Webinars

Advances in fault zone structure and property prediction: applications to reservoir geomechanics

Christopher WIBBERLEY

Senior Technical Advisor in structural geology, TotalEnergies

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Presentation outline

1) Fault geometry
   - fault propagation
   - fault linkage and relay ramps

2) Fault zone structural properties
   - core zone
   - fracture damage zones

3) Fault zone hydromechanical behaviour
   - leakage during fault reactivation
   - predicting active fault permeability

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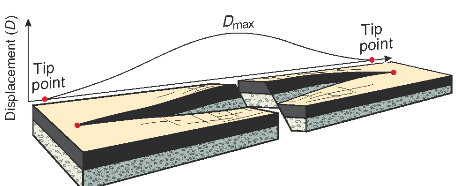
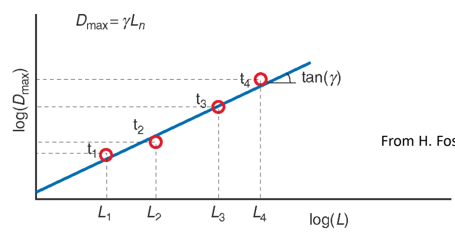
1. Fault geometry

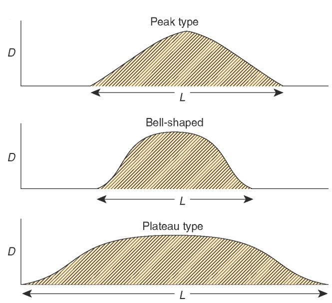
Fault propagation and scaling laws



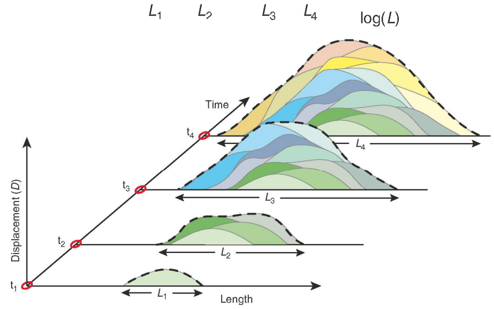
D_{max} is a function of Fault length



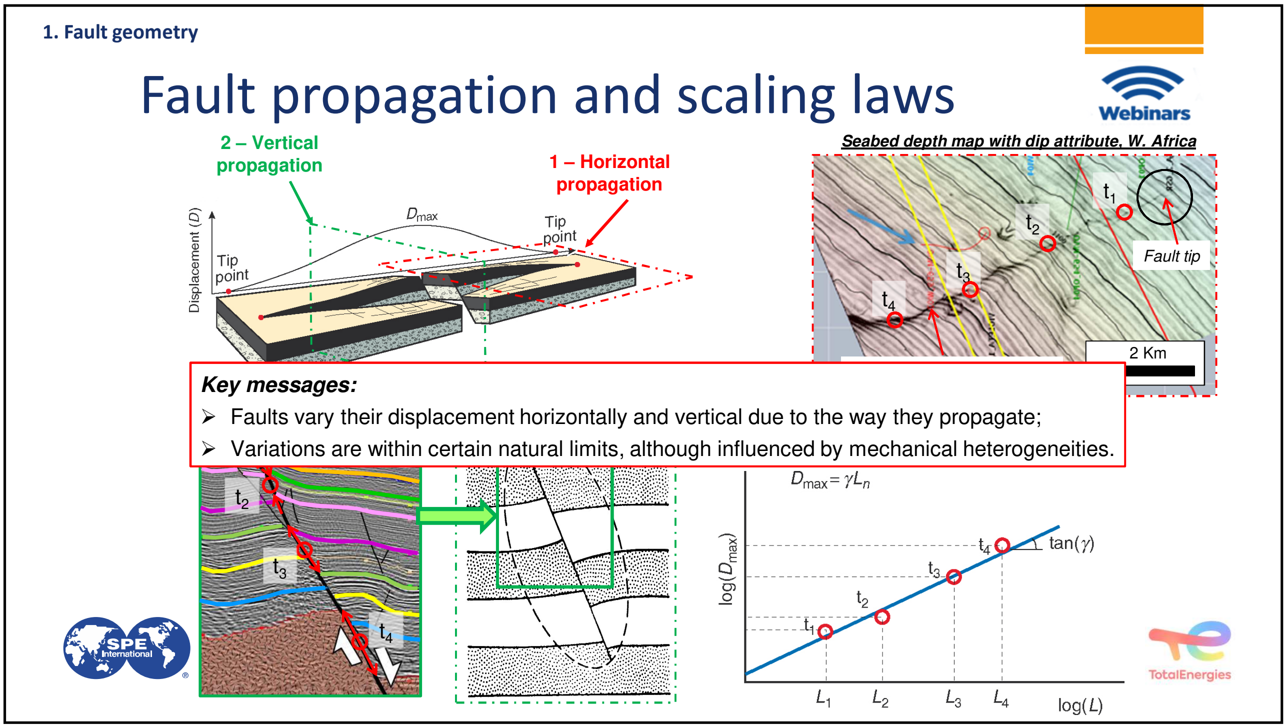
From H. Fossen e-book



Final profile



Accumulation of individual slip events


1. Fault geometry
Fault propagation and scaling laws
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2 – Vertical propagation
1 – Horizontal propagation
Displacement (D)
Tip point
Dmax
Tip point
Seabed depth map with dip attribute, W. Africa
t1
t2
t3
t4
Fault tip
2 Km
Key messages:
➢ Faults vary their displacement horizontally and vertical due to the way they propagate;
➢ Variations are within certain natural limits, although influenced by mechanical heterogeneities.
$D_{max} = \gamma L_n$
log(D_{max})
tan(γ)
L_1
L_2
L_3
L_4
log(L)
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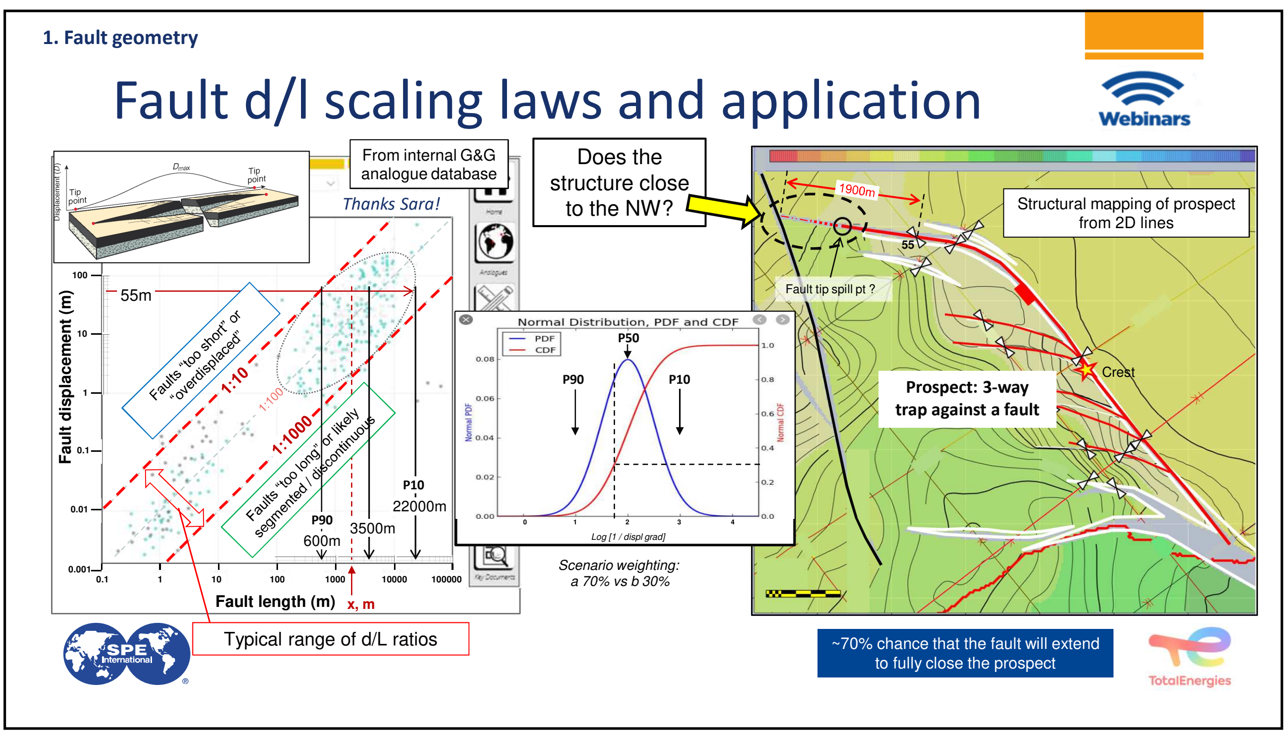
1. Fault geometry
Fault d/l scaling laws and application
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From internal G&G analogue database
Thanks Sara!
Does the structure close to the NW?
1900m
Structural mapping of prospect from 2D lines
55
Fault tip spill pt ?
Crest
Prospect: 3-way trap against a fault
55m
Faults "too short" or "overdisplaced"
1:10
1:100
1:1000
Faults "too long" or likely segmented / discontinuous
Fault displacement (m)
Fault length (m)
x, m
P90 600m
3500m
P10 22000m
Normal Distribution, PDF and CDF
PDF
CDF
P50
P90
P10
Log [1 / displ grad]
Scenario weighting: a 70% vs b 30%
Typical range of d/L ratios
~70% chance that the fault will extend to fully close the prospect
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1. Fault geometry

Fault linkage and relay ramps

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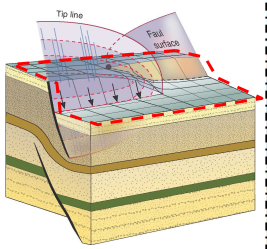
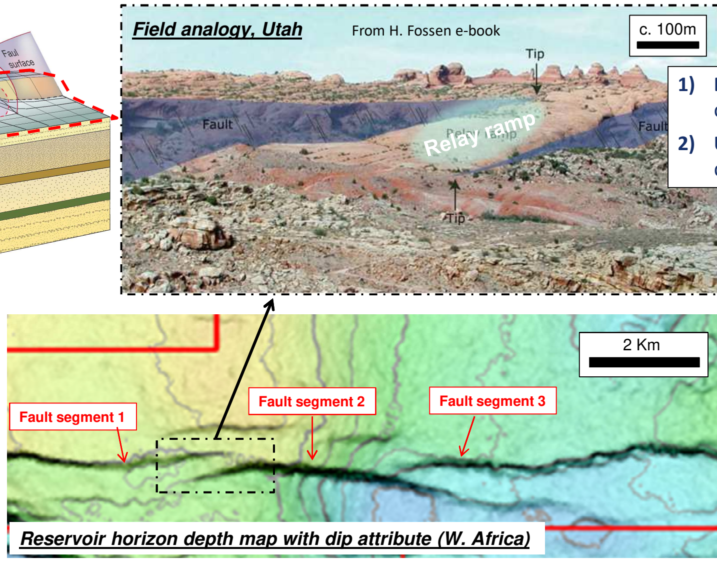
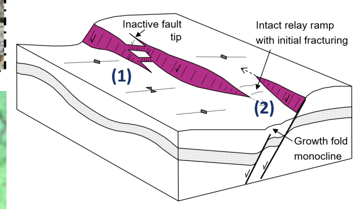




1) **Breached** = Enhanced deformation, may cause compartmentalisation;
2) **Unbreached** (open) = little/no deformation, fluid pathway through fault



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1. Fault geometry

Reservoir behaviour: open or closed faults?

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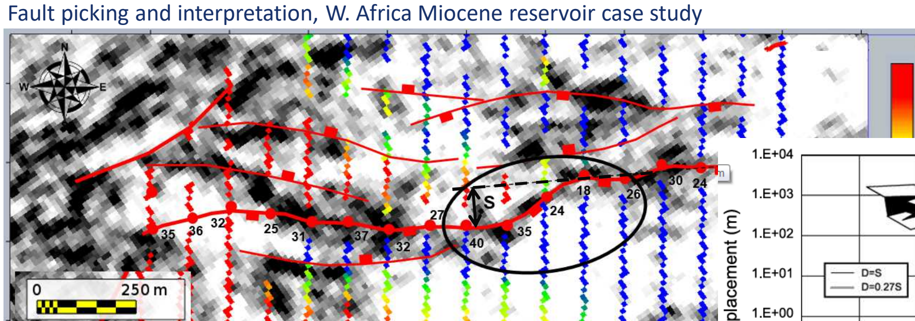
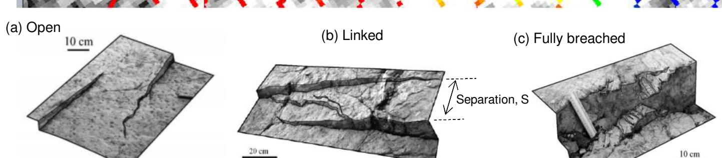
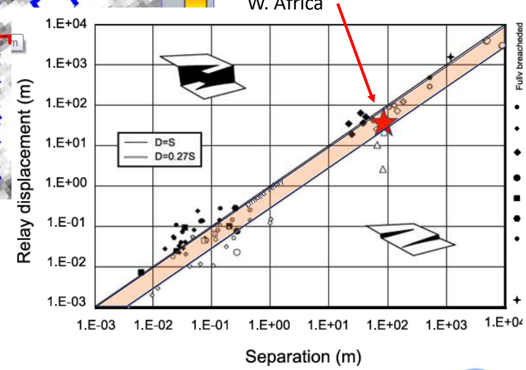
Fault picking and interpretation, W. Africa Miocene reservoir case study



Separation, S = 90m

Example from W. Africa





Analogue dataset from Soliva & Benedicto, Journal of Structural Geology 2004

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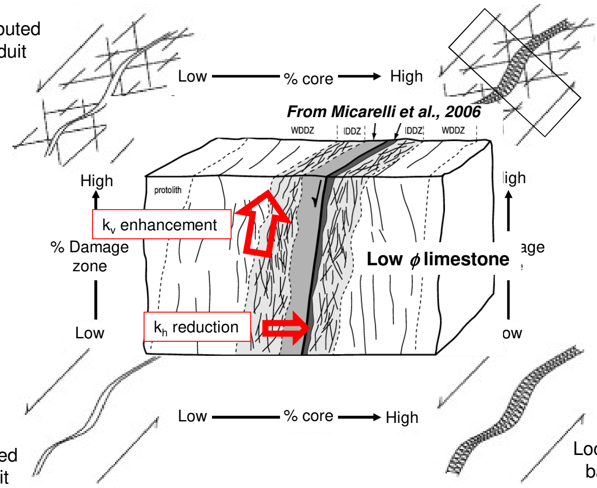
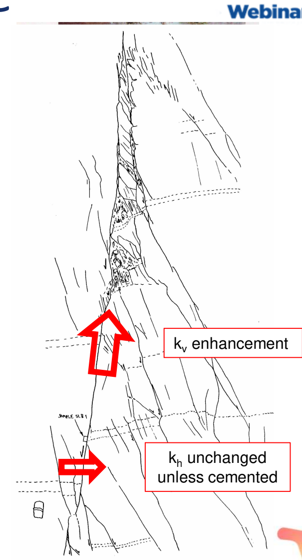
2. Fault zone properties

Fault zone internal structure





Fault zones as barriers and/or conduits to fluid flow…

2. Fault zone properties

Fault core zone properties: sandstone

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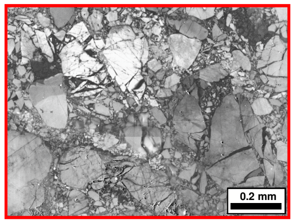
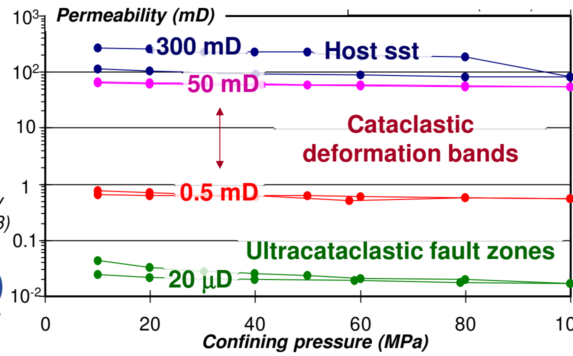


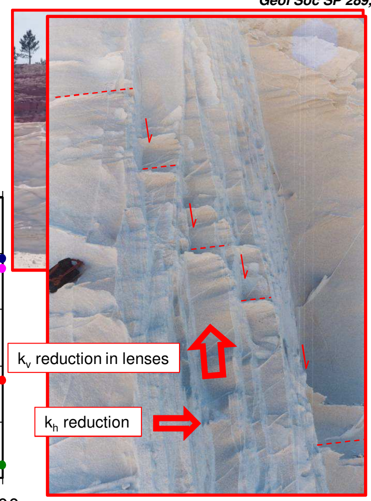
High ϕ Cretaceous sands, low burial

Provence, S.E. France

From Wibberley et al. Geol Soc SP 289, 2007



Bassin du Sud-Est, SE France (Saillet & Wibberley AAPG Bulletin, 2013)



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2. Fault zone properties

Fault core zone properties: shale gouge

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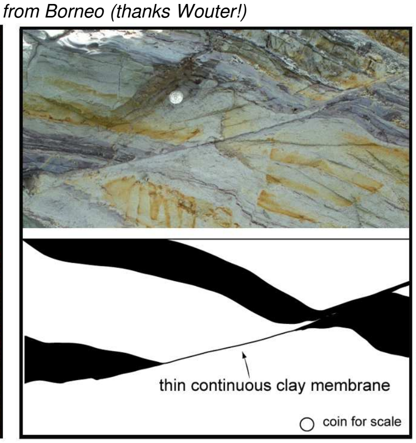
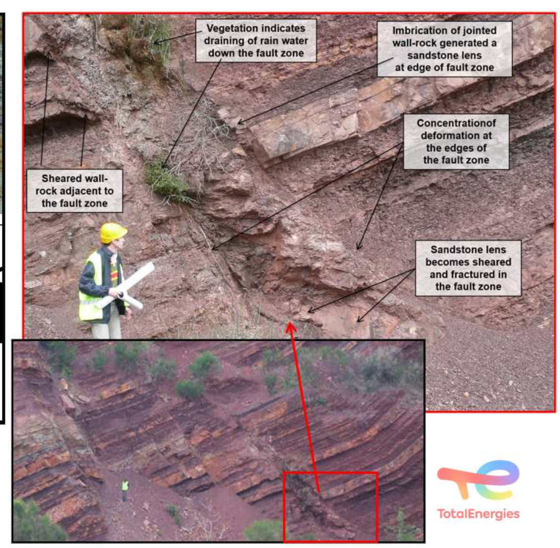
Examples from Borneo (thanks Wouter!)



Example from the Lodève Basin (S. France)



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2. Fault zone properties

Fault core zone permeability prediction

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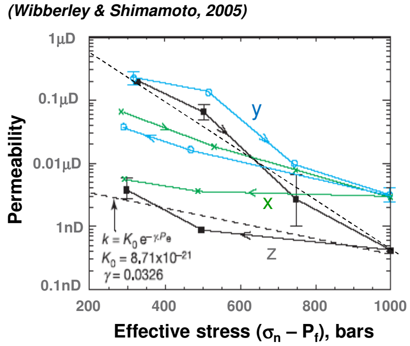
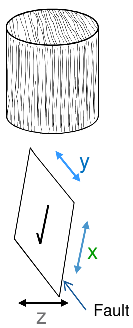
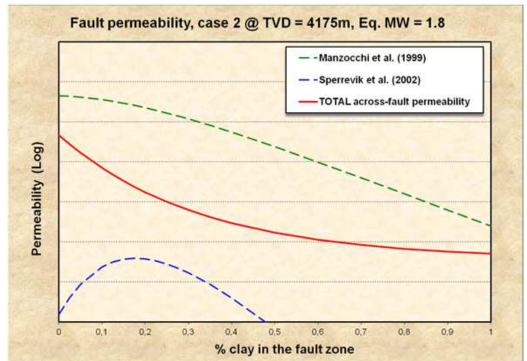
- **Taking into account :** **- burial depth** **- OVP** **- gouge anisotropy**

Example of a clay-rich fault, MTL, Japan, core zone
(Wibberley & Shimamoto, 2005)





Permeability anisotropy and fault rock microstructure



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2. Fault zone properties

Case 1 – Analytical model of fault barrier effect

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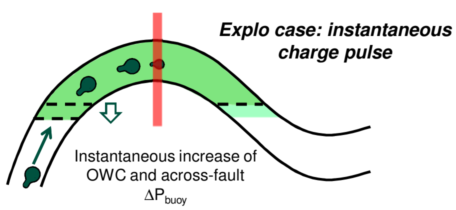
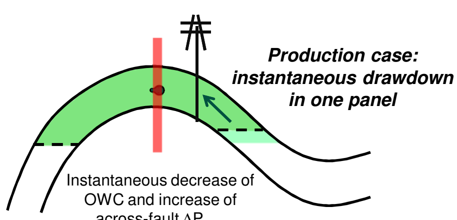
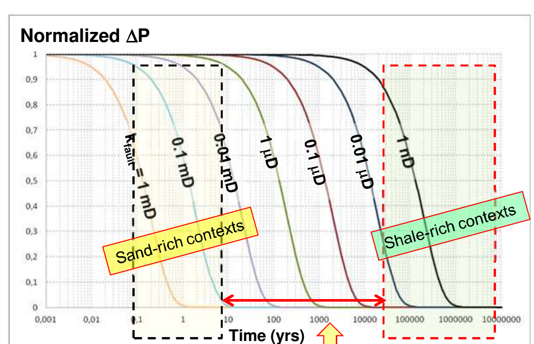




Decay of across-fault pressure difference after a pressure pulse



Significant drive to re-equilibrium during production

"Explo" time-scale fault sealing

"Geological" re-equilibration but temporary production seal

From Wibberley *et al.*, Petroleum Geoscience (2017)

A "partially-permeable" fault may re-equilibrate on the geological timescale but provide a short-term seal

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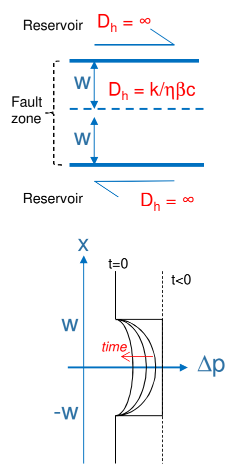
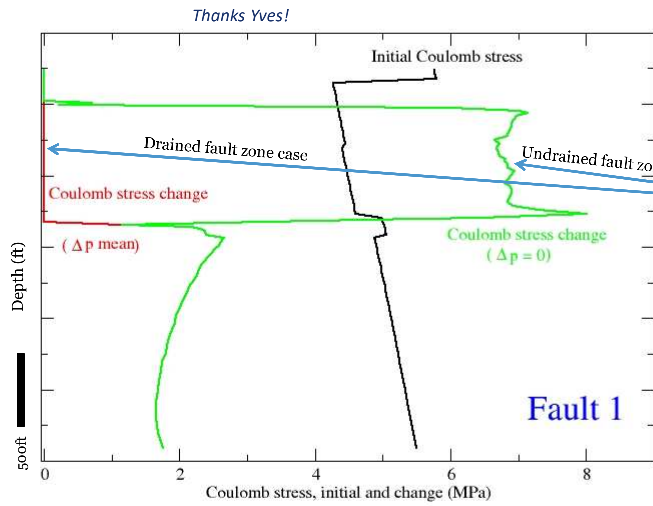
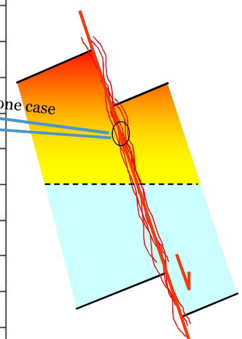
2. Fault zone properties

Case 2 – OVP depletion and fault stability



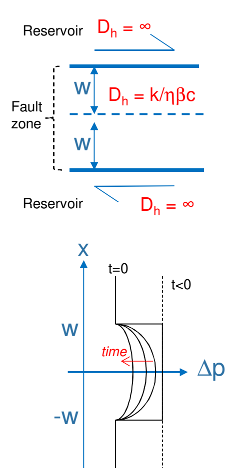


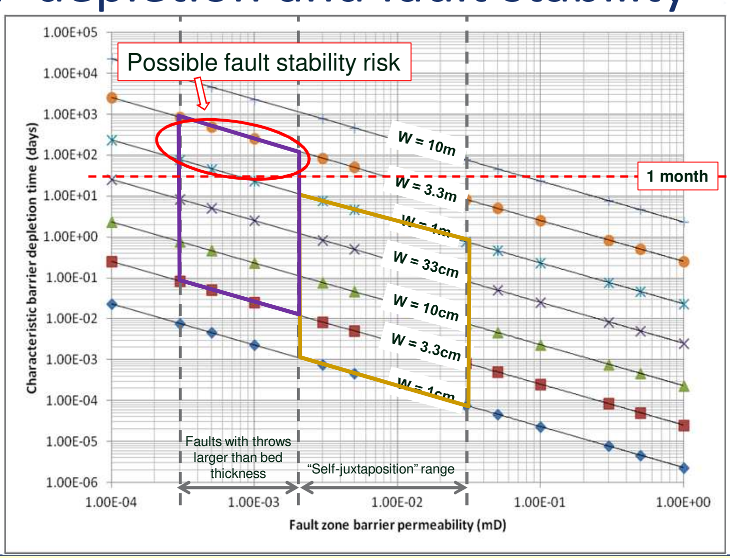


Fault stability can depend upon capacity to drain (over)pressures in line with reservoir depletion

2. Fault zone properties

Case 2 – OVP depletion and fault stability



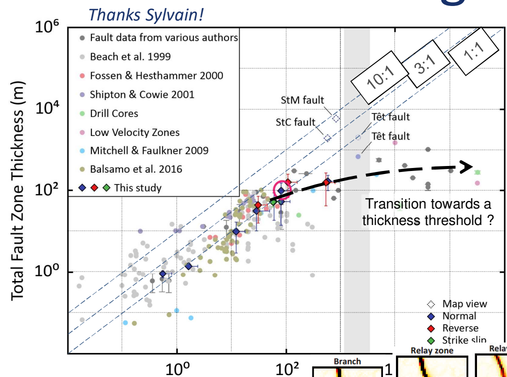


Fault stability can depend upon capacity to drain (over)pressures in line with reservoir depletion

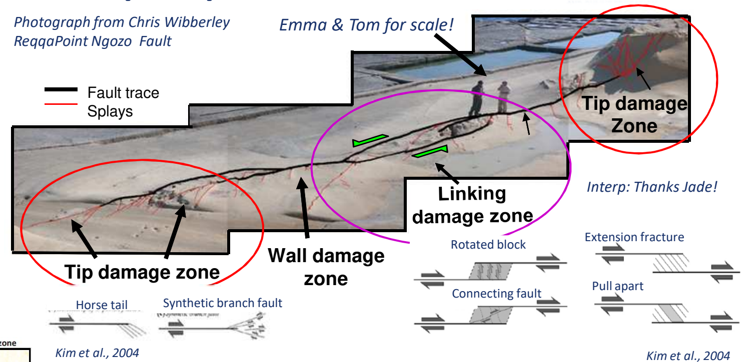
2. Fault zone properties

Fault damage zone properties

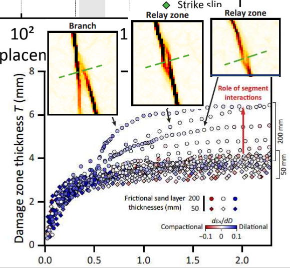
Thanks Sylvain!



from Mayolle *et al.*, J. Struc. Geol (2019)



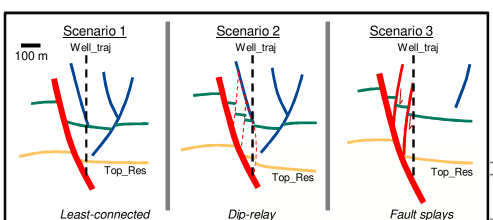
From Mayolle *et al.*, Geology (2021)



- Damage zone (DZ) width threshold is a real phenomenon
- DZ width grows with displacement, to the threshold
- **Threshold depends on mechanical unit thickness**
- **Wider DZ threshold at fault connections (branches, relays)**
- **DZ width saturates: dilation -> compaction in the fault zone**

2. Fault zone properties

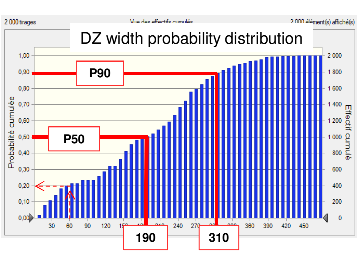
Case study: sub-seismic DZ prediction



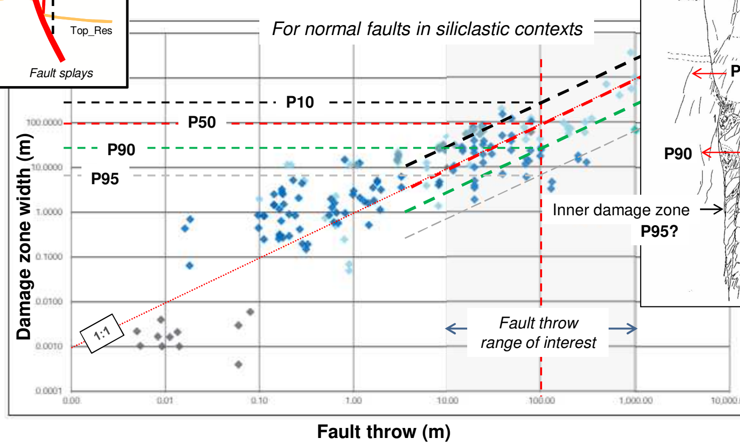
How close to the fault can I place my well ?

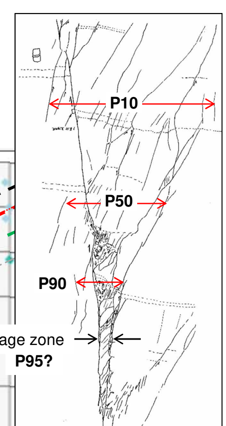
Results:

- ~ 80% chance of hitting the DZ;
- Nudge ~ 250m away from fault: <10% chance.



Thanks Amélie & Tatiana!





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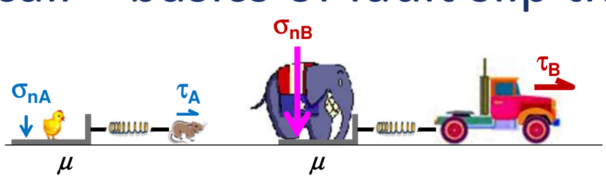
3. Fault hydro-mechanical behaviour

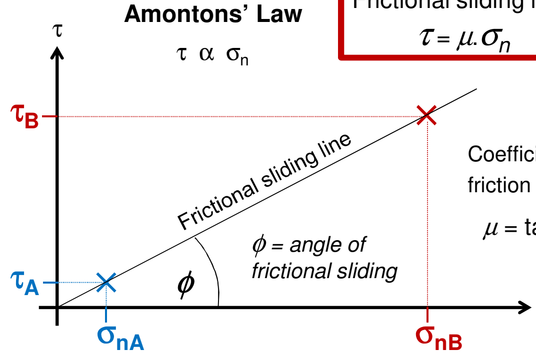
Recall – basics of fault slip theory



Amontons' Law

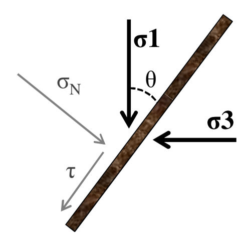
$\tau \propto \sigma_n$

Frictional sliding law:
$\tau = \mu.\sigma_n$



Coefficient of friction (τ/σ_n):

$\mu = \tan\phi$

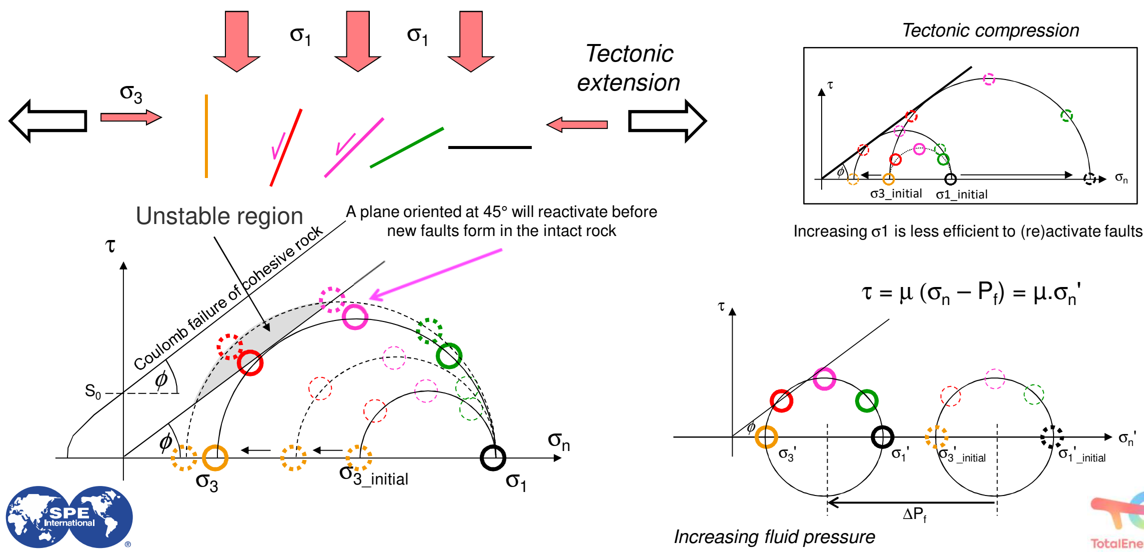


τ = shear stress on the plane

σ_n = normal stress on the plane

3. Fault hydro-mechanical behaviour

Recall – basics of fault slip theory



3. Fault hydro-mechanical behaviour

Fault-related leakage from seismic data

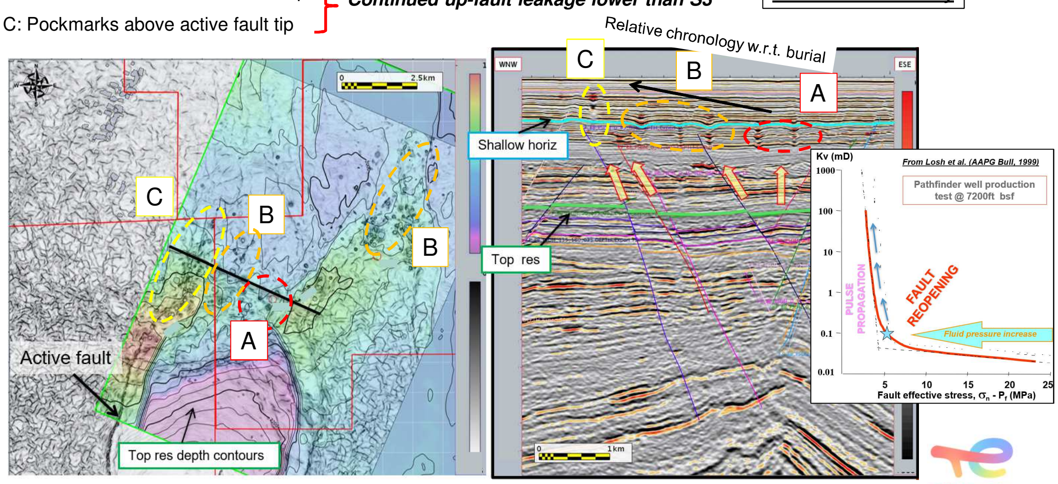
A: Pockmarks above UM anticline ***– buried and inactive due to S3 increase***

B: Pockmarks above inactive fault tips

C: Pockmarks above active fault tip

Continued up-fault leakage lower than S3

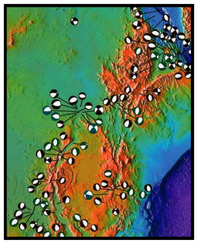
W. Africa case study



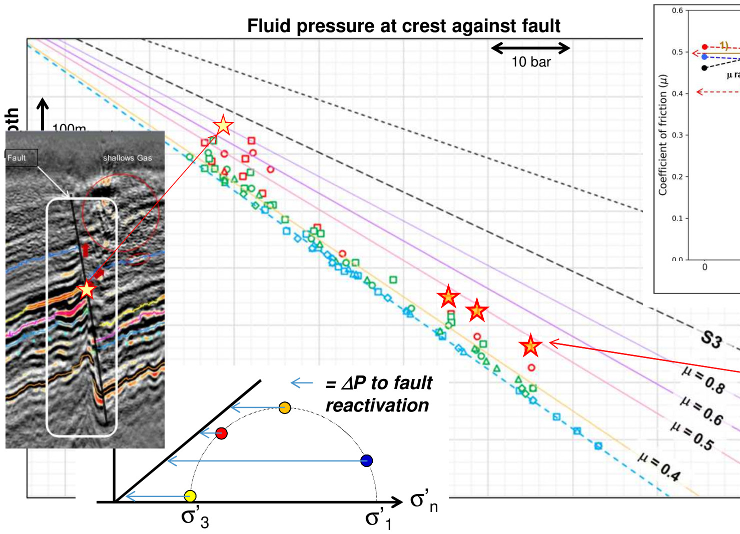
Up-fault leakage continues even after burial and S3 increase suppresses frac

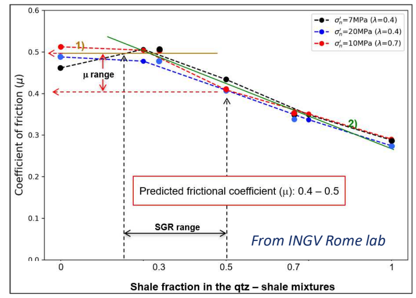
3. Fault hydro-mechanical behaviour

Fault-related leakage & active tectonics

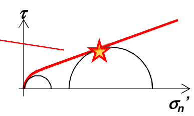


Regional seismicity





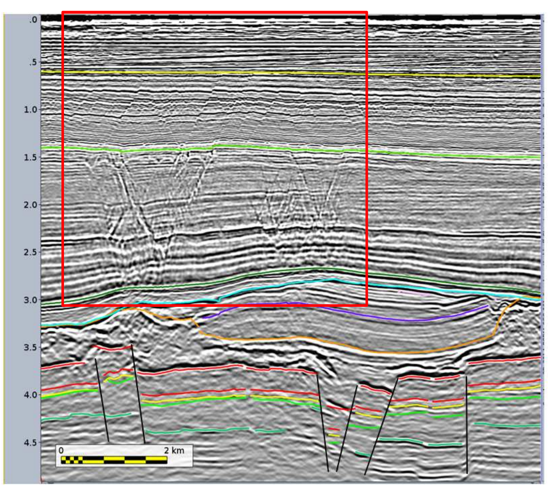
Thanks Marco & Cristiano!

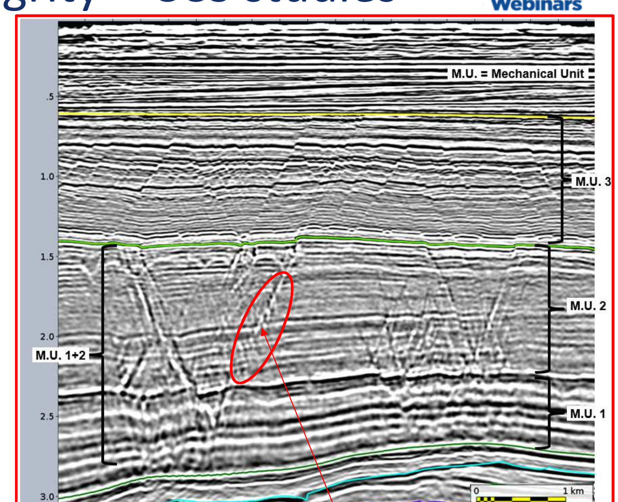


Gas retention limit and up-fault leakage on a lower gradient than S3, aligning with $\mu \sim 0.4 - 0.5$

3. Fault hydro-mechanical behaviour

Faulted overburden integrity – CCS studies





Fault permeability change during reactivation is still a challenge for modelling

Wrap-up

Take-home messages

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- ***Fault permeability*** is an important ***seal property*** both on the geological timescale and for reservoir compartmentalization issues and geomechanical stability during production;
- Fault ***permeability structure*** includes heterogeneity, anisotropy and depends on geological / tectonic history, context and lithology;
- Algorithms and scaling laws can help predict fault structure and permeability ***if used appropriately for the particulary geological context*** – this requires experience with fault zones!
- Applications to pressure/seal evaluation and production geomechanics include predicting ***fault slip during depletion***, and ***up-fault leakage and reactivation during injection***.

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