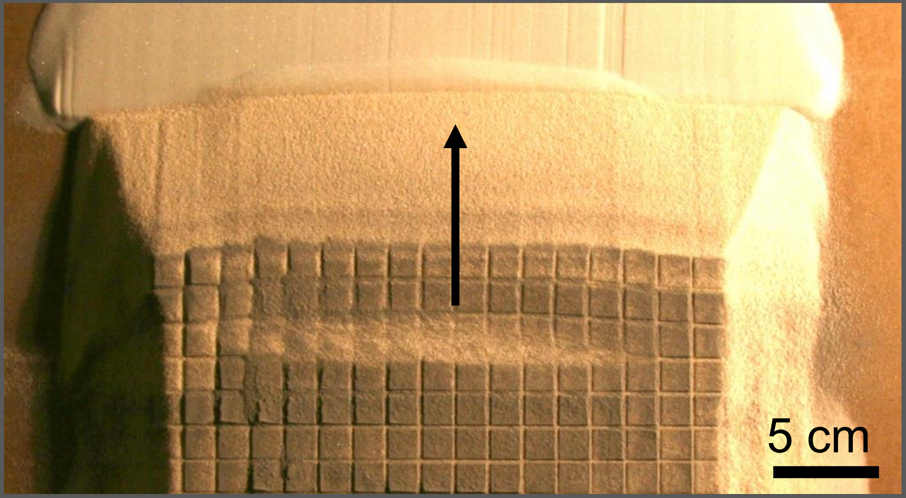
α = 15° ; β = 10°

- Increasing air pressure

3. Experimental modelling

Experimental procedure





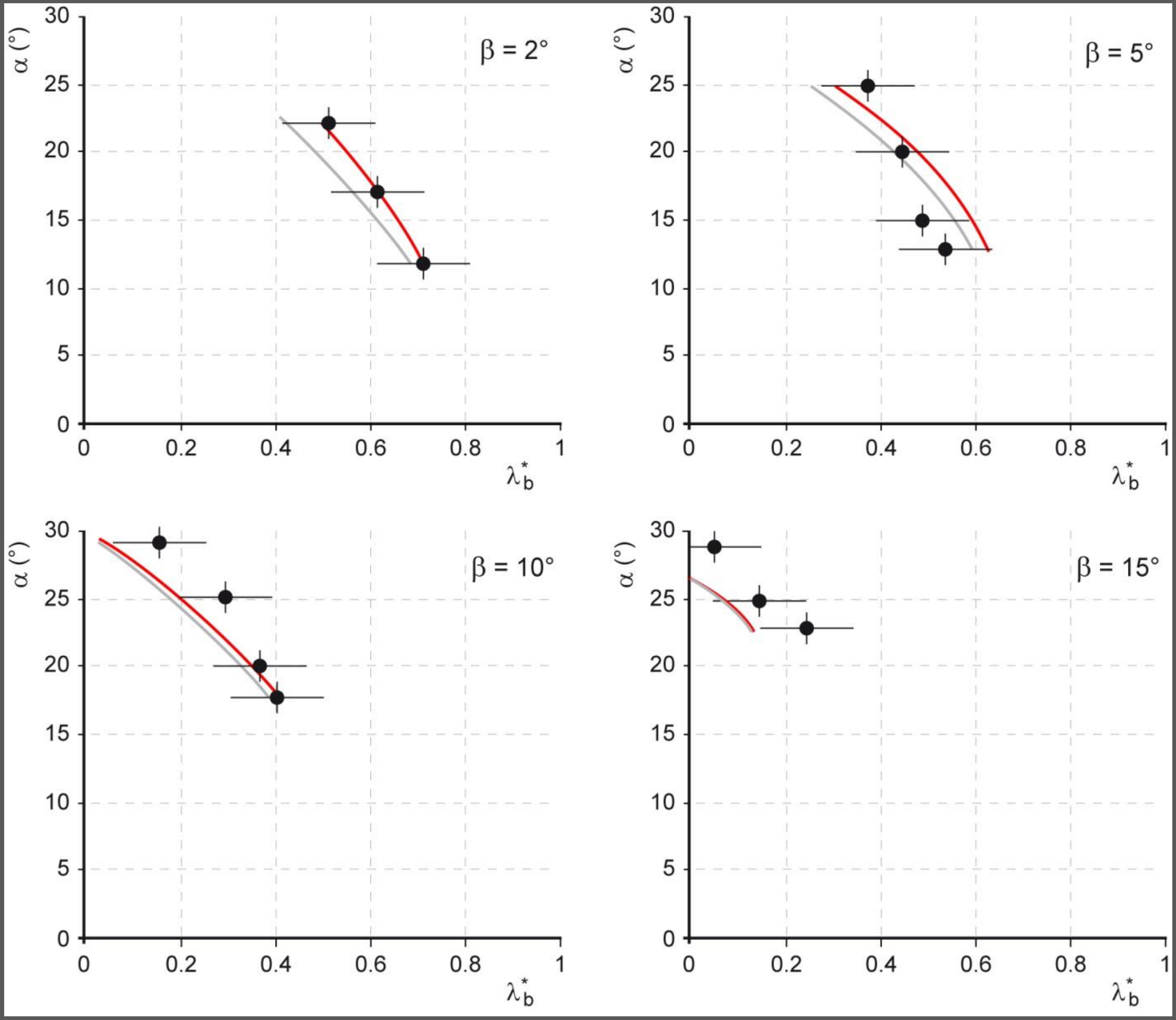
α = 15° ; β = 10°

- Increasing air pressure

- Measurements of the critical fluid pressure when sliding

3. Experimental modelling

Results



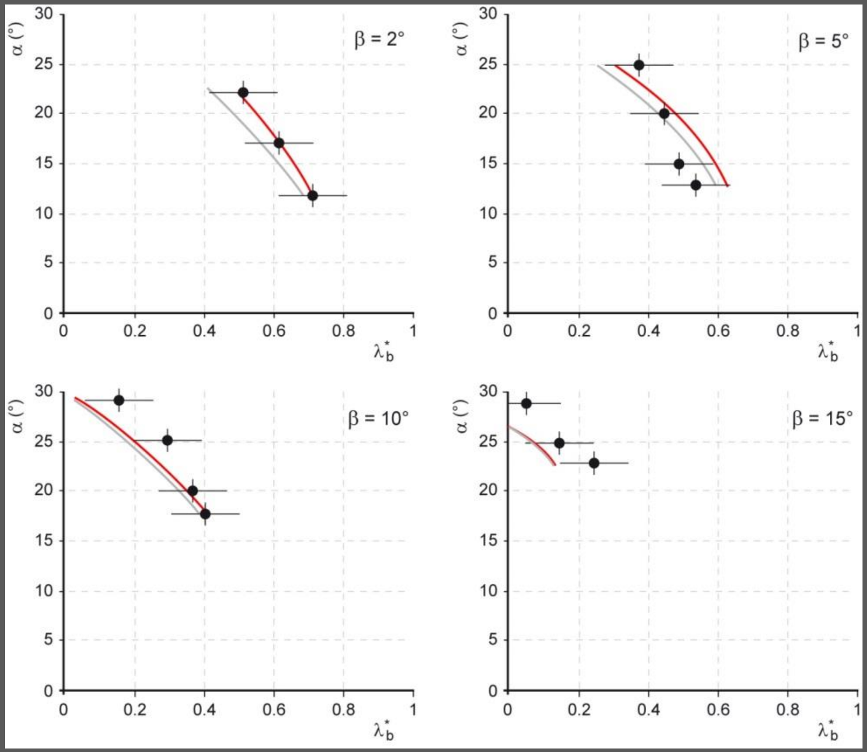
Experimental data

Model I solution

Alternative solution

4. Discussion

Good agreement between theory and experience



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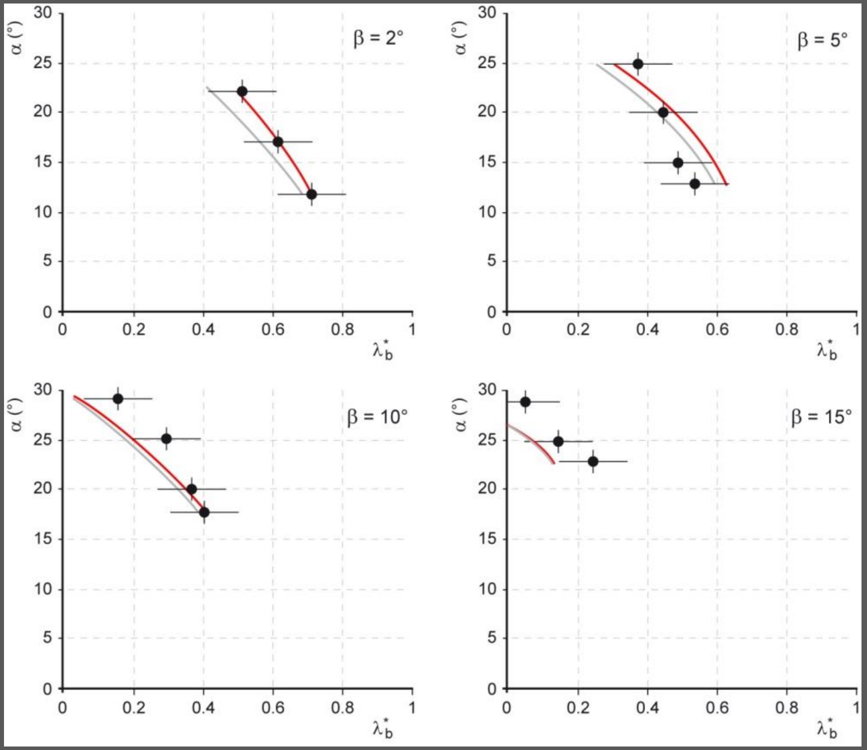
However, difficulties to discriminate (I or II?)



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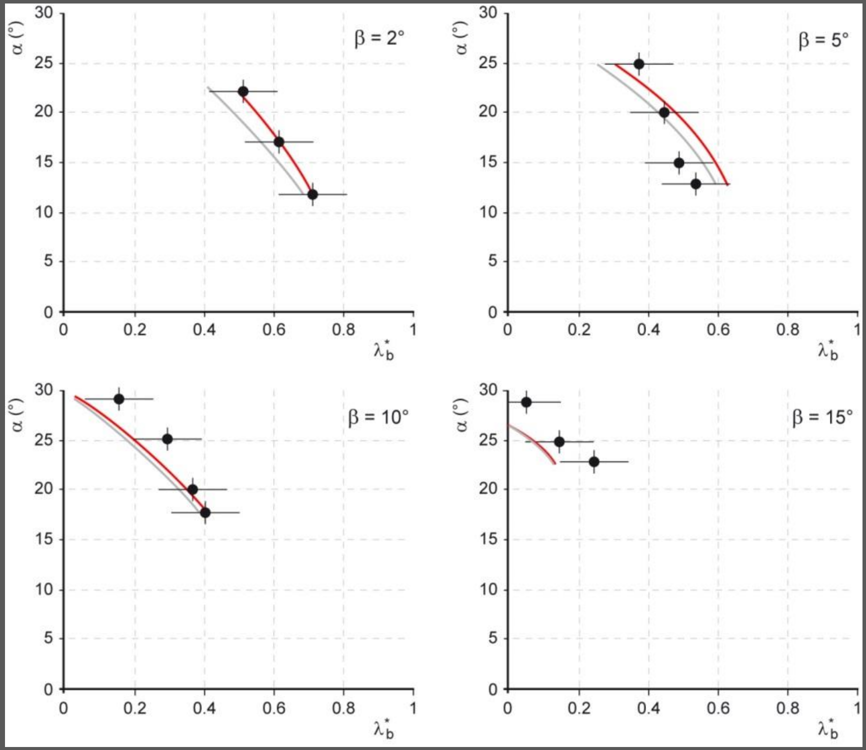

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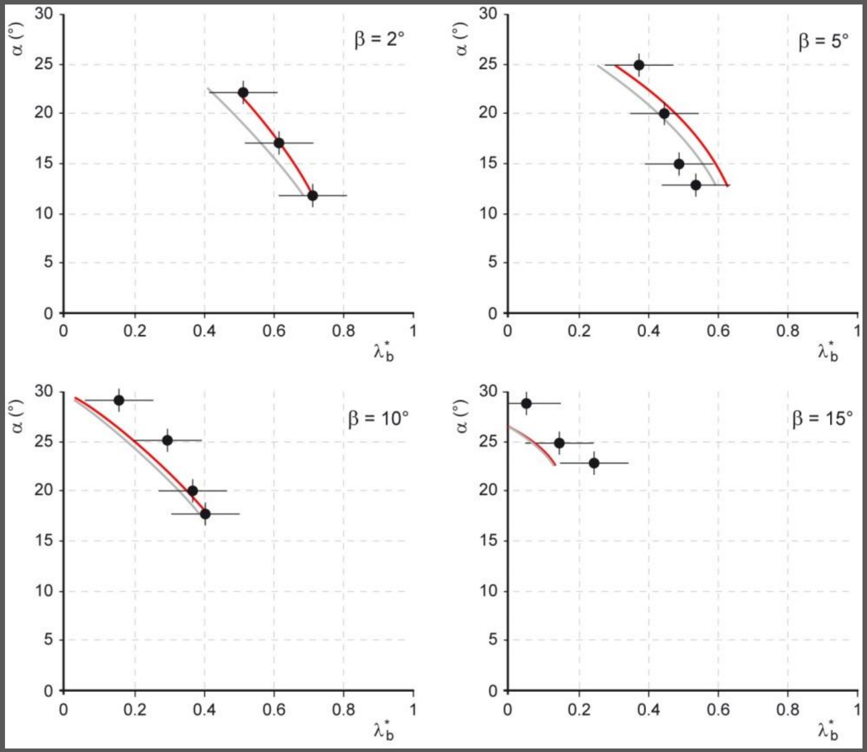

- Shape of the detachment

4. Discussion

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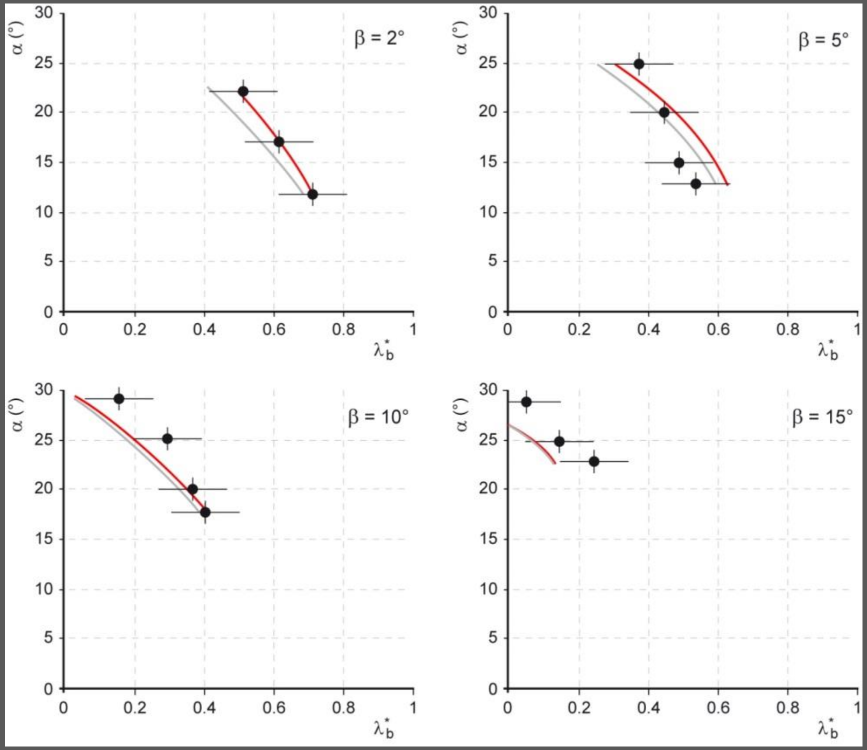

→ Experimental uncertainties:

- Shape of the detachment
- Permeabilities

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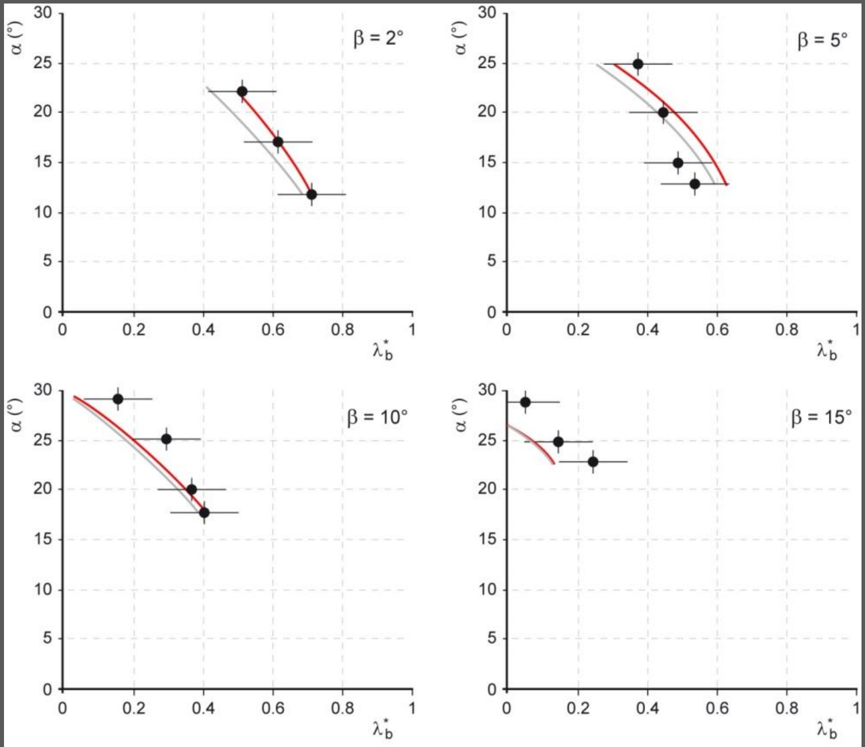

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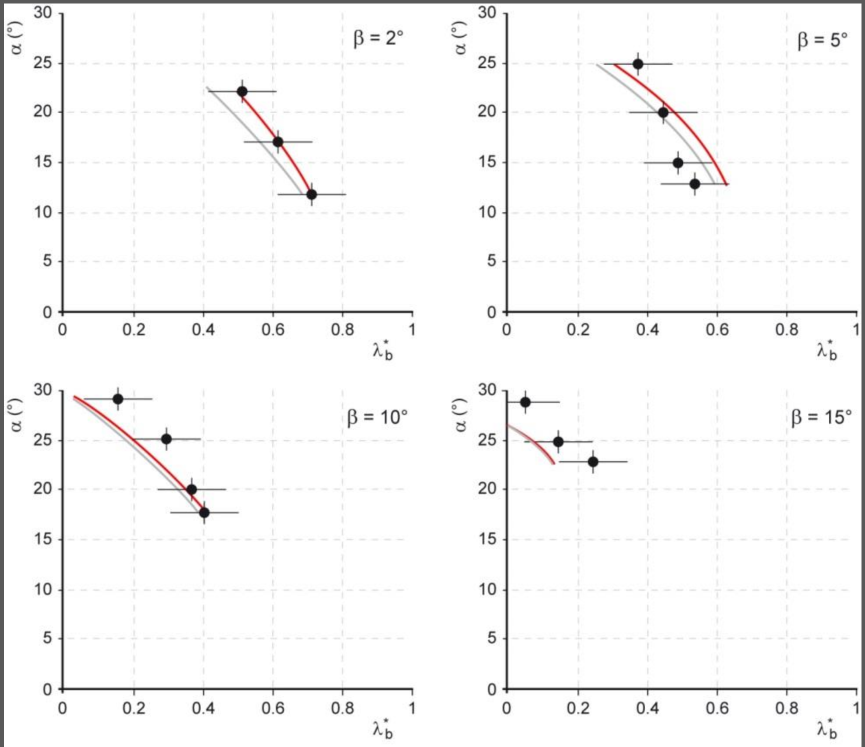

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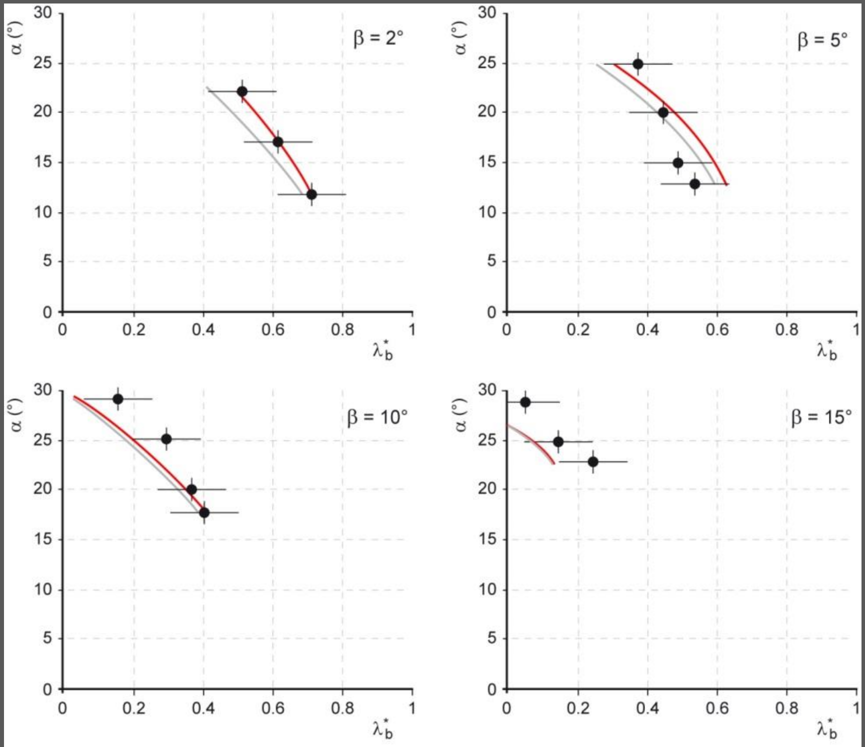

→ Experimental uncertainties:

- Shape of the detachment
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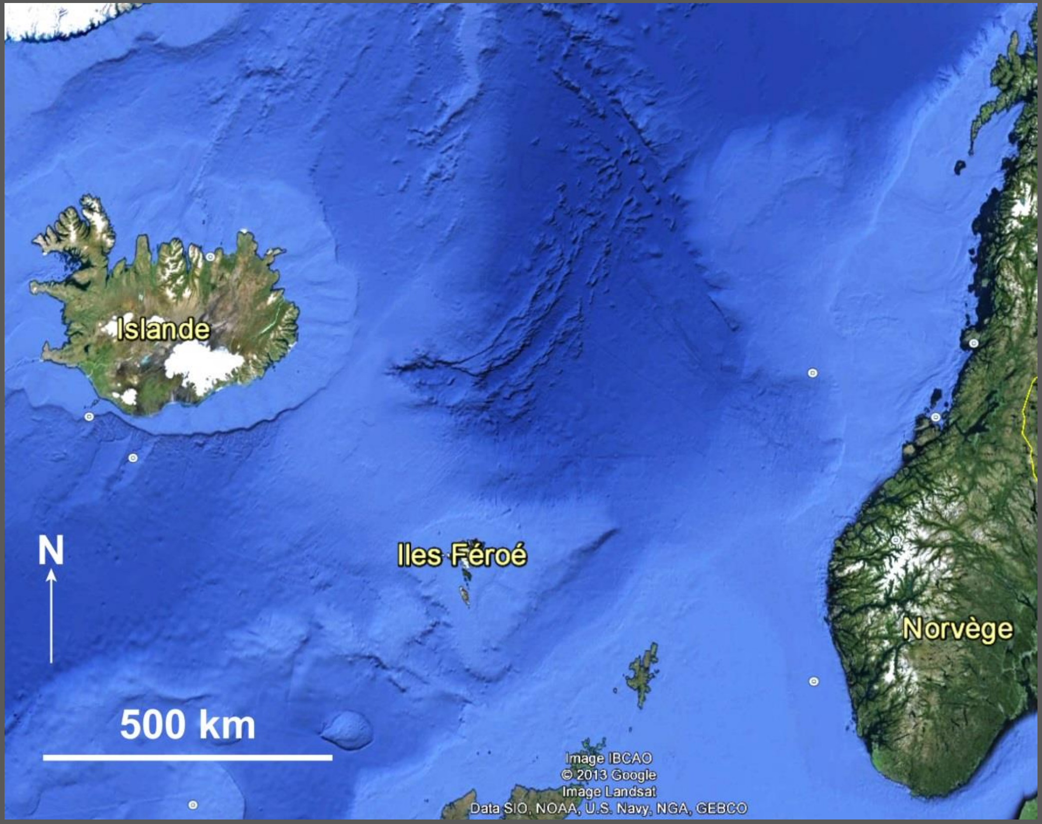
→ More models needed (low α)

5. Applicability to natural examples

- Not restricted to accretionary prisms

→ weak décollement and no downslope buttress

A- Large submarine slumping



Storegga slide, Norway

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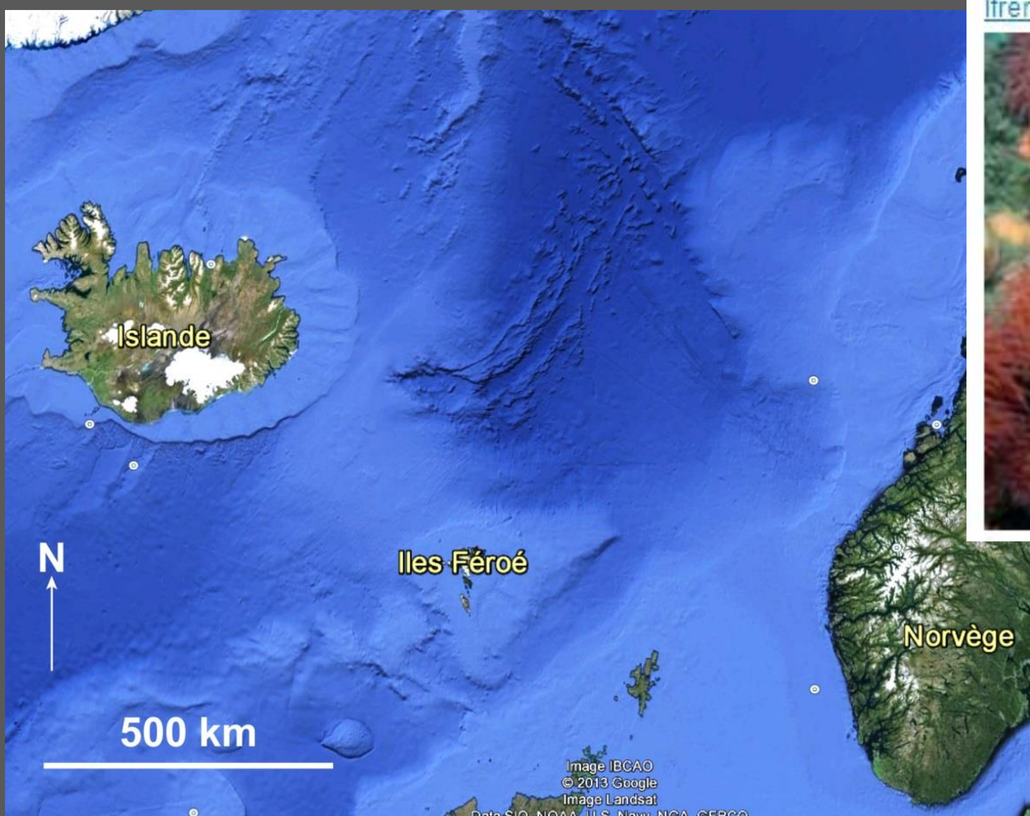

Rising fluids

Storegga slide, Norway

5. Applicability to natural examples

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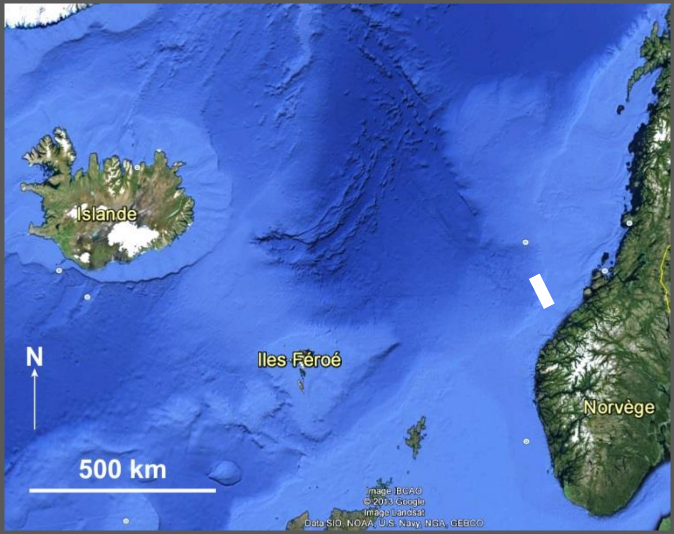
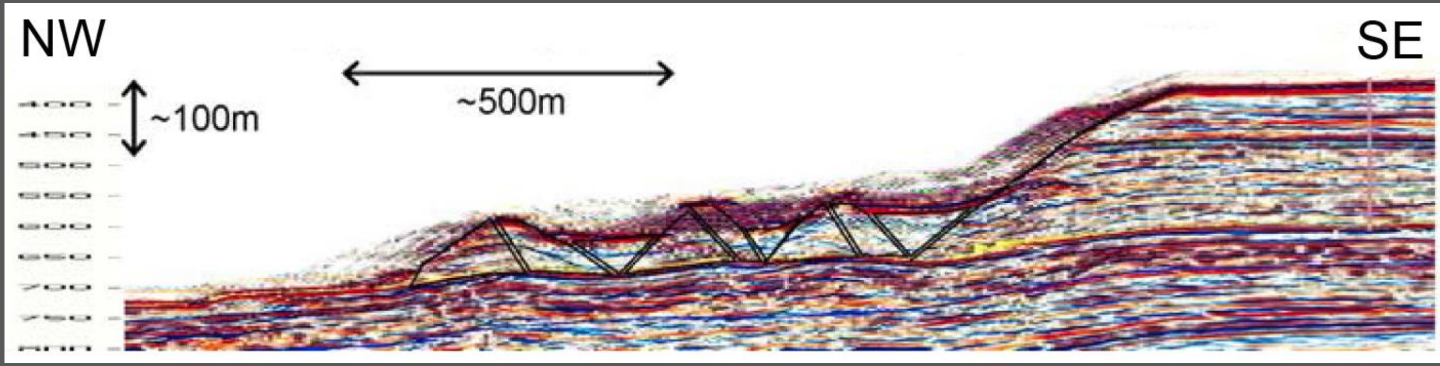
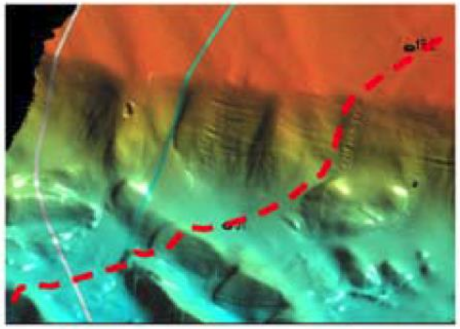


Modified after Kvalstad et al. (2005)





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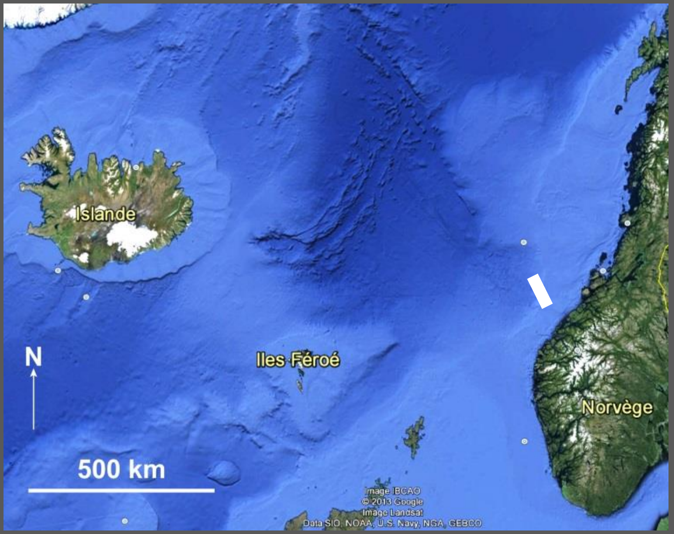

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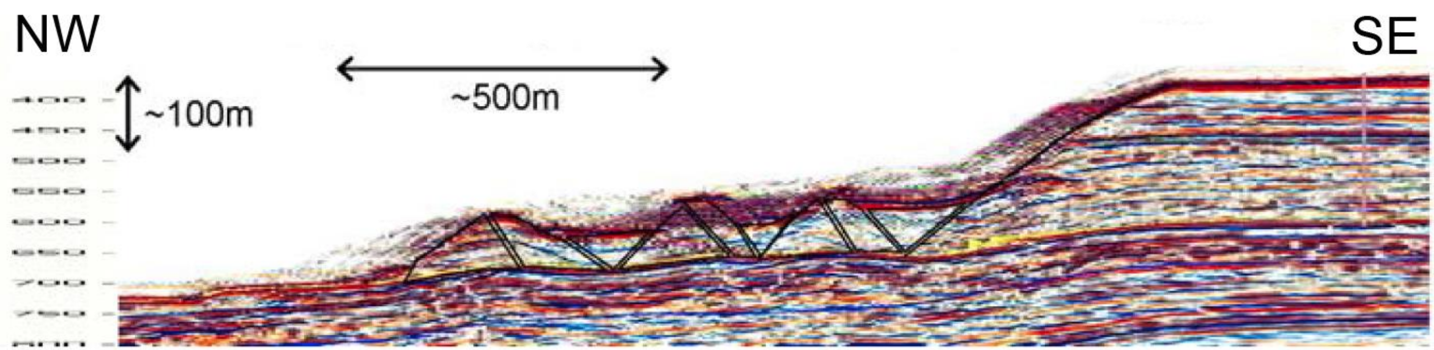

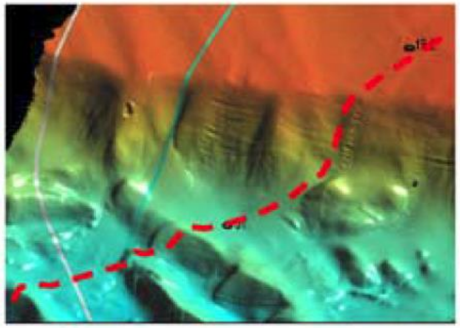

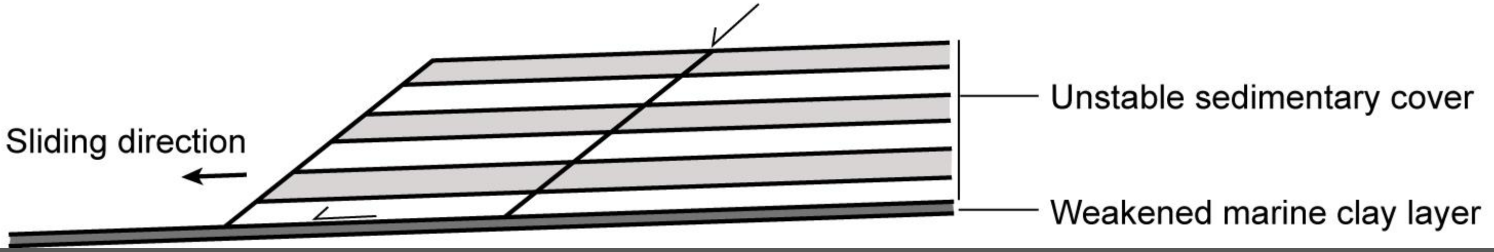

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B- Transform margins

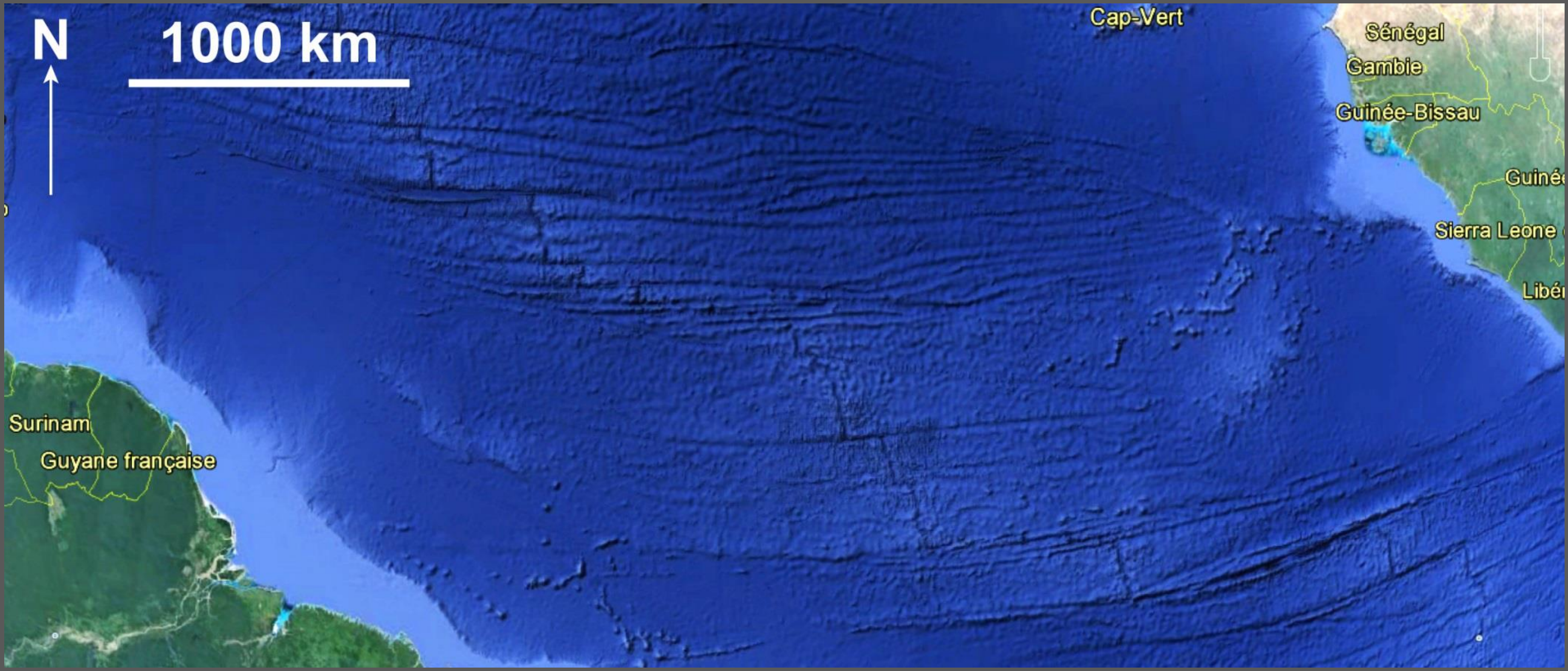

Image Google Earth

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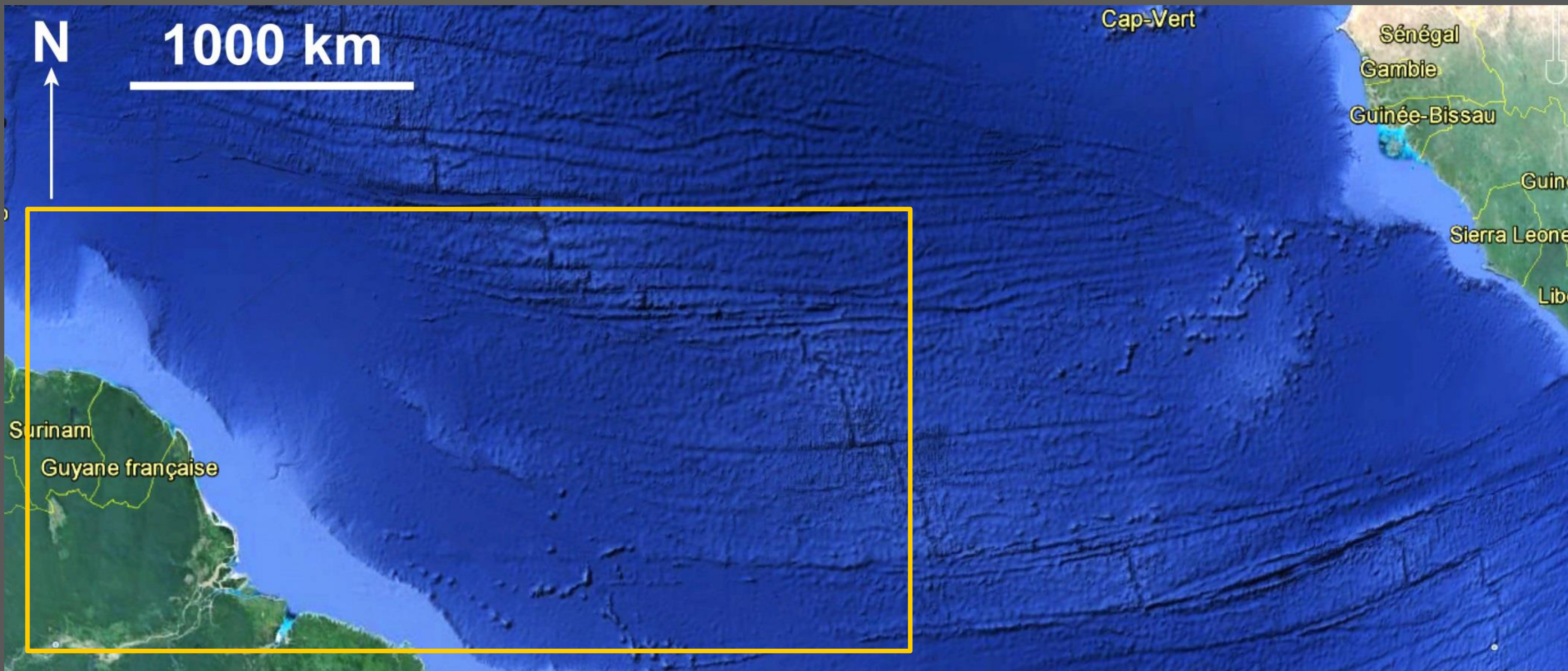

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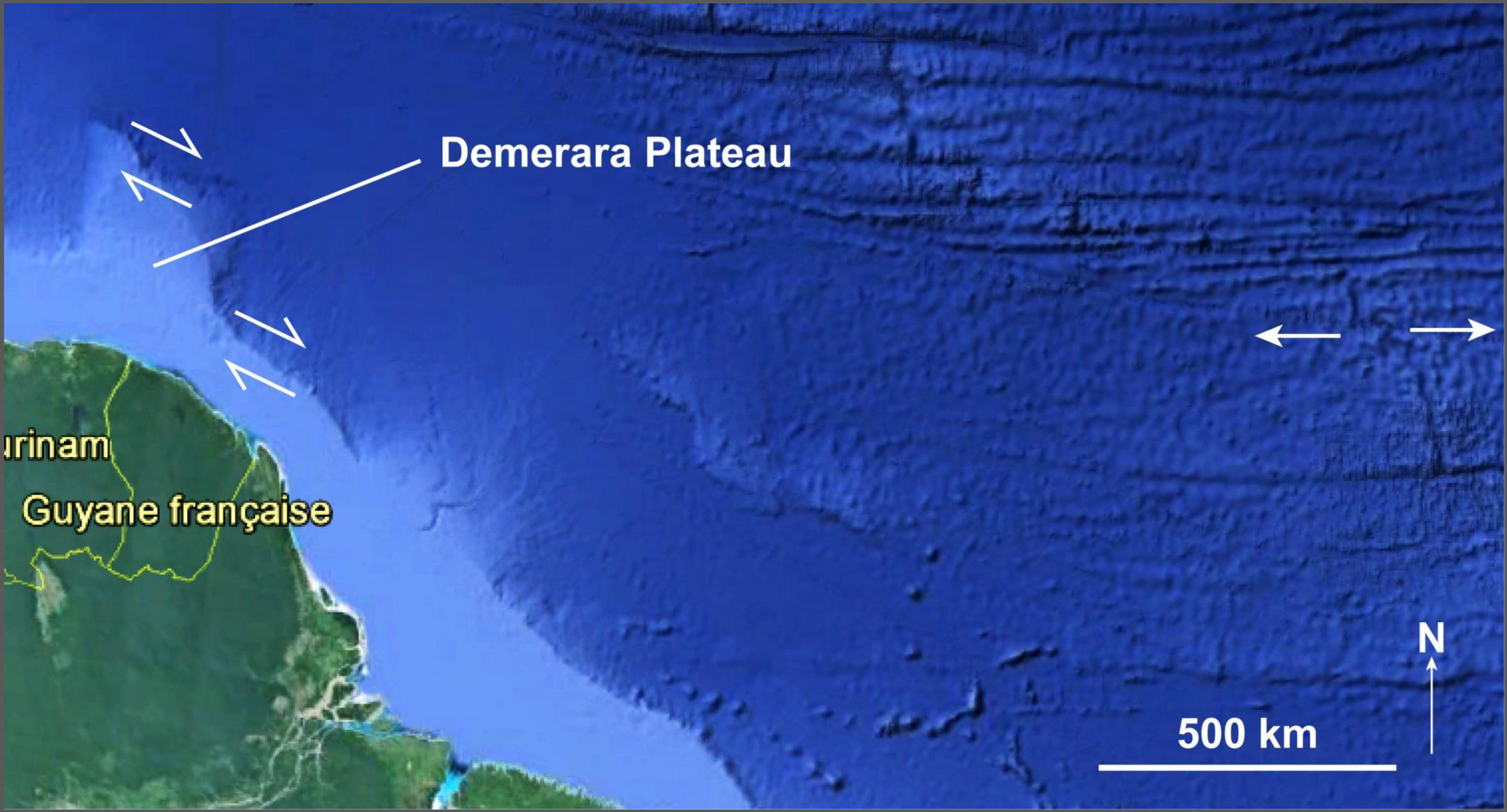

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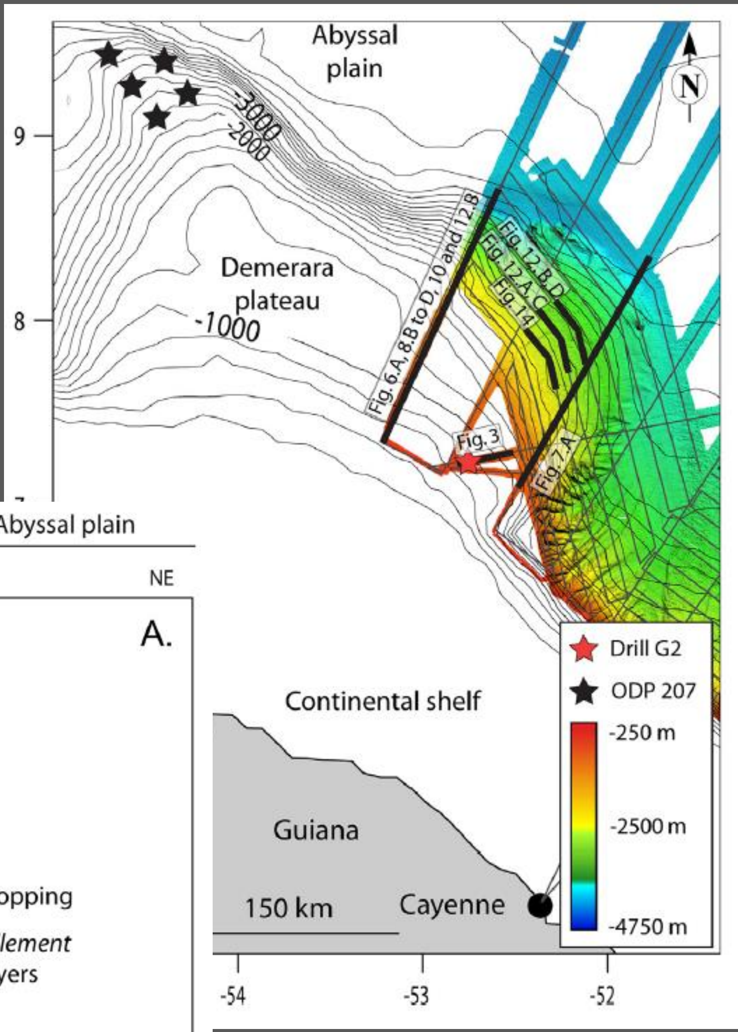
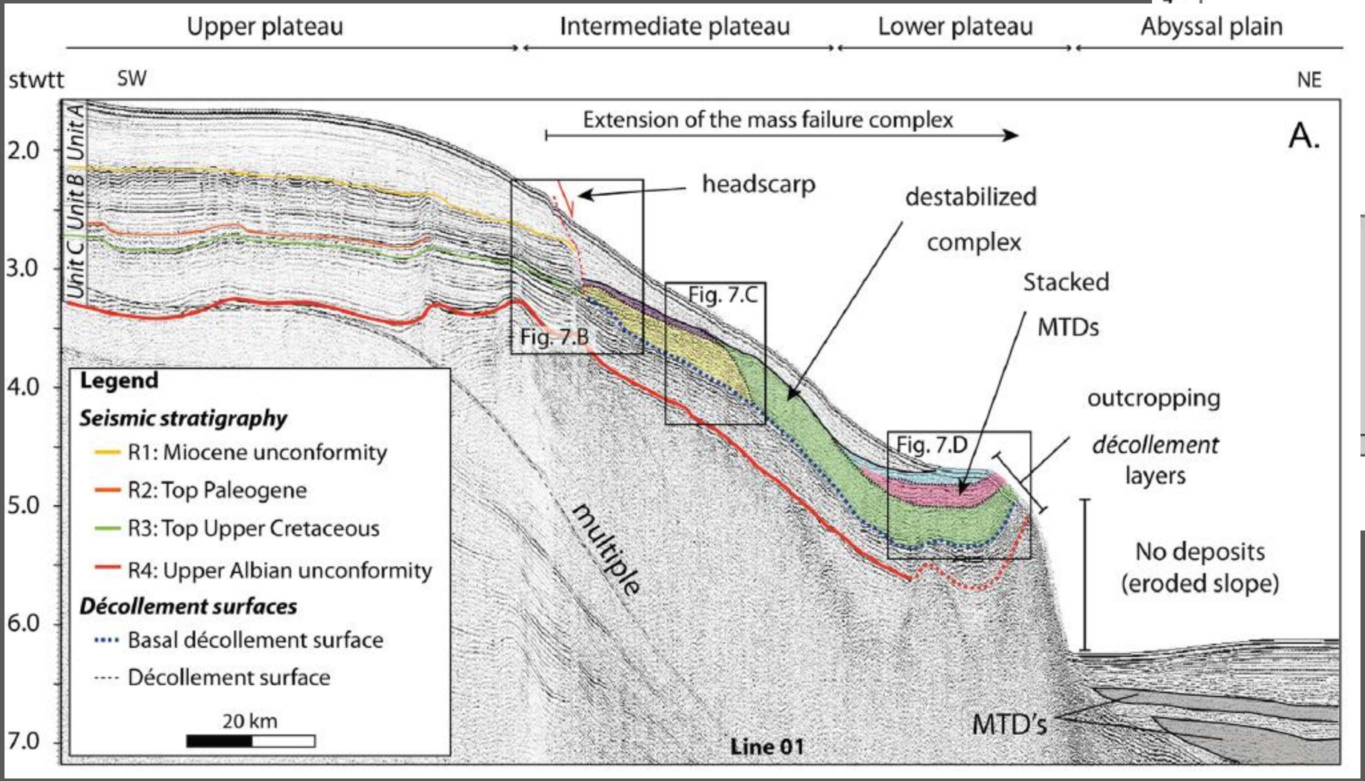
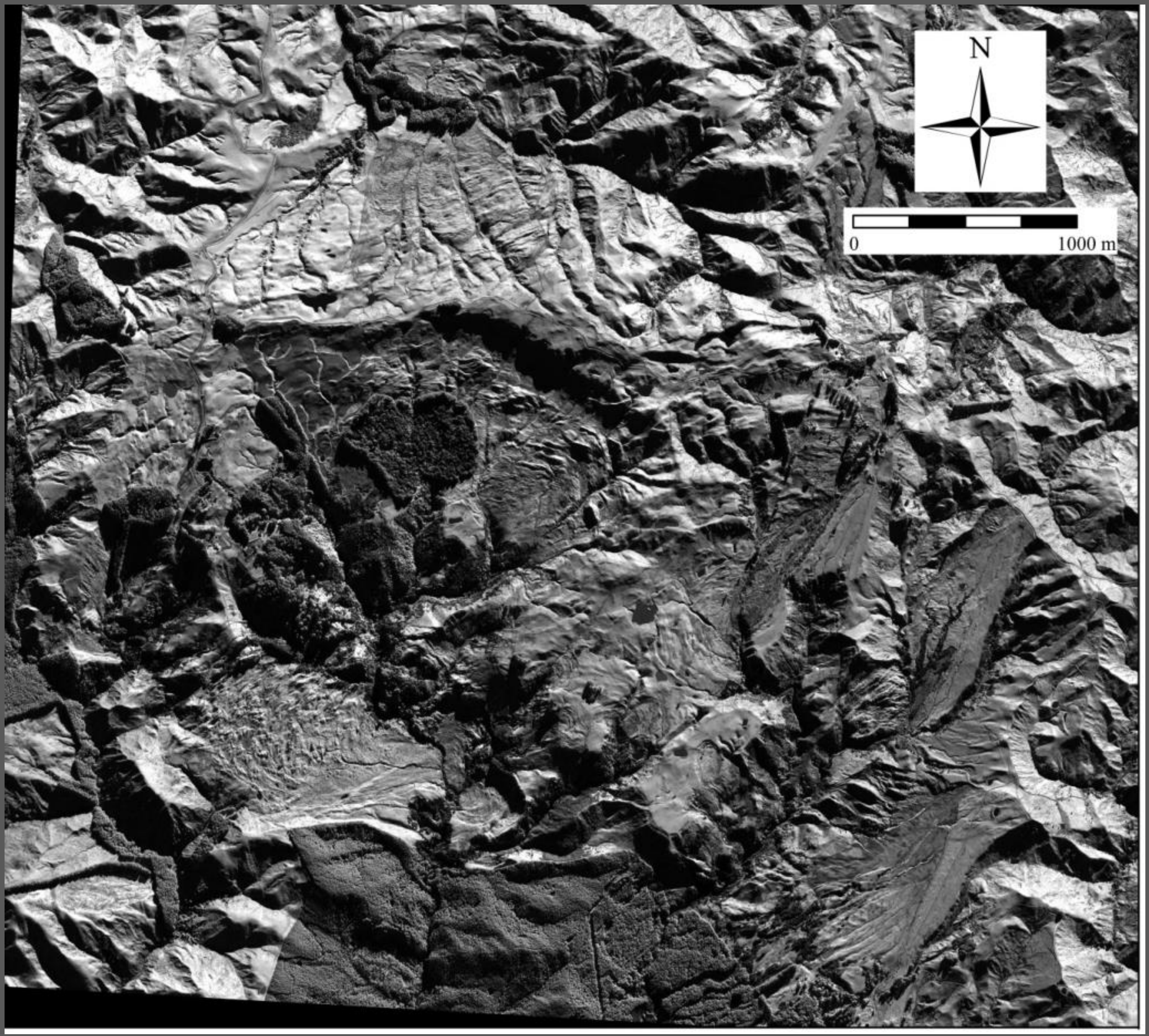




Pattier et al. (2013)

5. Applicability to natural examples

C- Onshore landslides

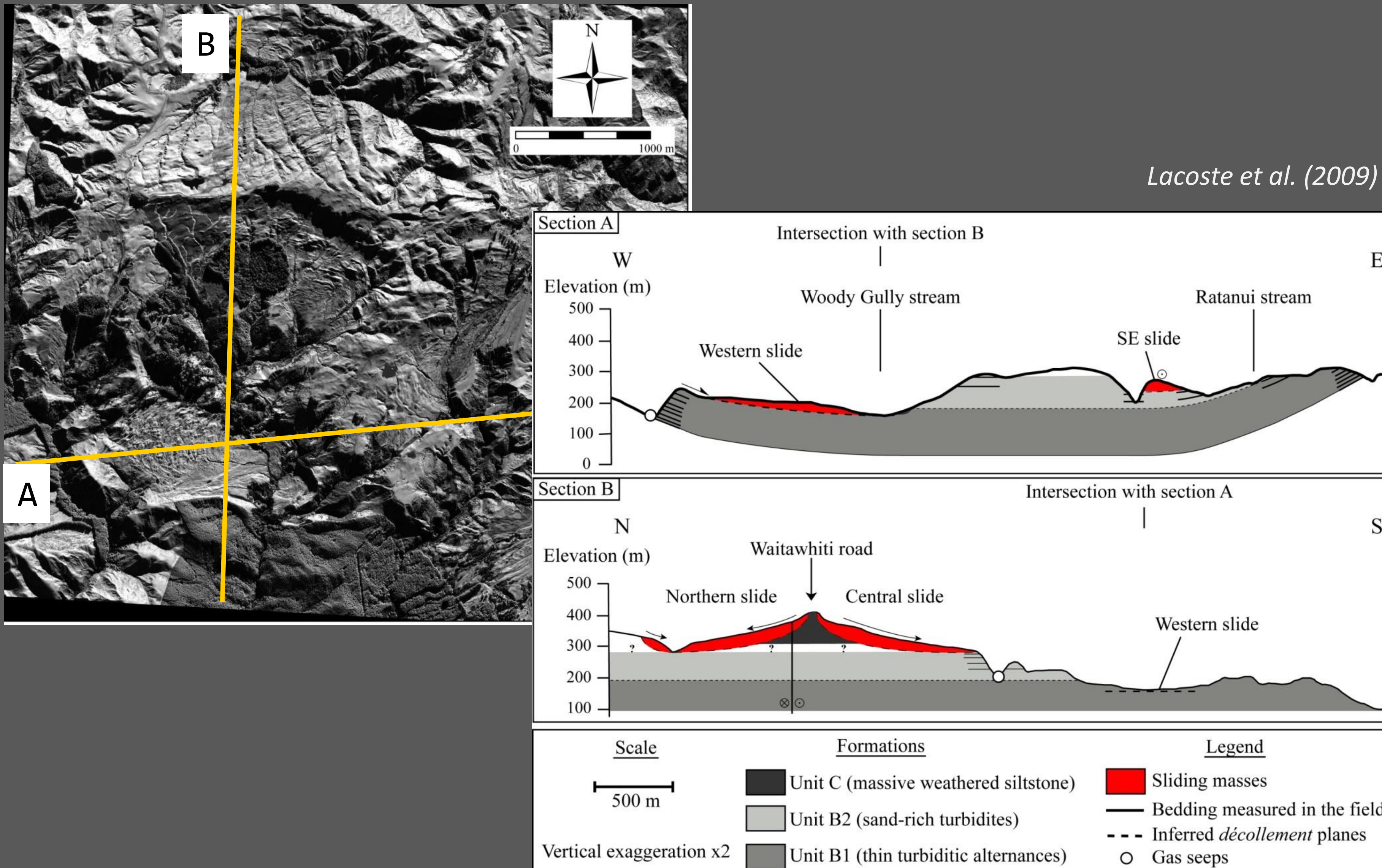


Waitawhiti, New Zealand

5. Applicability to natural examples

C- Onshore landslides

Lacoste et al. (2009)



5. Conclusions

- Critical Coulomb wedge theory applicable to systems subjected to gravitational forces only

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- Potential applications to natural systems: passive margins, landslides