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Endommagement et rupture autour des puits pétroliers

Drilling Integrity Analyses in Conventional and Unconventional Environments: Common Practices and Current Challenges

Vincenzo De Gennaro
PhD , Geomechanics Advisor
Europe & Africa Geomechanics Technical and Business Manager
Pau (F)

Software Integrated Solutions (SIS)
vdegennaro@slb.com

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Presentation outline

- Introduction
- Conventional failures
- Unconventional failures
- What’s next ? …
- Concluding remarks

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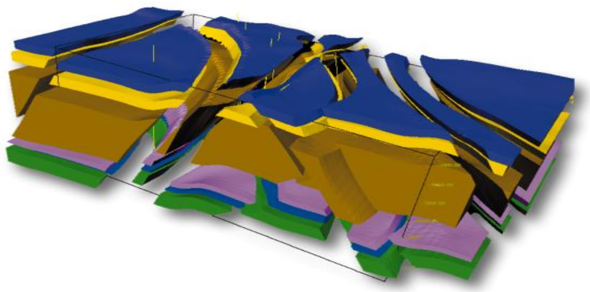
Introduction : Well Centric Geomechanics (1D)

Performed building a Mechanical Earth Model (MEM)

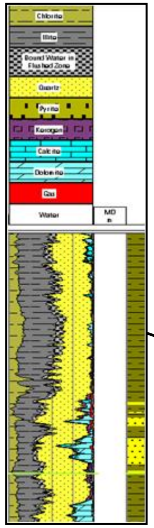
<u>Continuous description of mechanical properties and stresses along the well calibrated against measurements and observations</u>

Structure



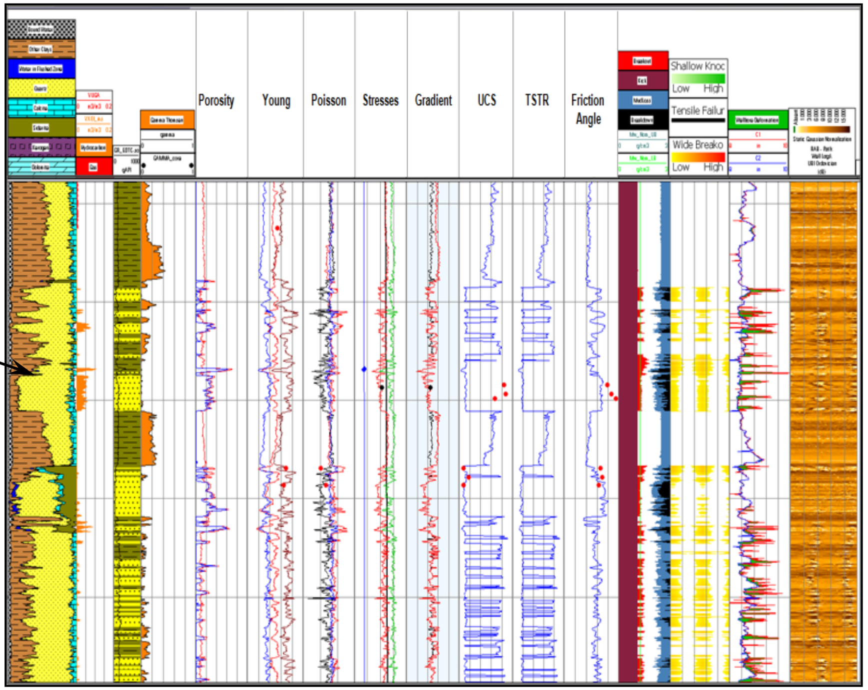
- Formation tops
- Unconformities
- Faults

Mechanical Stratigraphy

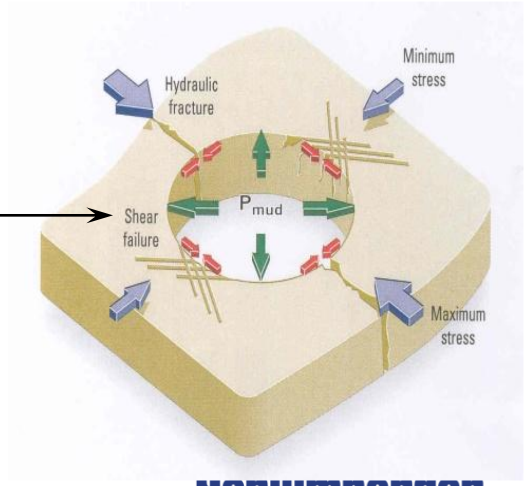


- Rock Fabric
- Mechanical support
- Deformation Mechanisms

Rock Mechanical Parameters



Predict Wellbore Failure



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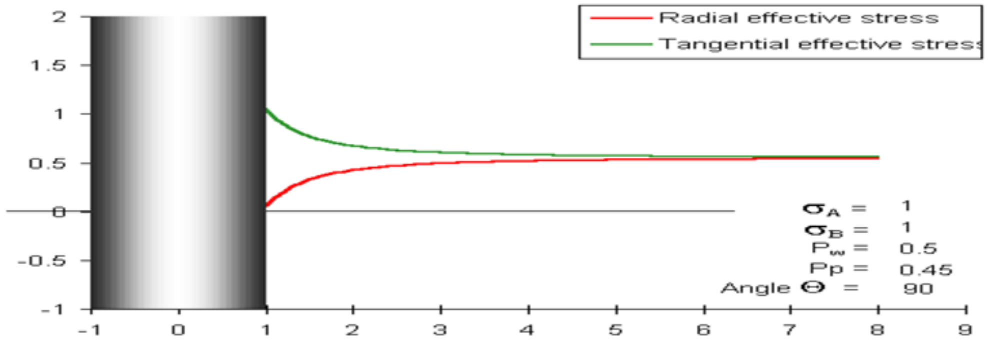
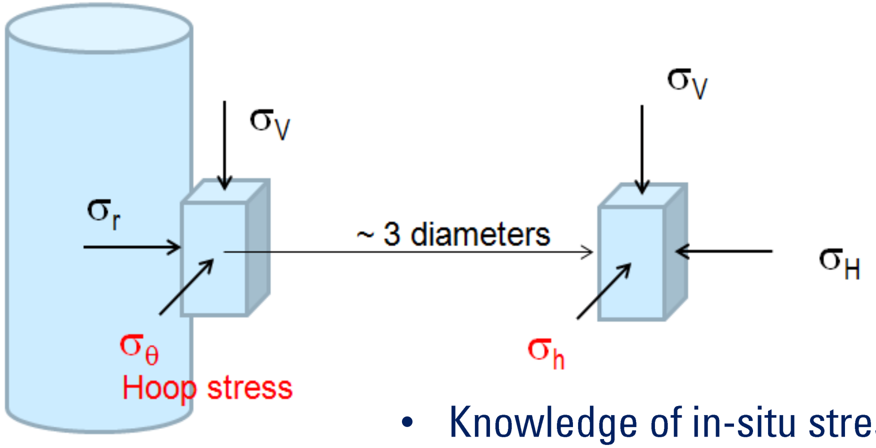
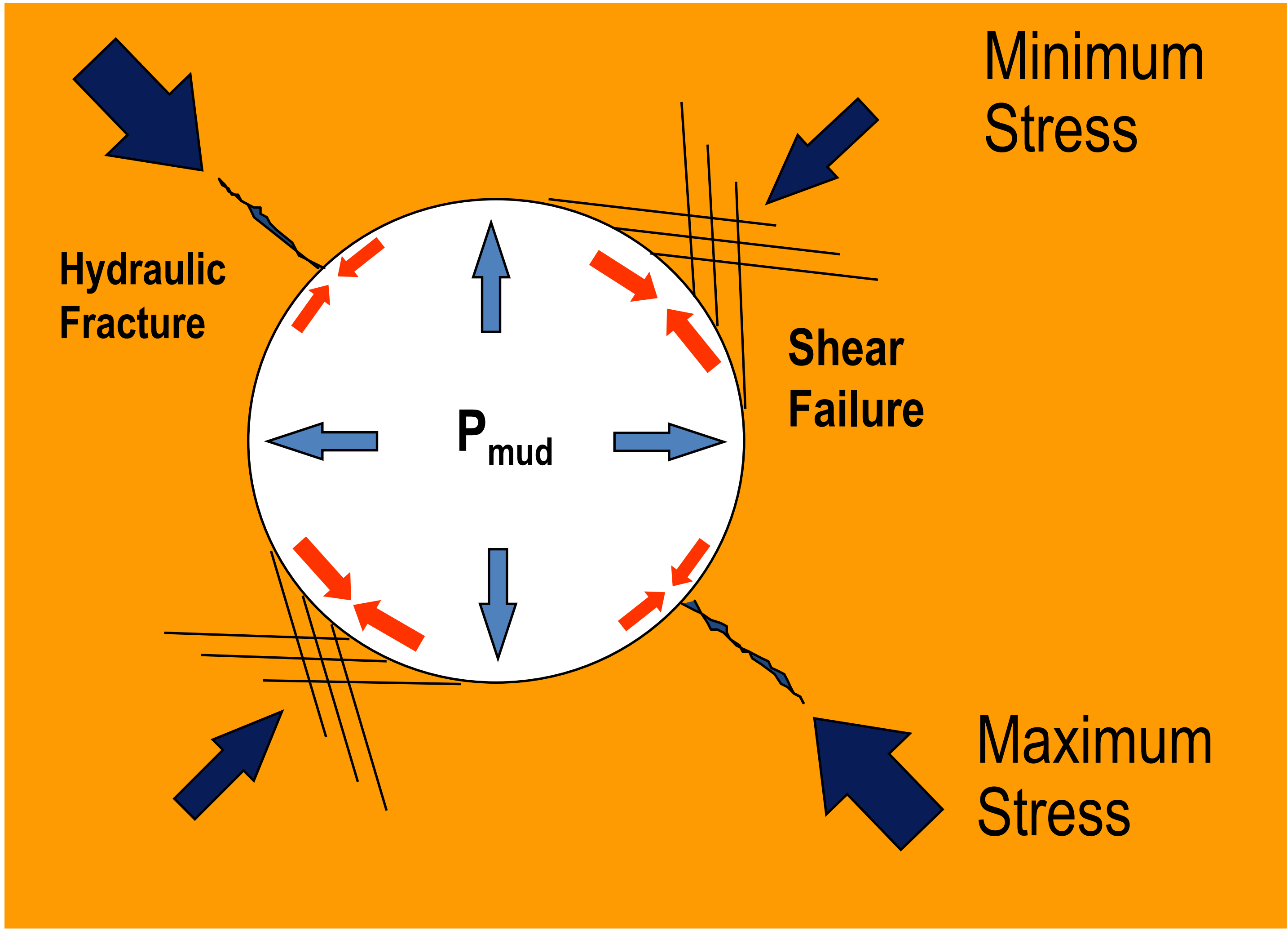
Conventional failures





- Knowledge of in-situ stresses is not a trivial task
- Calibration is correlated with wellbore failure



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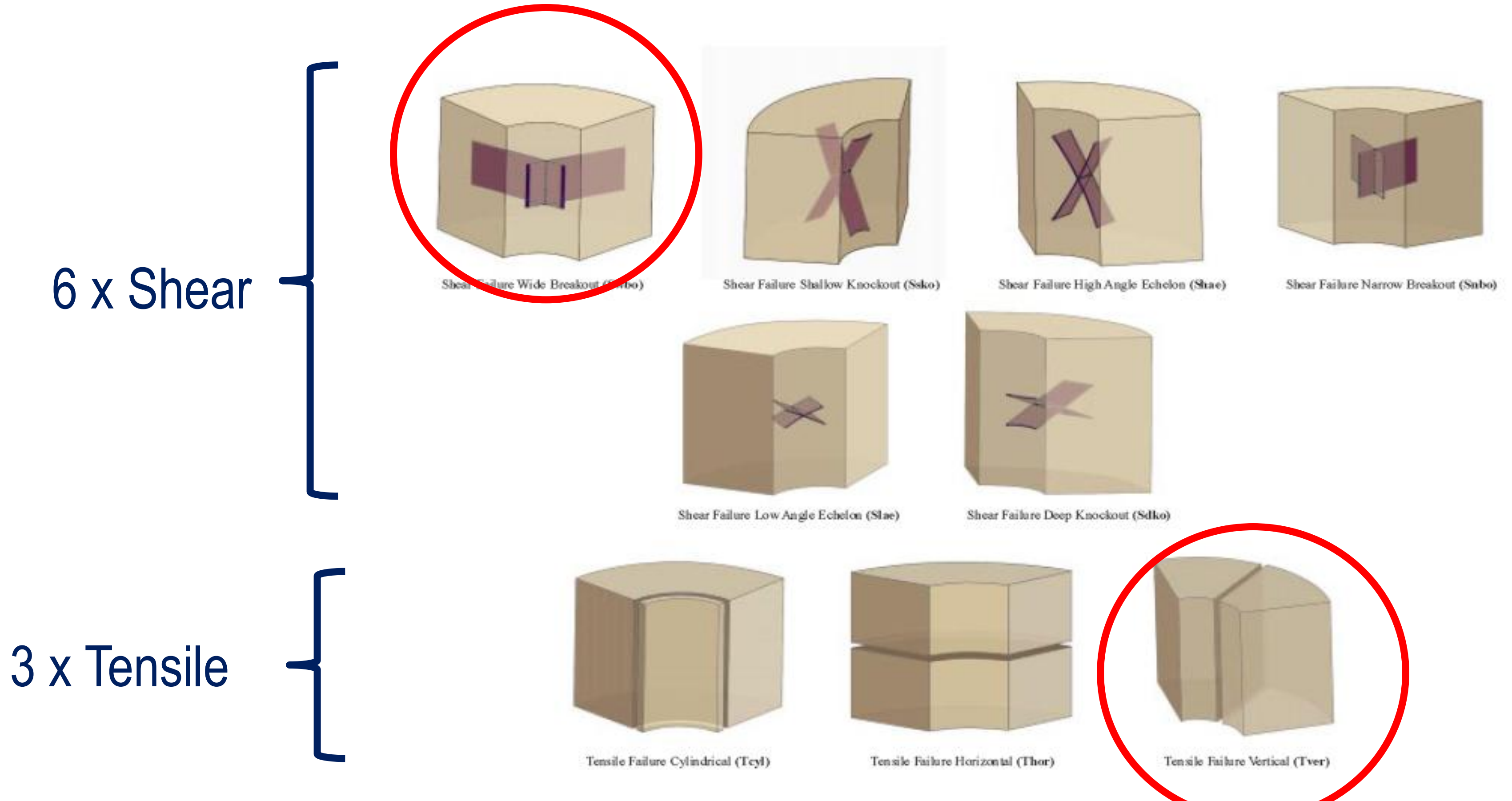
Other conventional failures



After Bratton et al., 1983 (SPWLA)

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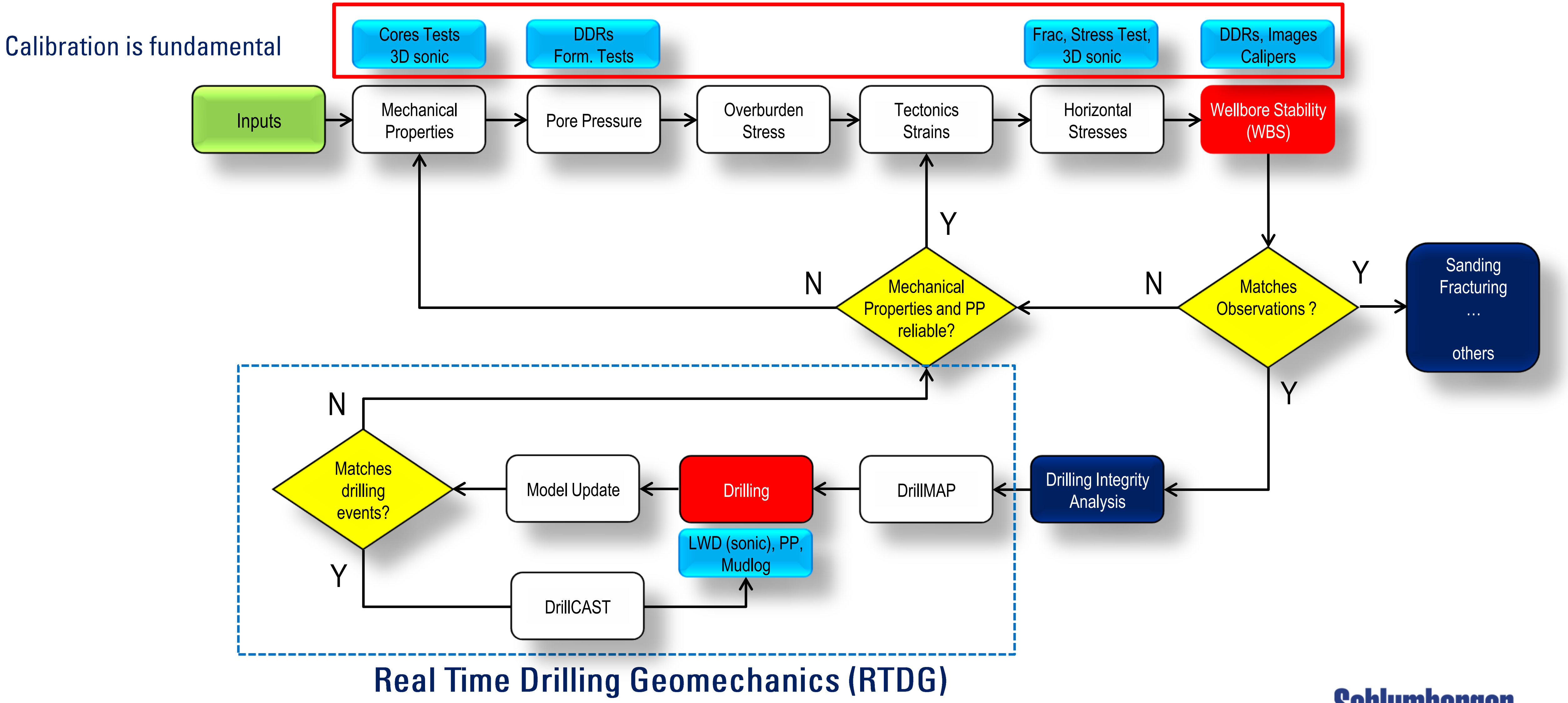
Single Well Drilling Geomechanics Modelling



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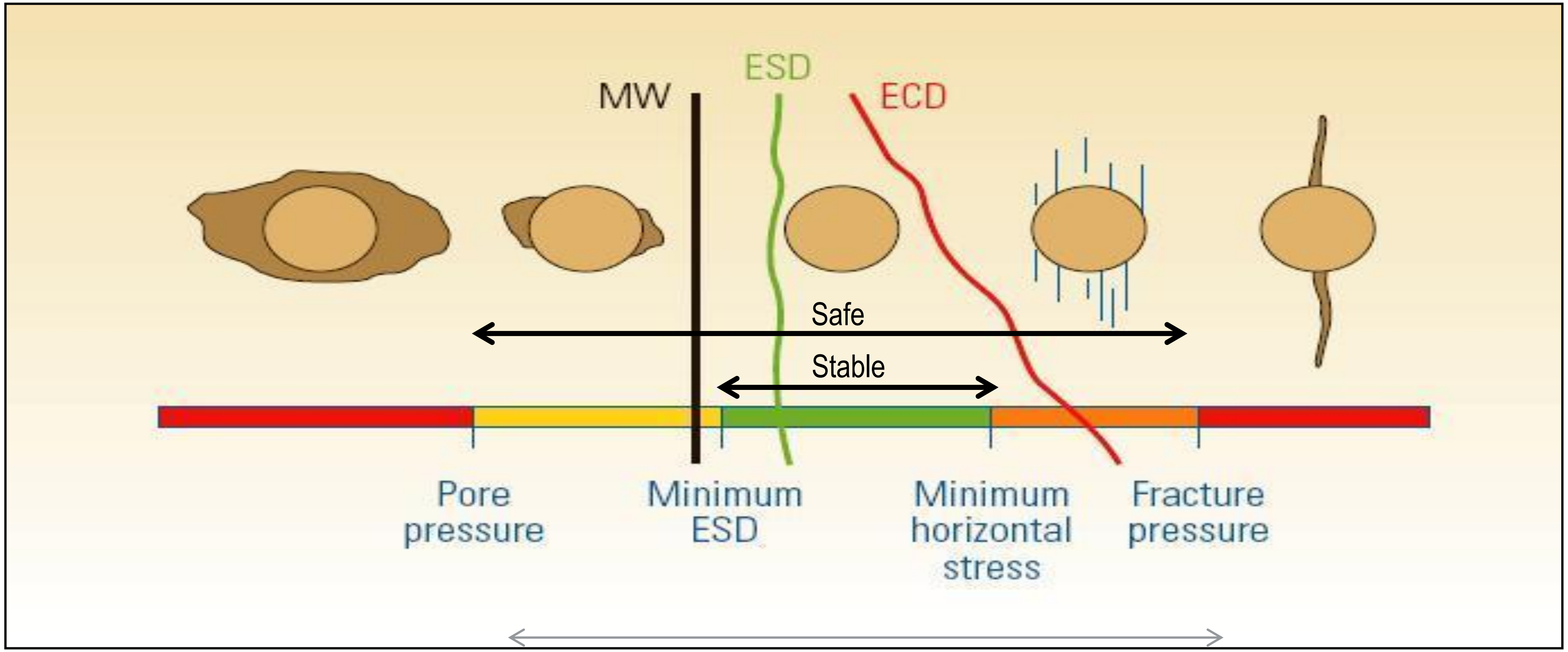
Mud Weight Window



Wide Breakout

Mud weight too low

Tensile Induced Fractures

Mud weight too high

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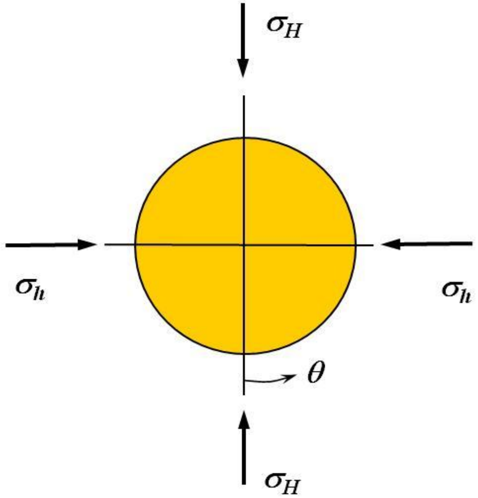
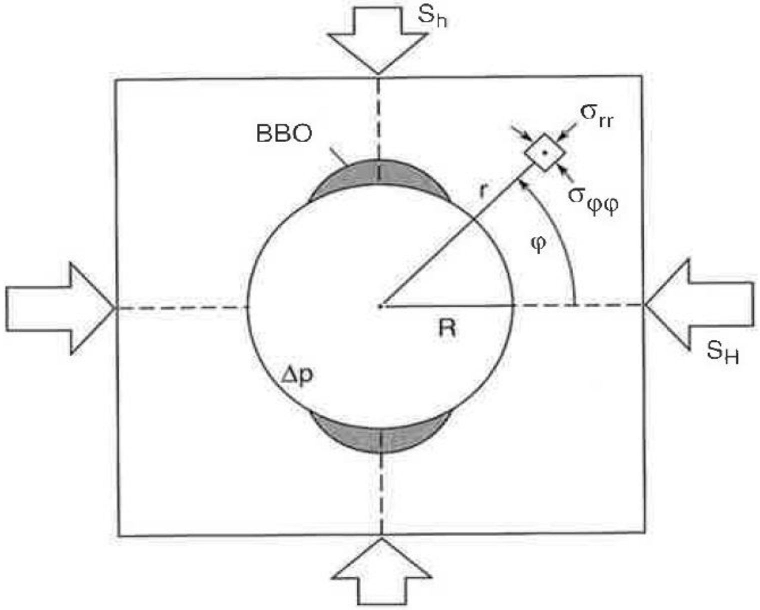
Classical 1D approaches – Kirsch's solution

- The simplest stress calculation approach is the Linear Elastic rock behavior model
- Calculated at the borehole wall
- Minimum pressure to keep all the points around the wellbore in the elastic range

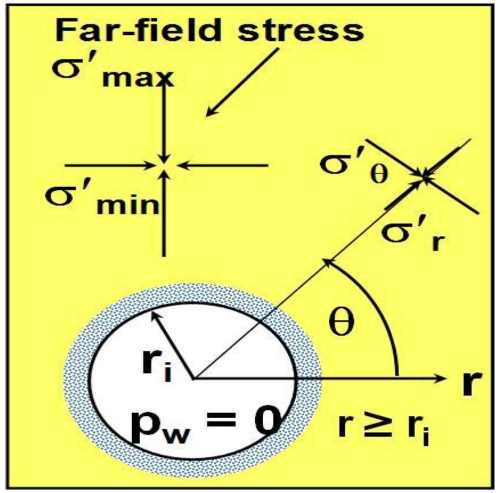
$$\sigma_r = P_w$$
$$\sigma_\theta = \sigma_H + \sigma_h - 2(\sigma_H - \sigma_h)\cos(2\theta) - P_w$$
$$\sigma_a = \sigma_z - 2\nu(\sigma_H - \sigma_h)\cos(2\theta)$$
$$\tau_{r\theta} = \tau_{\theta z} = \tau_{rz} = 0$$

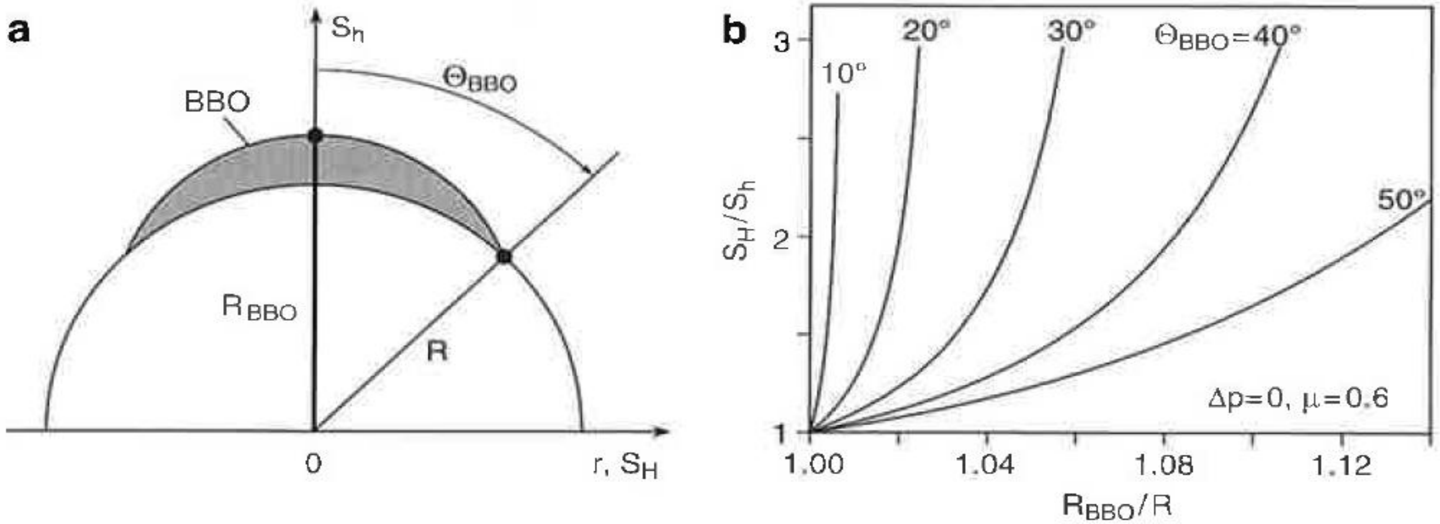




After Zang & Stephansson (2010)

Classical 1D approaches – Breakouts angle

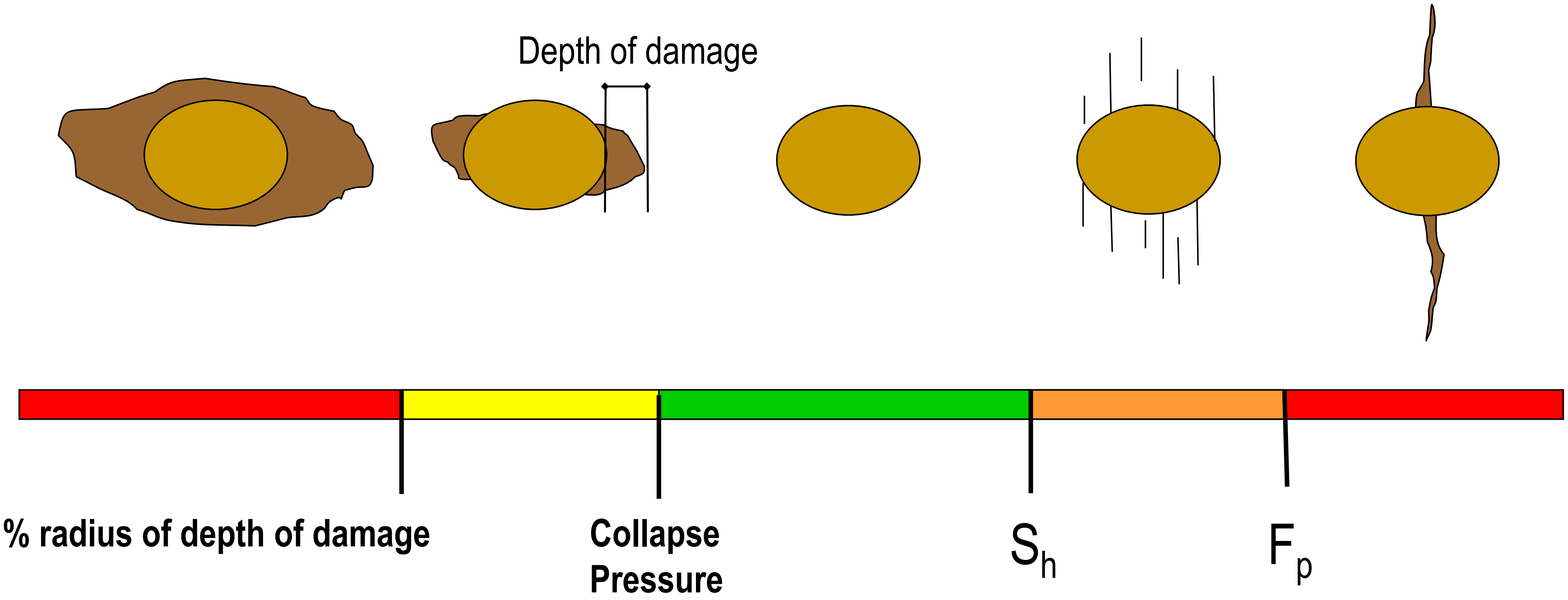




After Zang & Stephansson (2010)

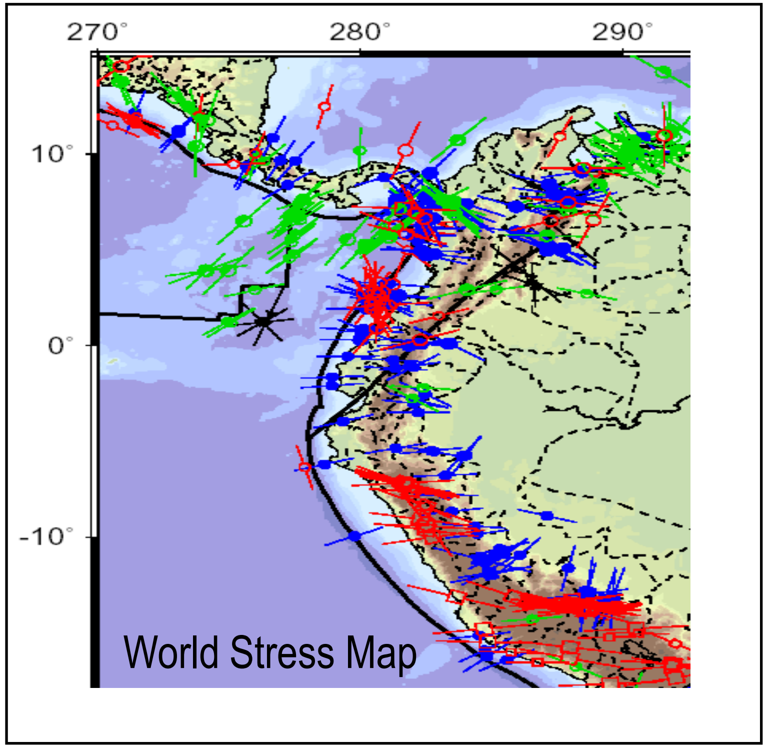
- Stresses vary away from wellbore wall
- Rock obeys Mohr-Coulomb failure criterion
- Clear physical meaning
- Not easy to calibrate also relying on available wellbore images (fluids effects, filtering, pads contact)
- Extension of breakouts (failure angle) is a function of the stress contrast (stress polygons). Vertical wells would have different breakouts angle than horizontal

Depth of Damage (DoD) model

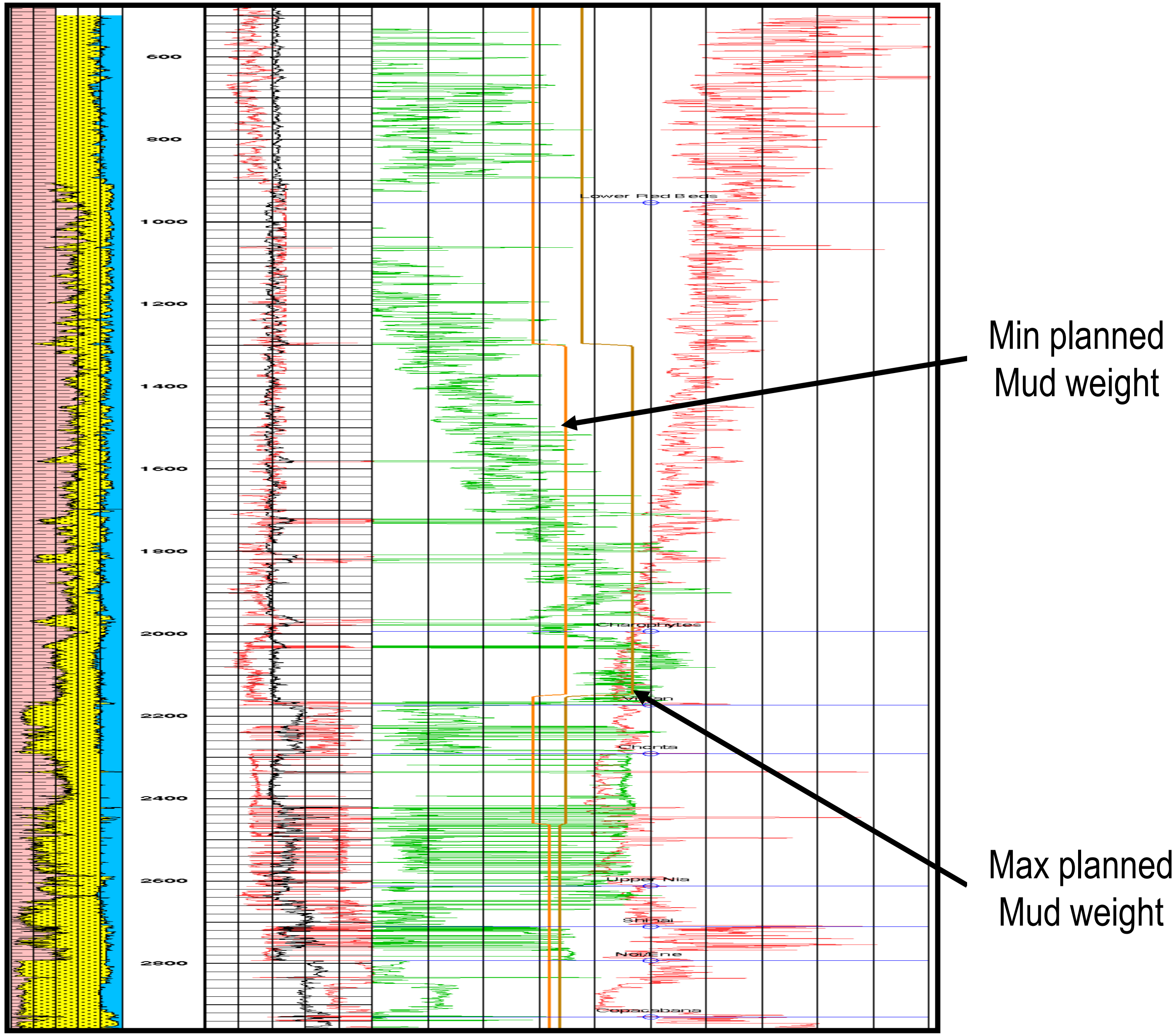


Can we drill with less than the collapse pressure?

Motivation



- Tectonically active area
- Initial models had no mud window
- What mud weight to use?
- How to define a fast and effective solution that includes real rock behaviour?



After Frydman et al. (2011)

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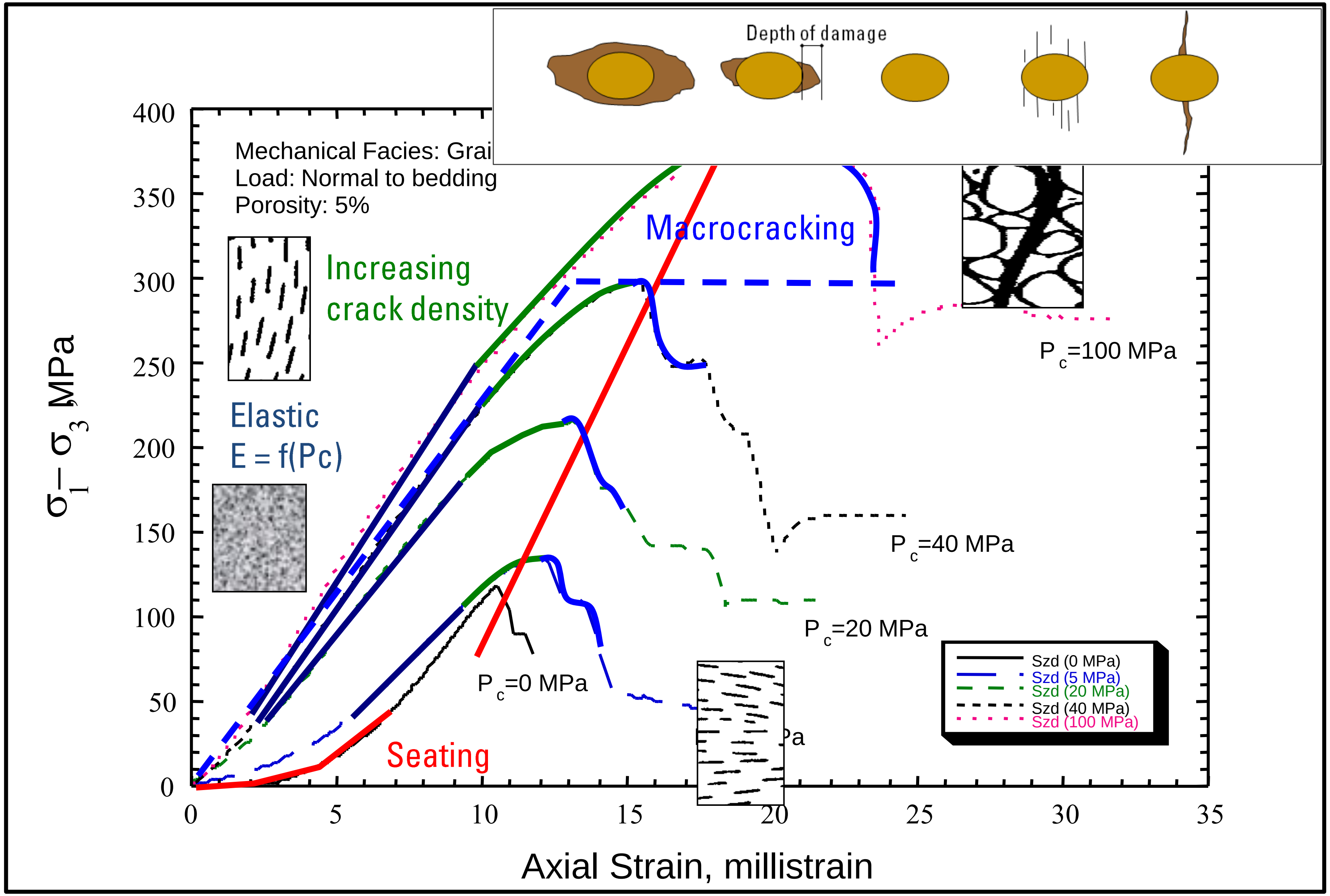
Strain hardening/softening behaviour



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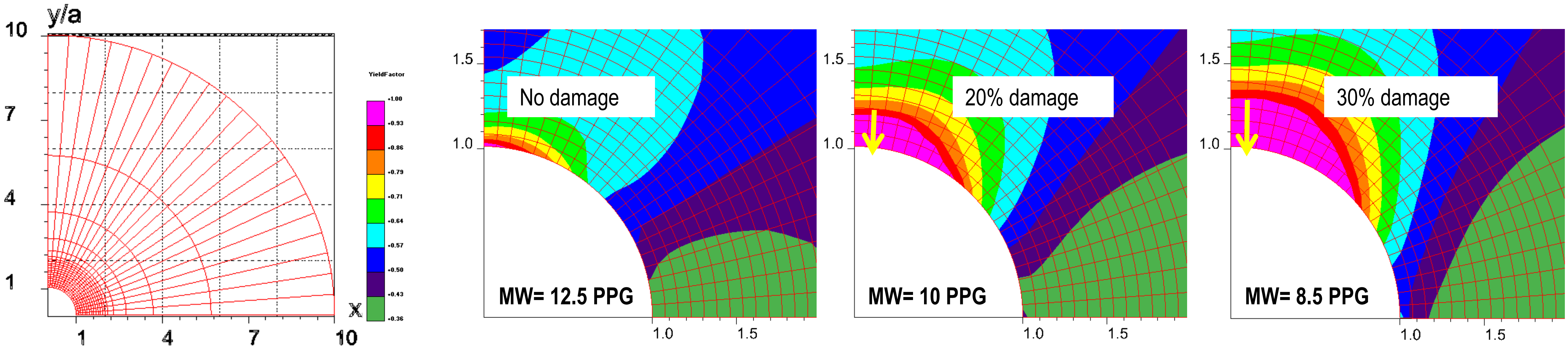
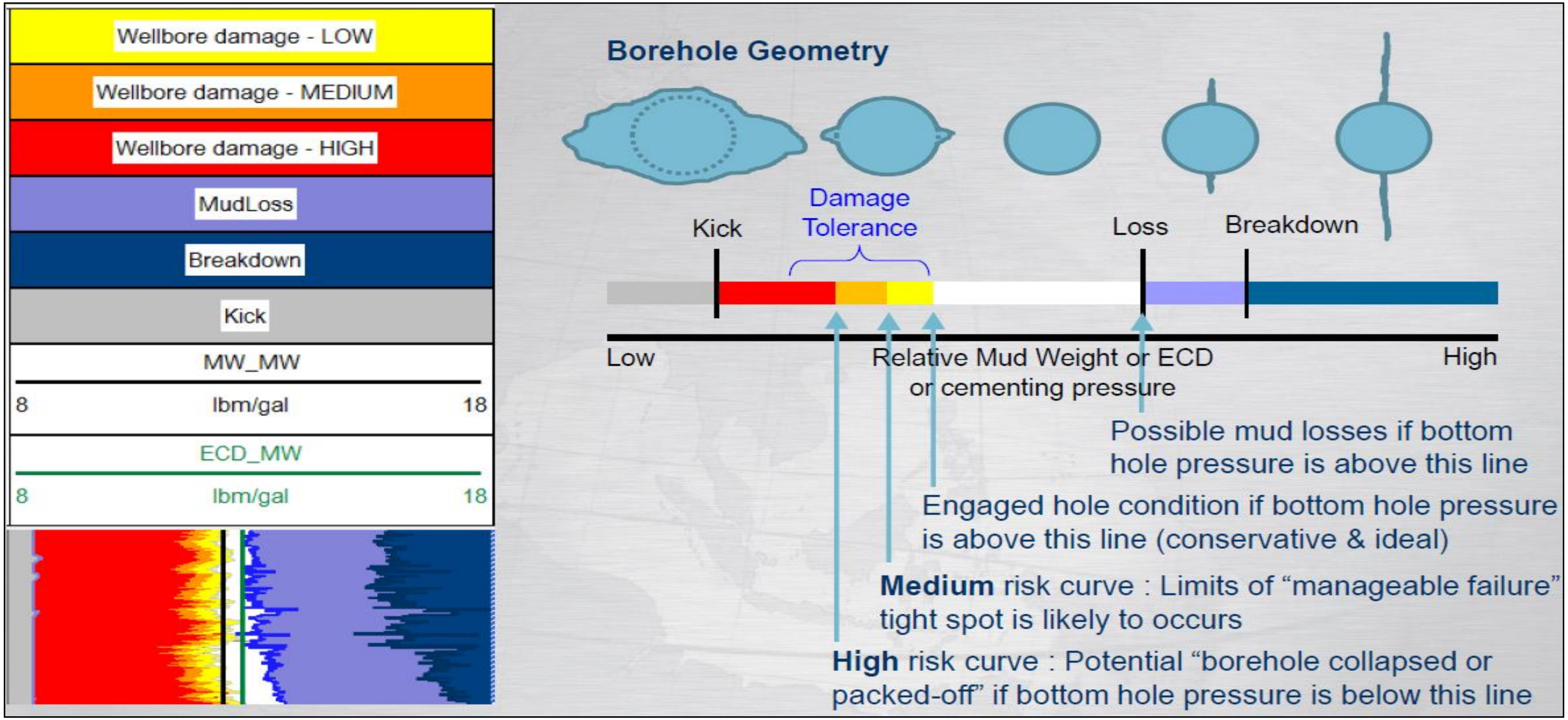
Depth of Damage (DoD)



- Stresses vary away from wellbore wall
- Failure quantified via DoD percentage (r_{damage} / r_{well})
- Calibrated on wellbore stability and actual MW (offsets wells)
- An optimum DoD is identified over the studied area based on observations from DDRs

Mud Weight Window and Wellbore Damage



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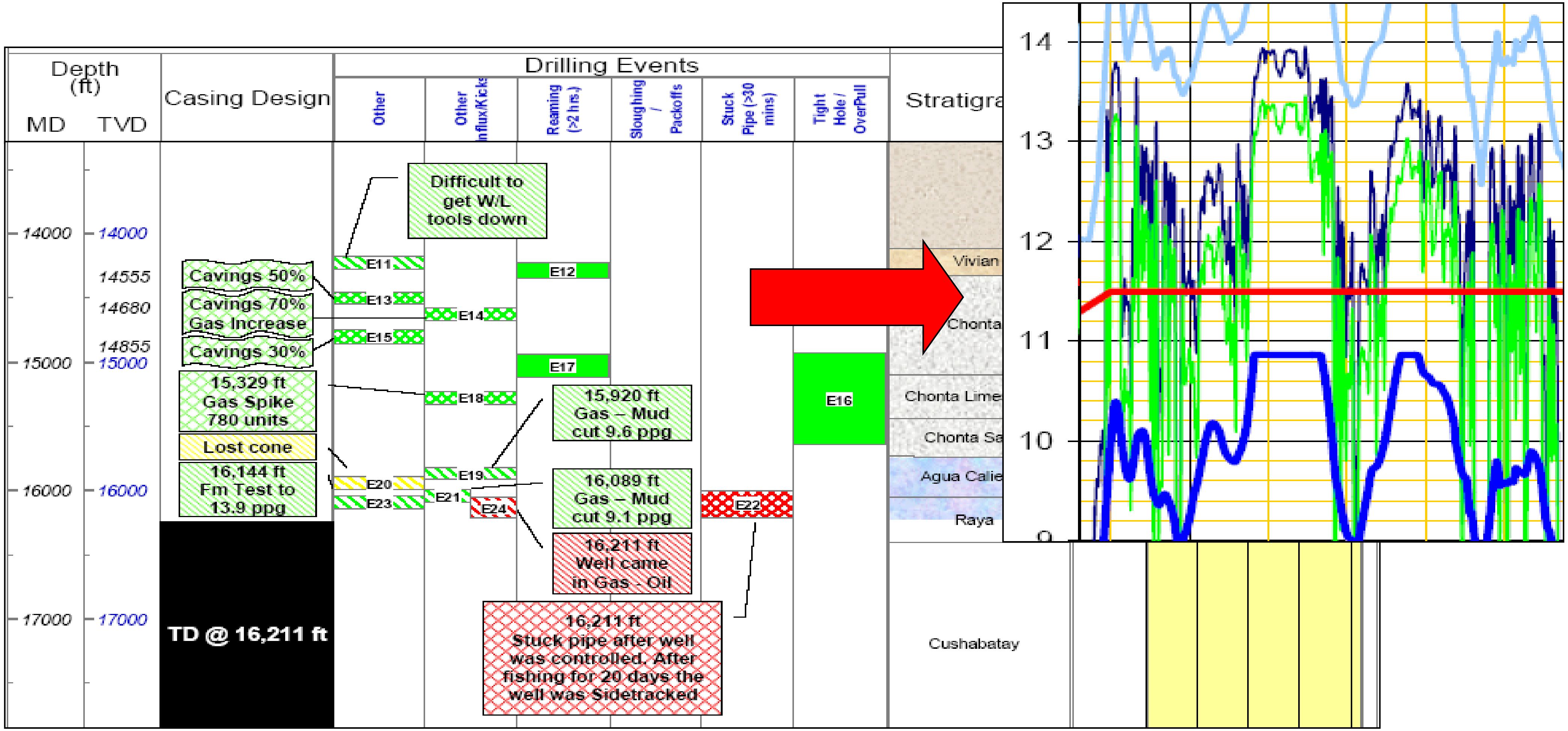
Drilling events & depth of damage



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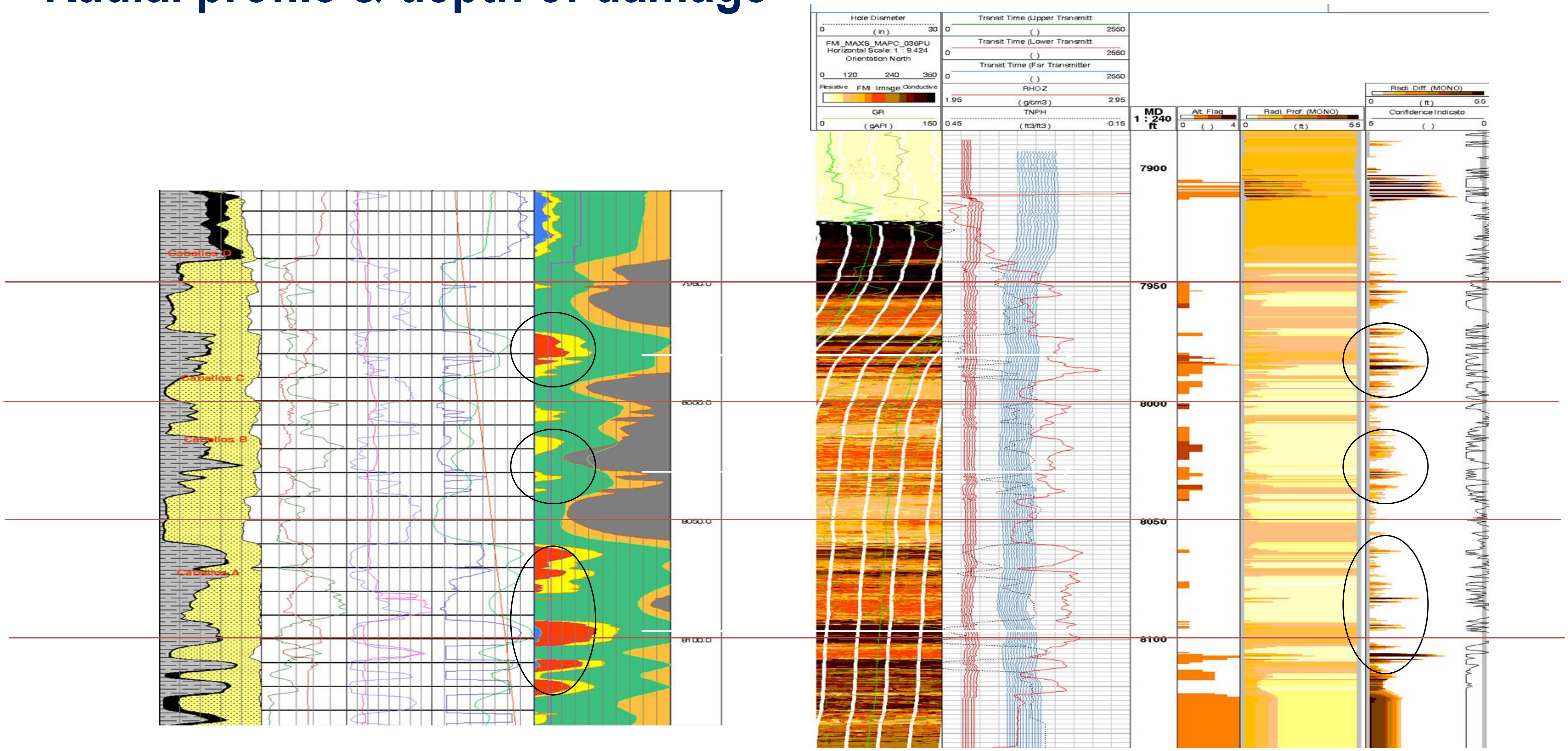
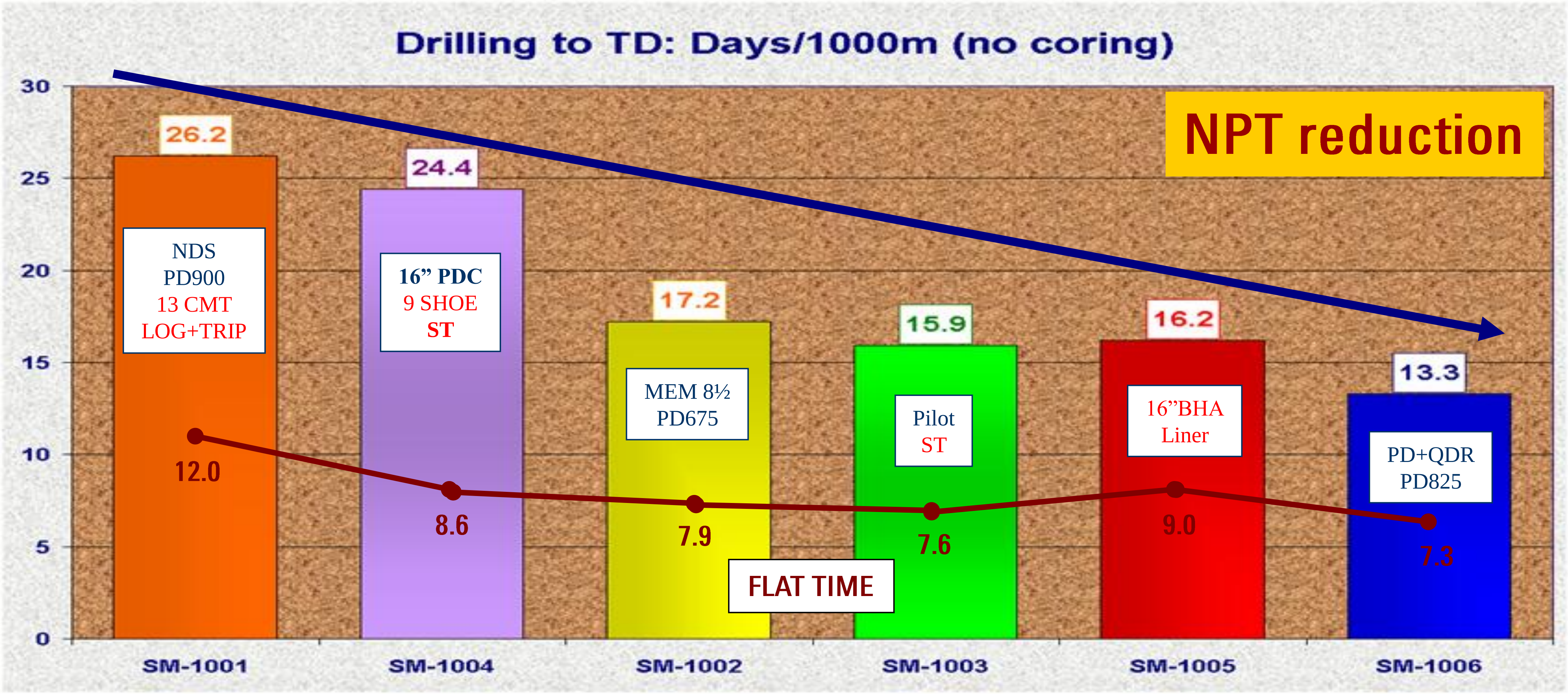
Radial profile & depth of damage



Improvement in Drilling Performance



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Unconventional failures: anisotropy

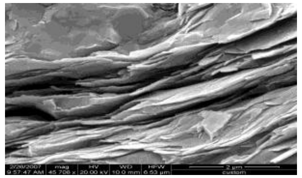
- Material and strength anisotropy of shales can effect the stability of any kind of cavity such as boreholes, tunnels, caves etc.

- The initiation of fractures as well as the collapse of cavities depends on stress field, orientation, pre-existing fractures and **intrinsic anisotropic properties of the rocks.**

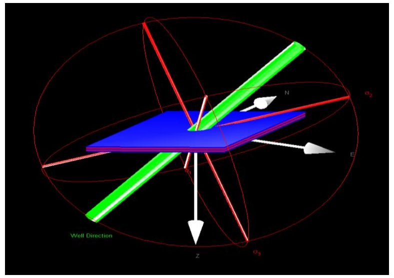
- Especially for boreholes the **anisotropic nature of shales** has significant impact on **magnitude and orientation of failure**

- It is crucial to provide an **analytic solution** for the borehole stress concentration as well as an **anisotropic failure criterion**

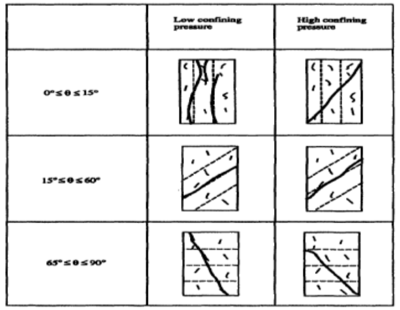
Intrinsic anisotropy

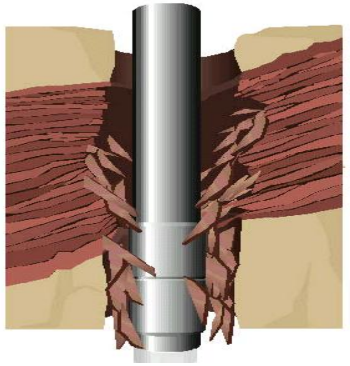


Anisotropic stress
(FF and BH)



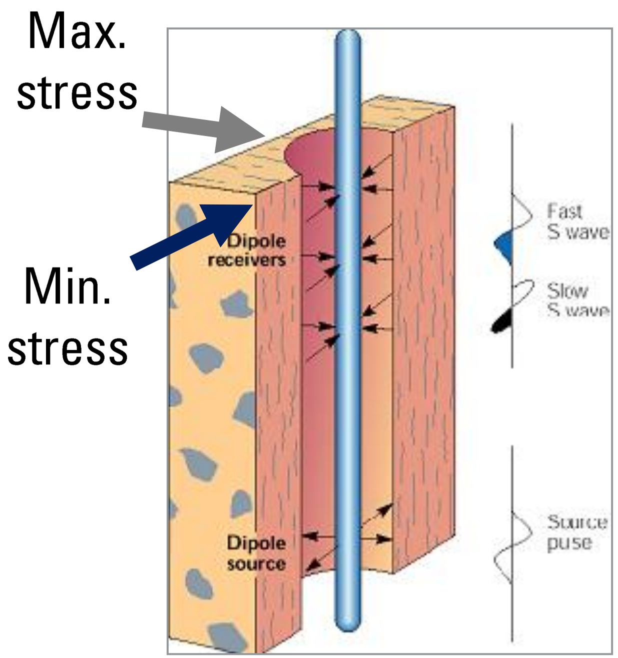
Anisotropic Strength





Anisotropies

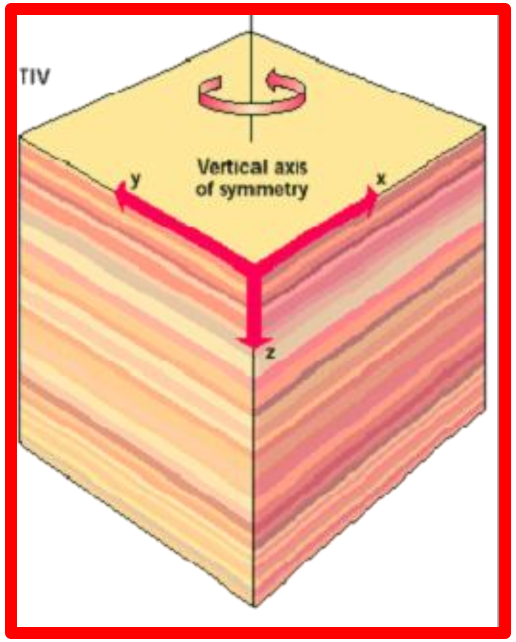
Stress-Induced



Stress

$V_S(r,\theta)$

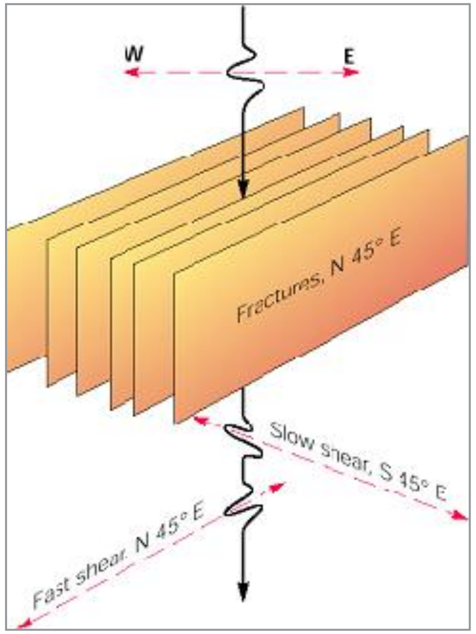
Intrinsic



Bedding
(transverse isotropic vertical)

$V_S(\theta)$

Intrinsic



Fractures

$V_S(\theta)$

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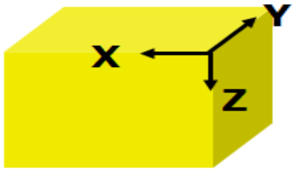
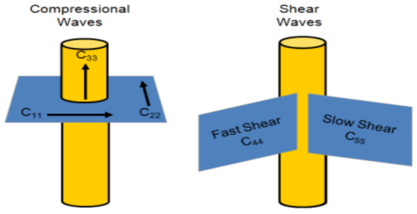
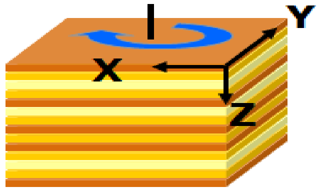
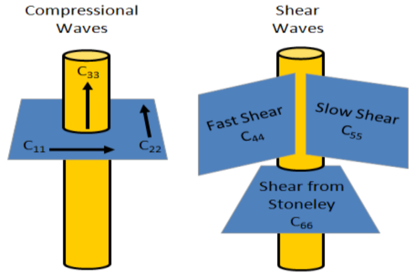
Elastic Mechanical Properties from Acoustic

<table>
<tr><th>Rock type</th><th>Available Sonic Measurements</th><th>Unknown Parameters</th></tr>
<tr><td>

Isotropic</td><td>2
VERTICAL COMPRESS. SLOWNESS
VERTICAL SHEAR SLOWNESS

</td><td>2
YOUNG'S MODULUS
POISSON'S RATIO</td></tr>
<tr><td>

TIV</td><td>3
VERTICAL COMPRESS. SLOWNESS
VERTICAL SHEAR SLOWNESS
HORIZONTAL SHEAR SLOWNESS

</td><td>5
VERTICAL YOUNG'S MODULUS
HORIZONTAL YOUNG'S MODULUS
VERTICAL POISSON'S RATIO
HORIZONTAL POISSON'S RATIO
VERTICAL SHEAR MODULUS</td></tr>
</table>

Use anisotropic stress models and core data to define the remaining 2 unknowns

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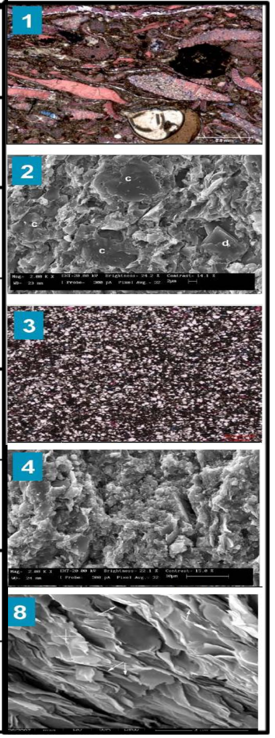
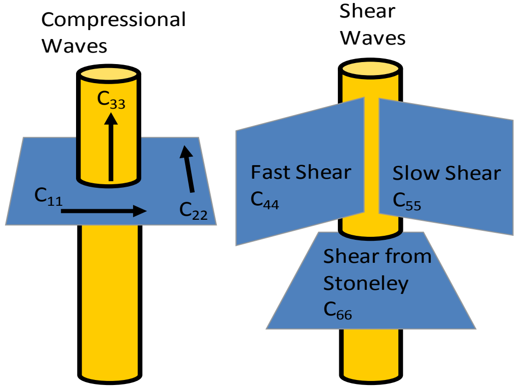
Rock Fabric, Mechanical Properties & Stresses

#	Matrix Composition	Elasticity E_h/E_v	Elasticity ν_h/ν_v
1	Carbonate	1.03	0.97
2	Calcareous Mudstone	1.05	0.88
3	Silty Mudstone	1.52	1.25
4	Siliceous Mudstone	2.06	1.47
5	Organic/Argillaceous Mudstone	2.49	1.34
6	Argillaceous/Siliceous Mudstone	2.99	1.60
7	Argillaceous/Calcareous Mudstone	3.79	1.26
8	Argillaceous Shale	4.01	2.07



ISOTROPIC

$$\sigma_h = \frac{\nu}{1-\nu}\left(\sigma_V - \alpha P_p\right) + \alpha P_p + \sigma_{h-tect}$$



SONIC SCANNER LOGS

ANISOTROPIC (TIV)

$$\sigma_h = \frac{E_h}{E_v}\frac{\nu_v}{1-\nu_h}\left(\sigma_V - \alpha P_p\right) + \alpha P_p + \sigma_{h-tect}$$

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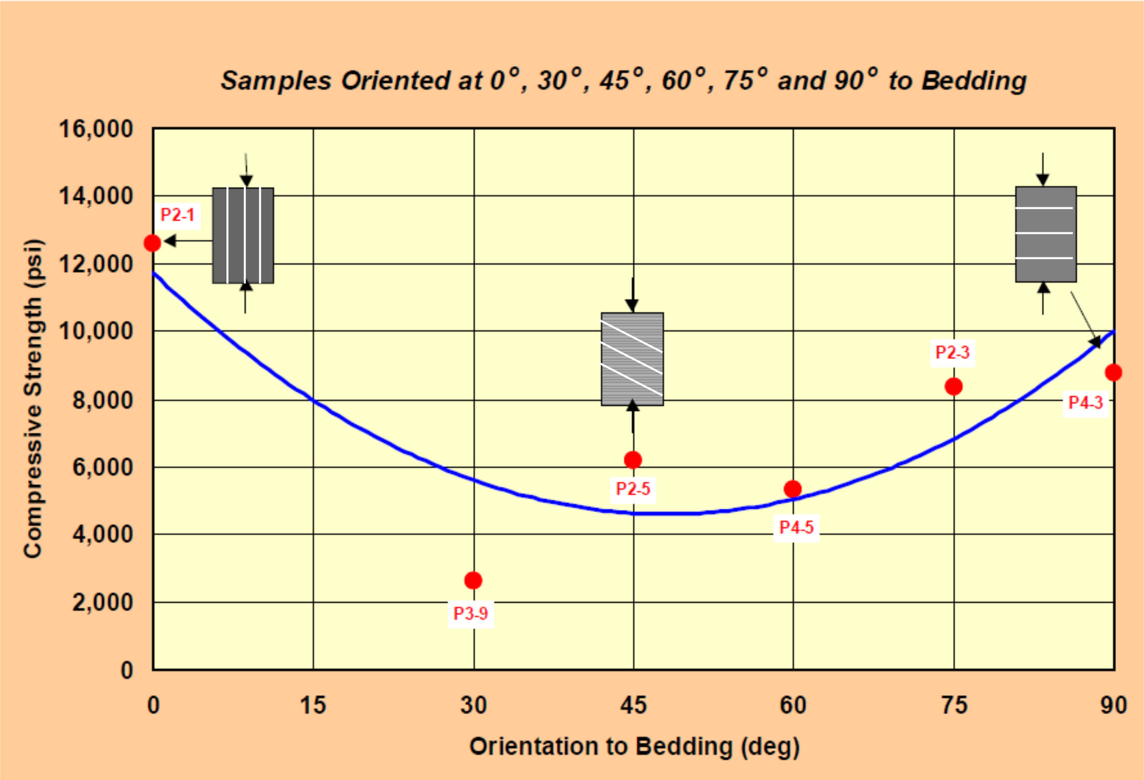
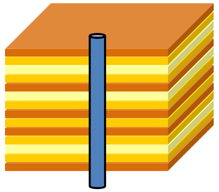
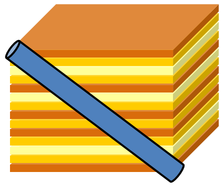
Strength Anisotropy in Shale

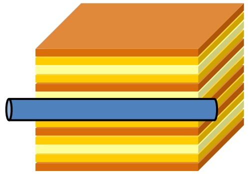




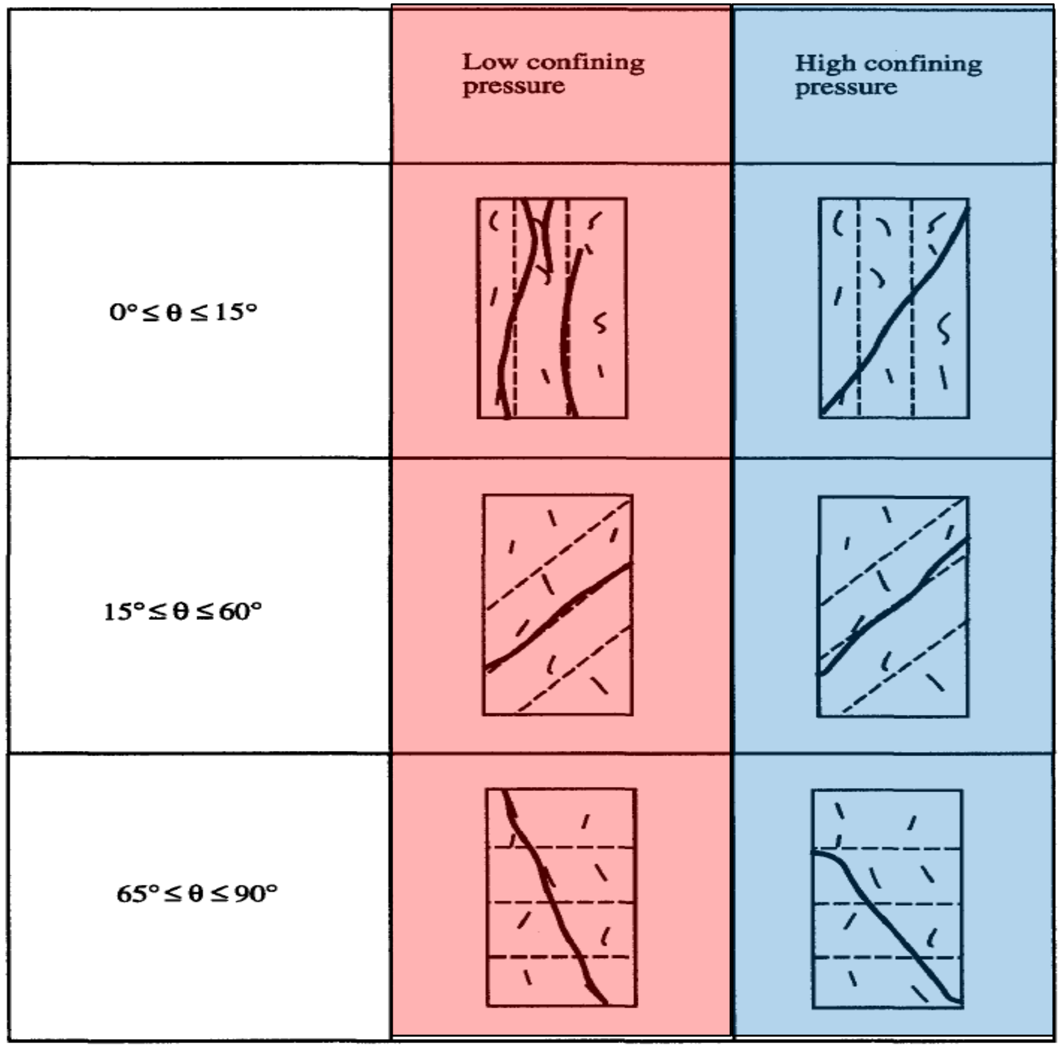
V-well



Deviated-well



H-well



after Niandou et al., 1997 (IJRMMS)

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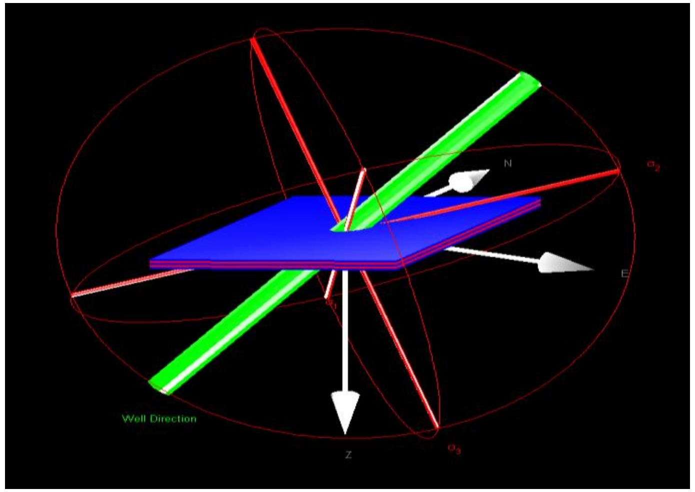
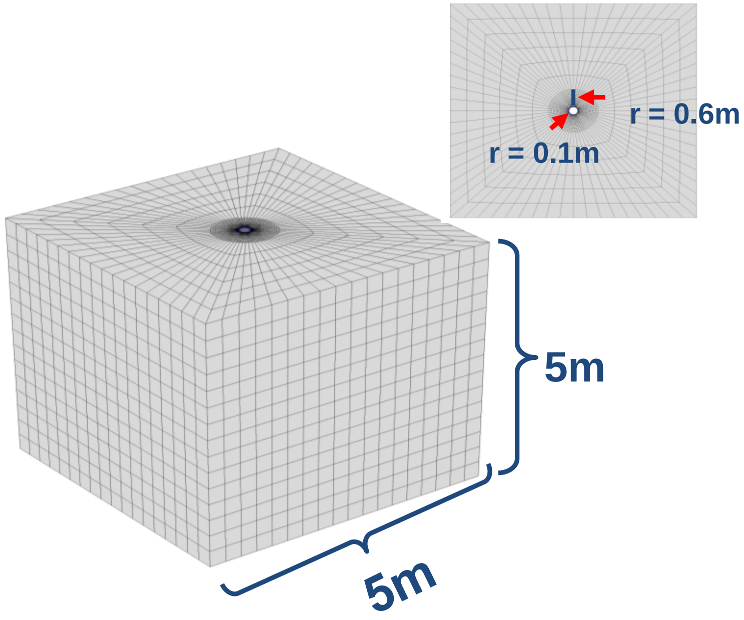
Stress Concentration

- Based on classical elastic solutions for anisotropic media by Lekhnitskii (1963), Amadei (1983)
- This solution computes the state of stress around borehole for any
  - *stress field*
  - *borehole orientation*
  - *material anisotropy and orientation*
- The analytical solution is fast, accurate and 3D
- Validated via FEM analysis



Validation with a FEM model



After Gaede et al., 2012, (IJRMMS 51)

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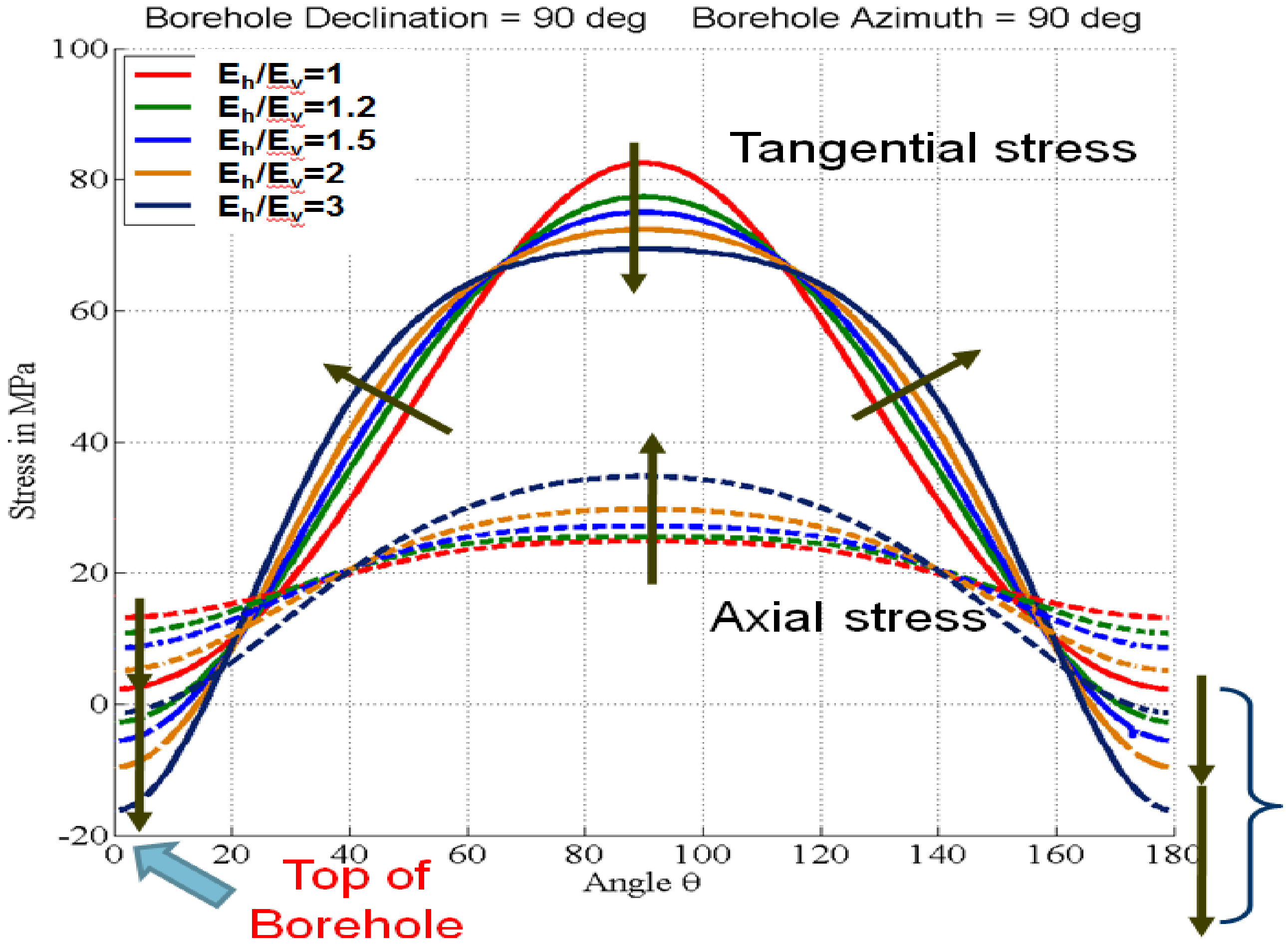
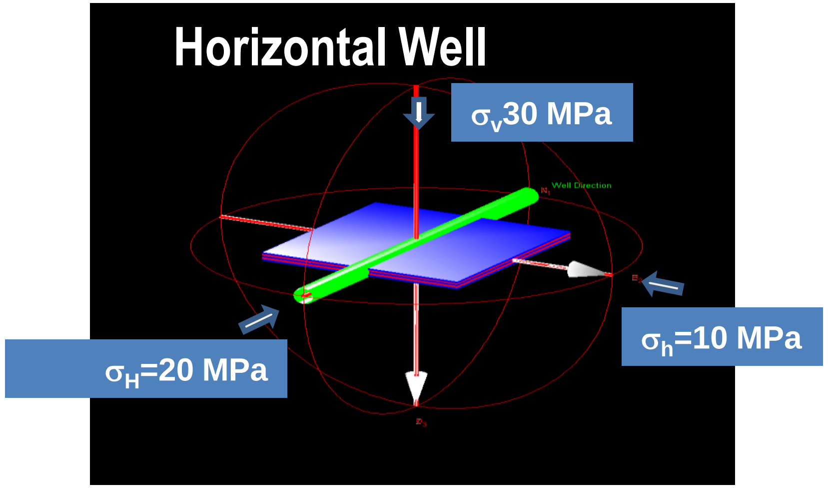
Anisotropy Impact on Stress Concentration





Borehole Stresses for Increasing Ratio of Young's Moduli

The Hoop stress remains the smallest stress and it decreases → it will be easier to create a L-frac

After Prioul et al. (2012)
SPE 147462

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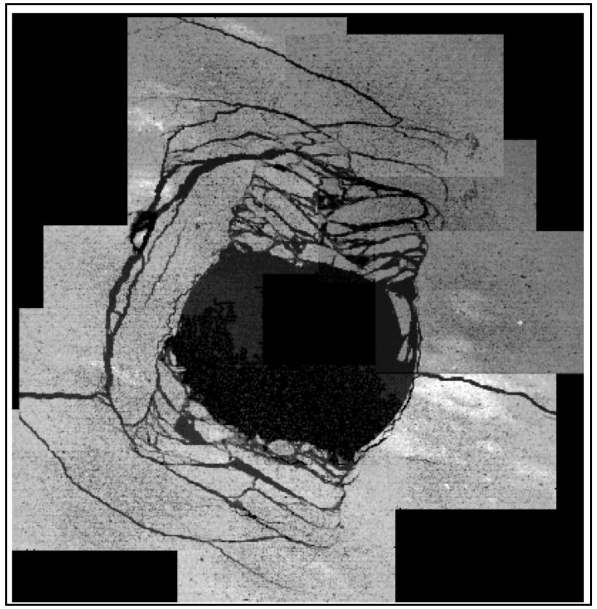
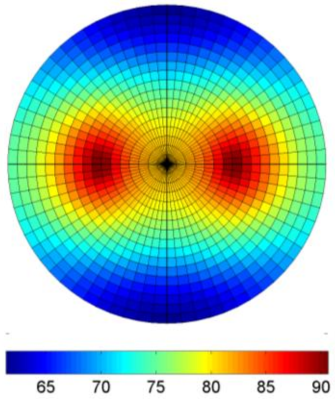
Effect of Shale Lamination (anisotropy) on Failure





- Kirsch's solution no longer valid
- Amadei's solution for anisotropic media

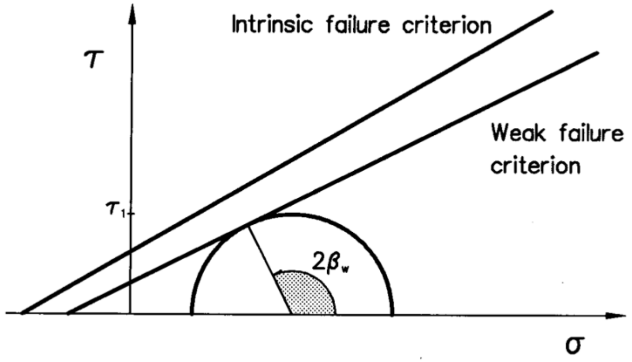
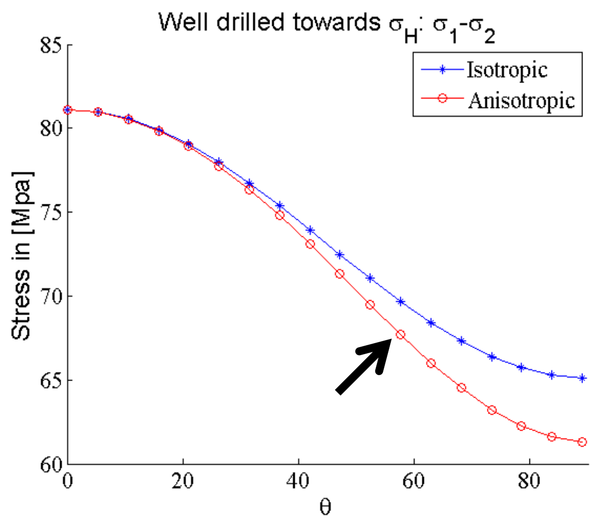
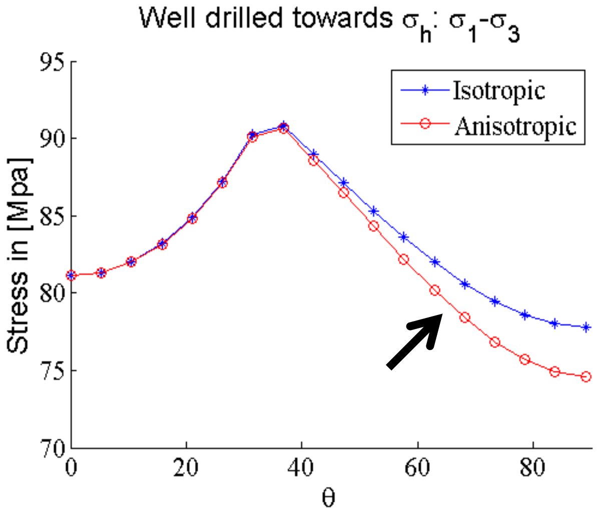


Figure 2.33. Mohr-Coulomb criterion for a material with a plane of weakness. The major principal stress has been increased such that the Mohr circle touches the failure plane along the weak planes.

After Fjaer et al.



Lower stress needed for Tensaile failure in anisotropic rock



After Karpfinger (2011)

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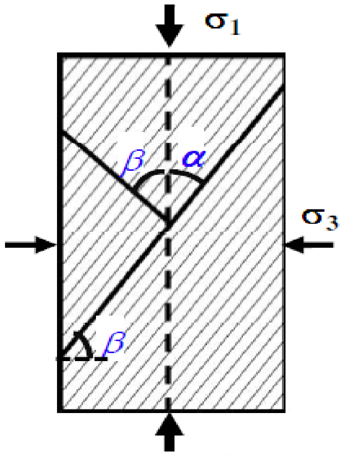
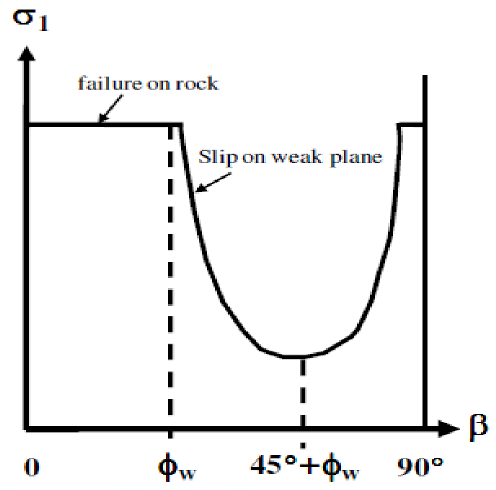
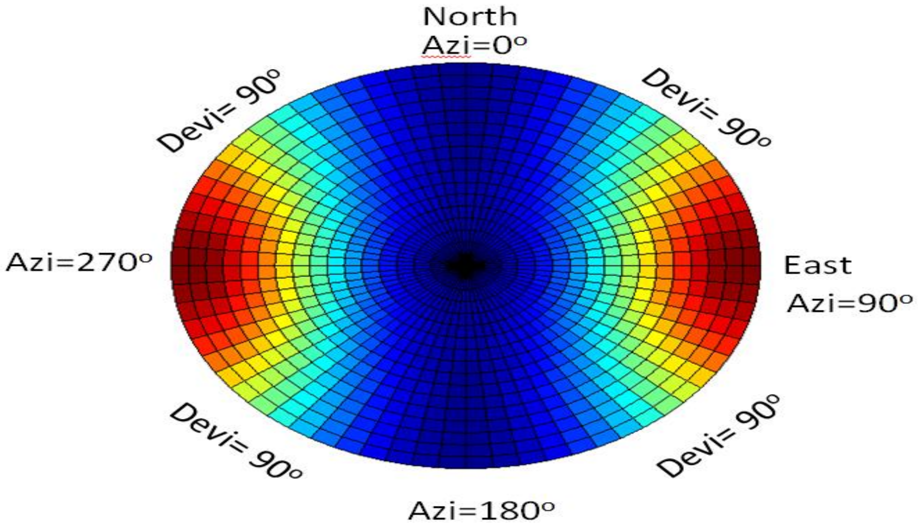
Anisotropic Failure criterion

- Anisotropic failure model: Plane-of-Weakness model (Jaeger's sliding model,1960), other possible (Pariseau, Pei, etc.)
- Mohr-Coulomb – intact rock failure
- Plane of Weakness – sliding on weak surfaces
- Validated against analytical solution for vertical well
- Required inputs – cohesion and friction angle for intact rock and weak plane
- Evaluation of failure criteria: both criteria are evaluated for a given depth
- Various ways of analysis:
  - single depth – for full borehole circumference
  - single depth 3D – provides stress directions around borehole circumference and zone of failure
  - single depth Schmitt plot – e.g. fixed material orientation changing borehole orientation
  - evaluation of failure criteria along well – mudweight window & pseudo image





Stereonet for mud window



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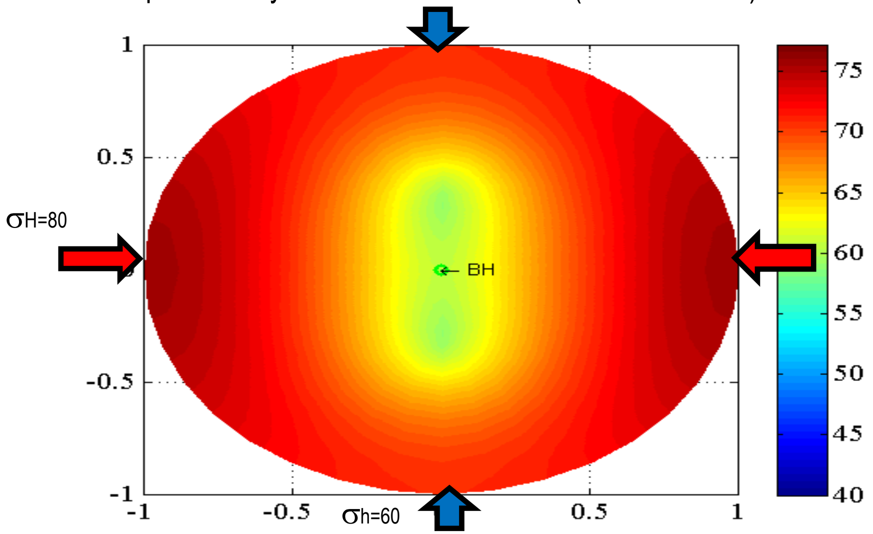
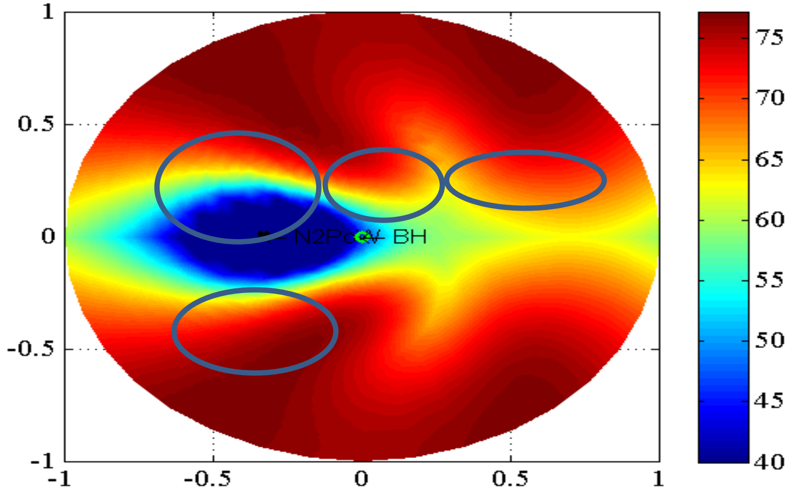
Wellbore Stability Vs. Borehole Orientation

Well trajectory optimization considering borehole stability

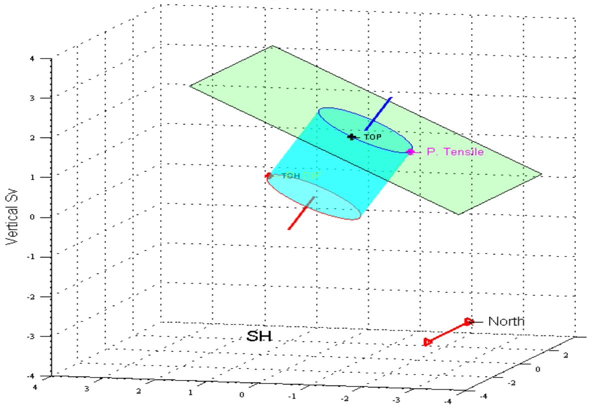
Well pressure by Intact Rock M-C Failure (σV =100MPa)



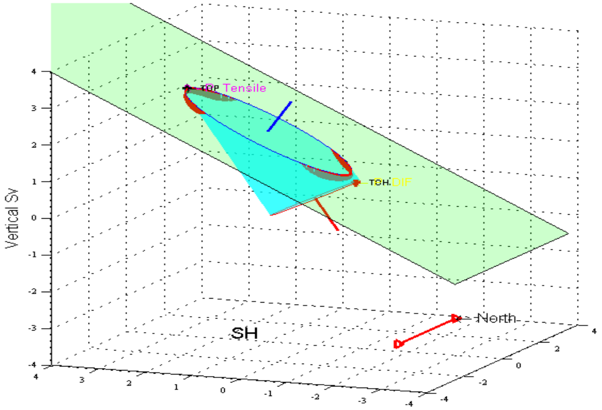
Well pressure by PoW Failure model (PoW dip/angle =90/30)



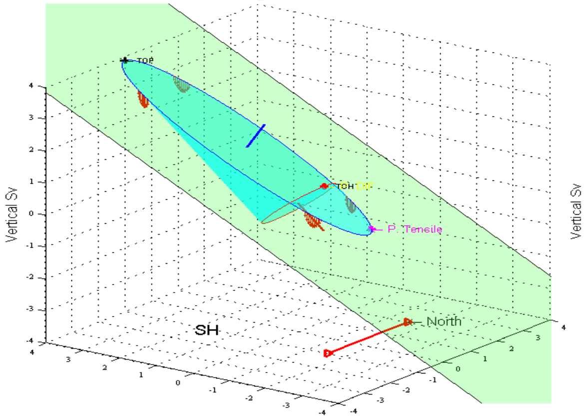
BH Attack Ang & Azim to PoW =0,90



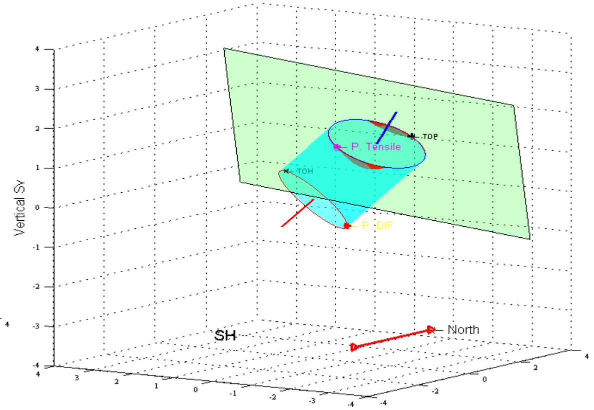
BH Attack Ang & Azim to PoW =60,0



BH Attack Ang & Azim to PoW =75,0



BH Attack Ang & Azim to PoW =42,-41



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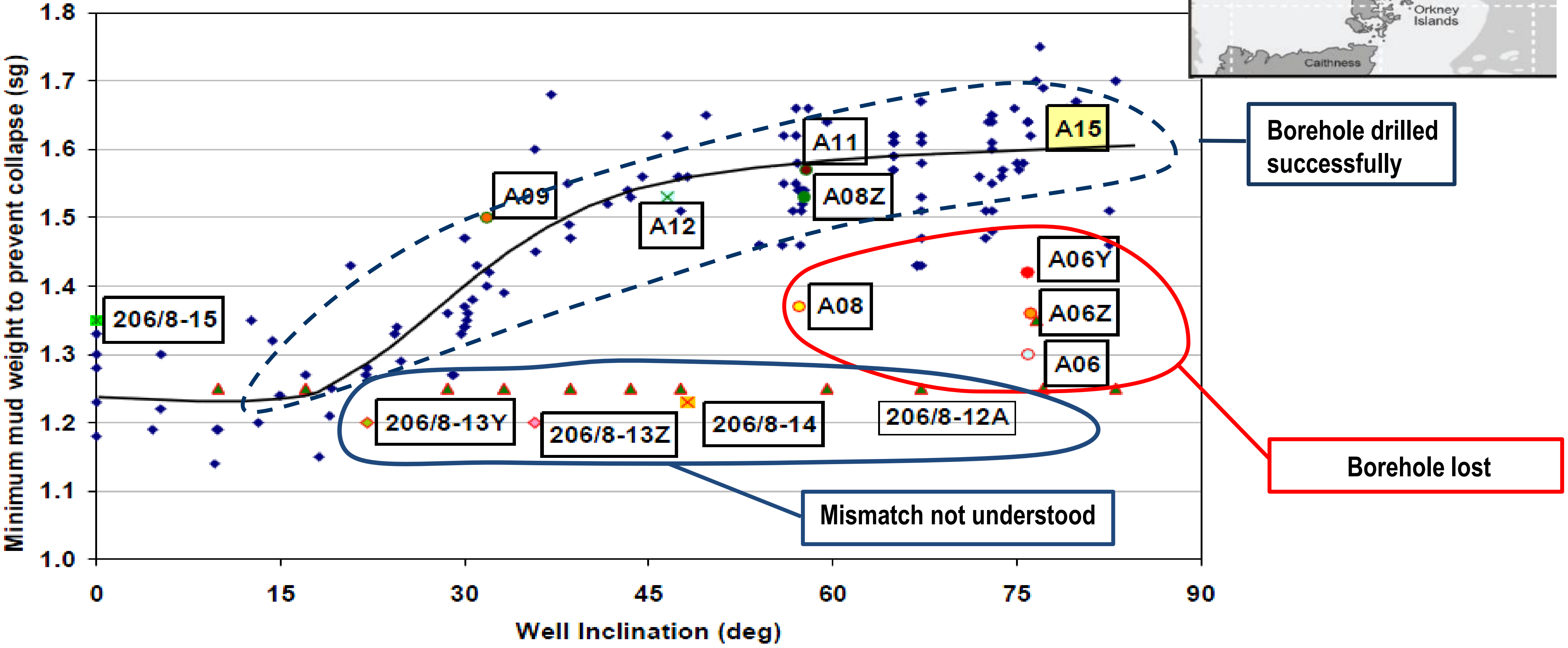
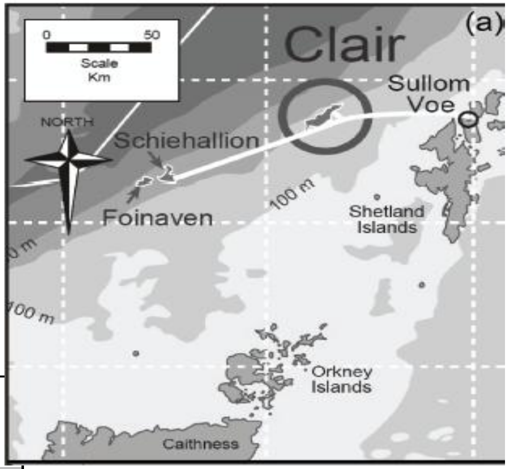
Field Example – Clair Field

Field data published in SPE 124464





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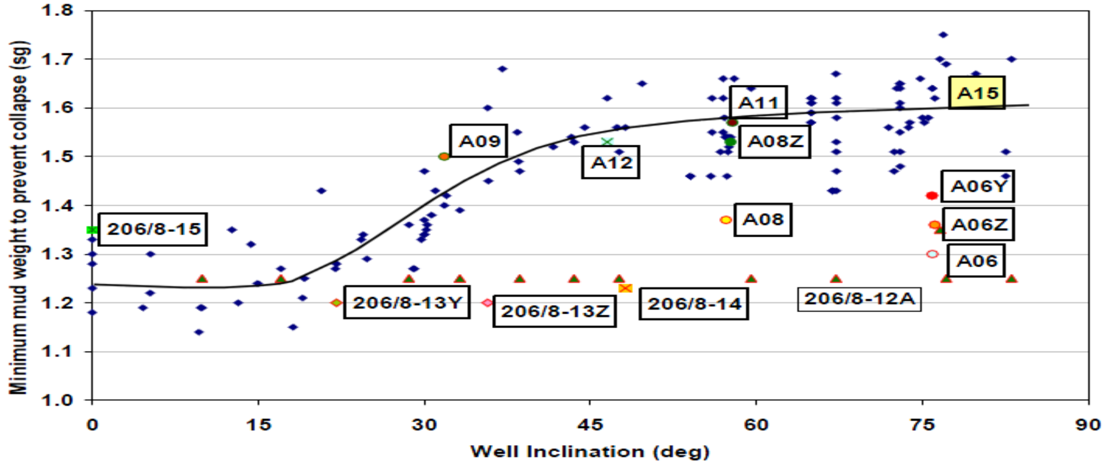
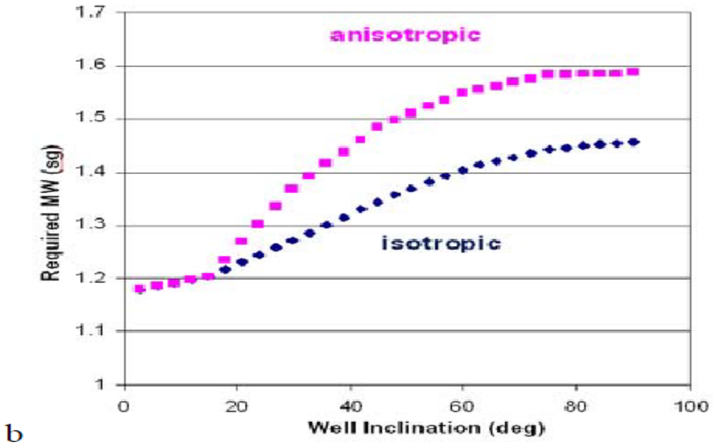
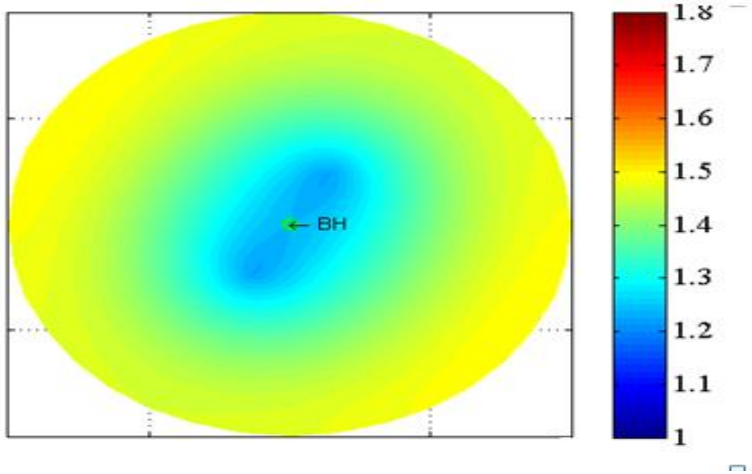
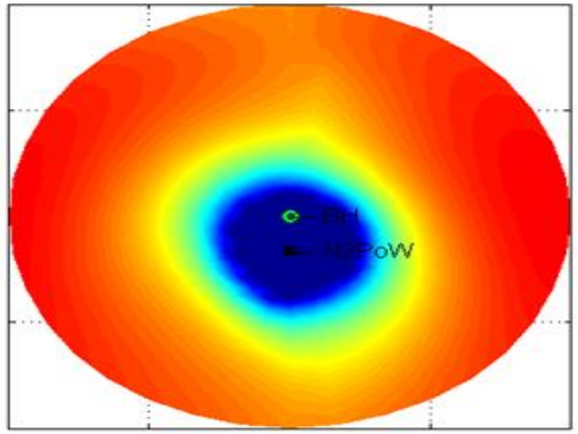
Field case study – Clair Field in UK Continental Shelf

Field data published in SPE 124464 (BP)

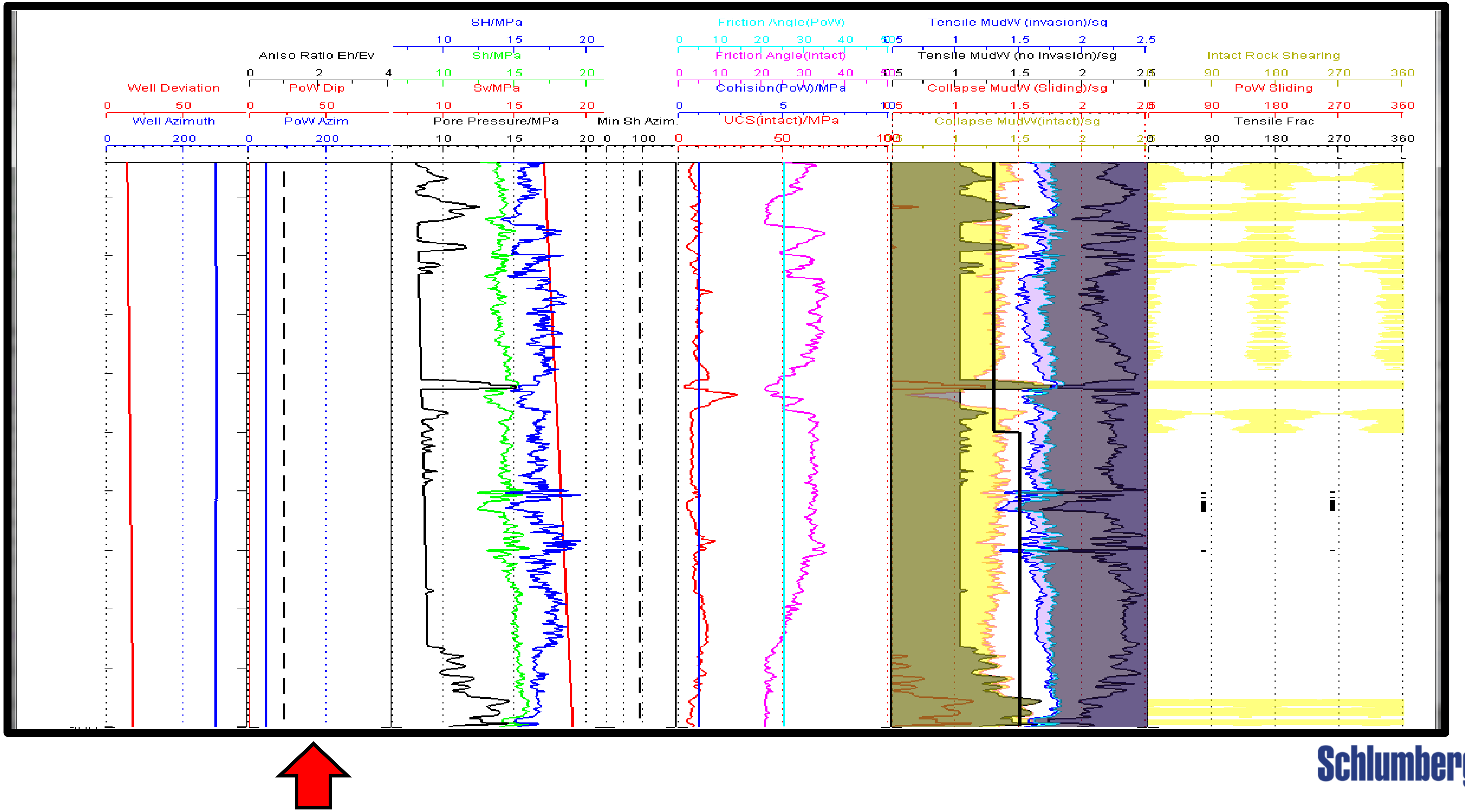








WBS with PoW Model (PoW dip 0 – 30 – 45 – 60 – 75 - 85)



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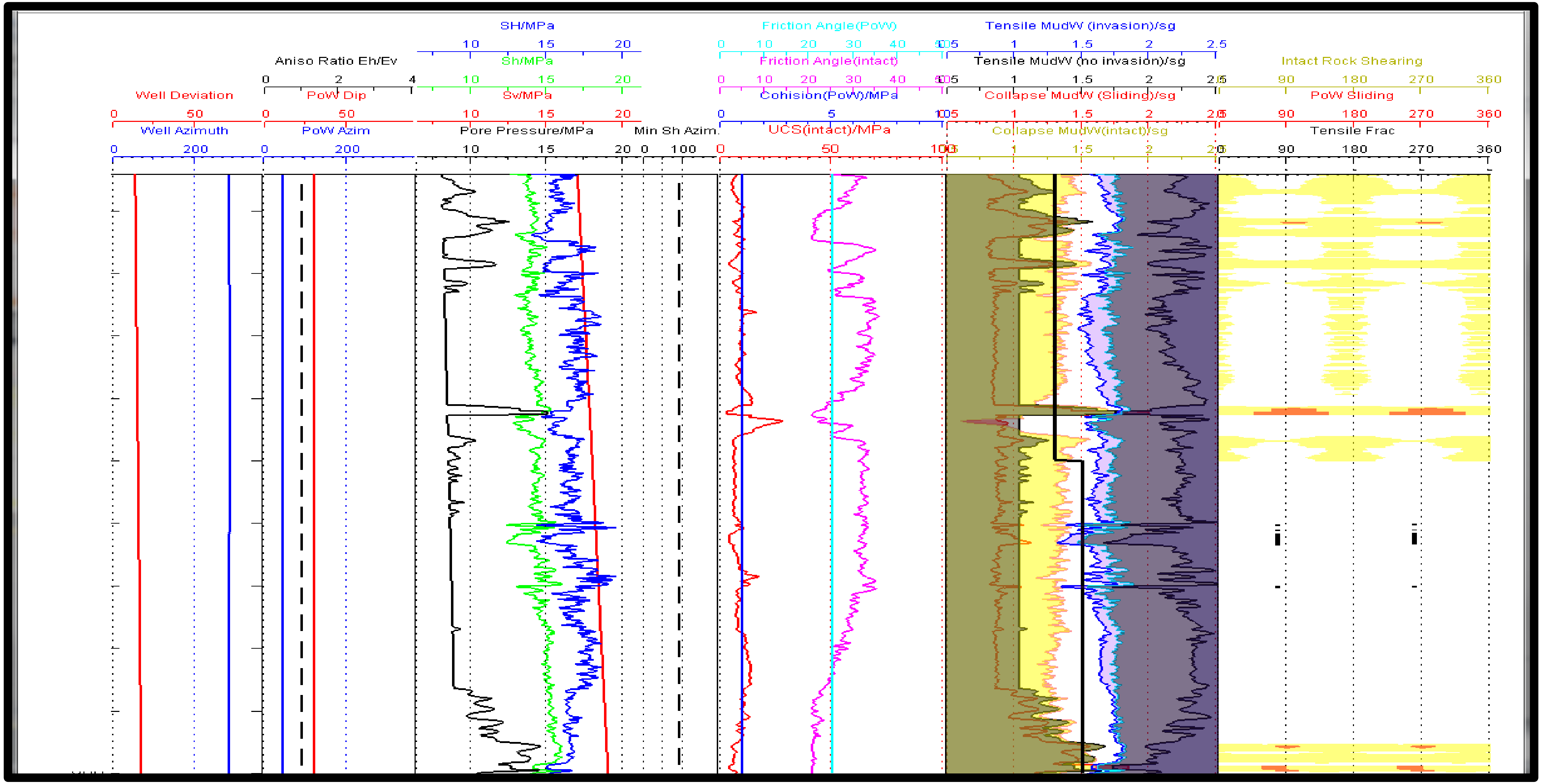
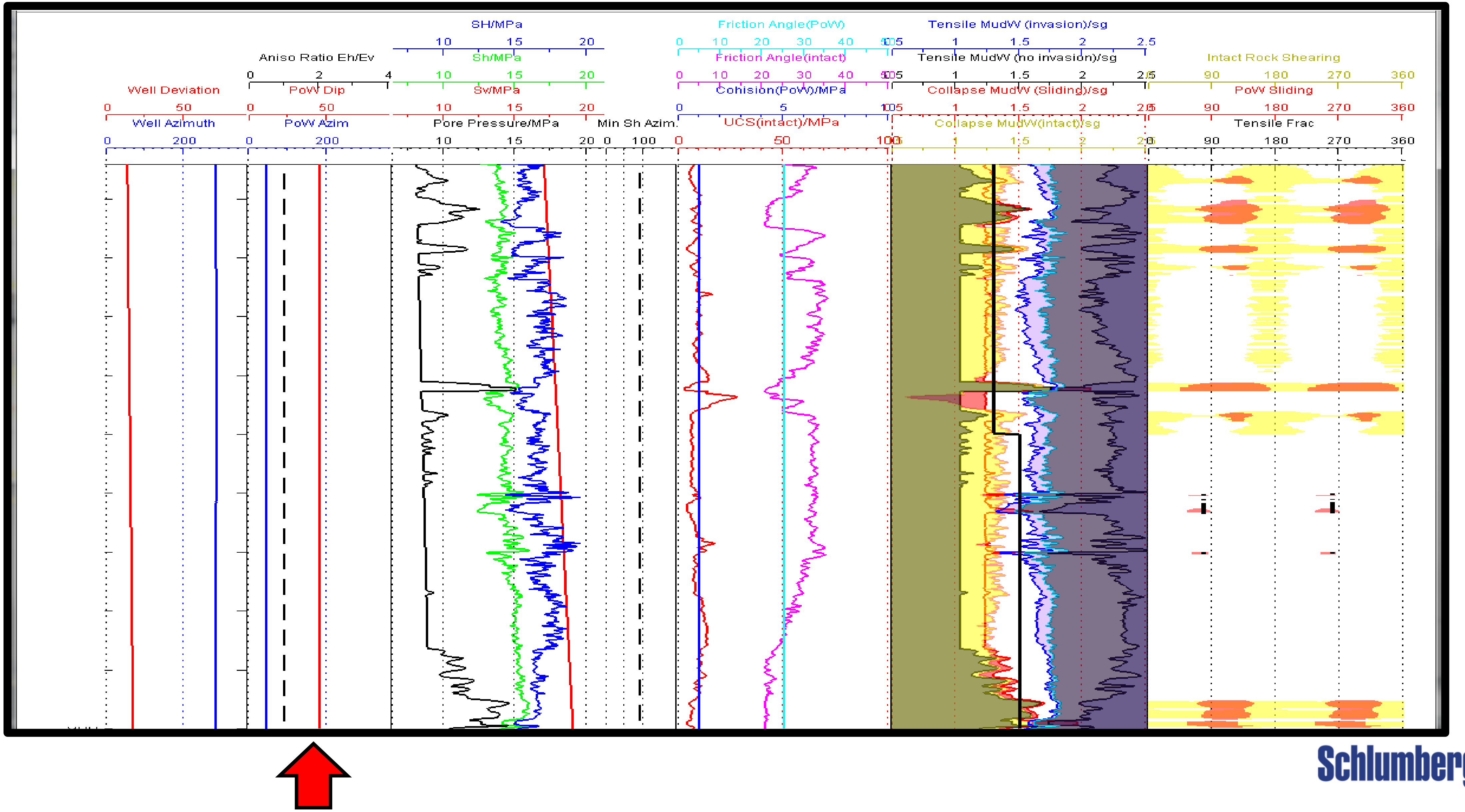
WBS with PoW Model (PoW dip 0 – 30 – 45 – 60 – 75 - 85)



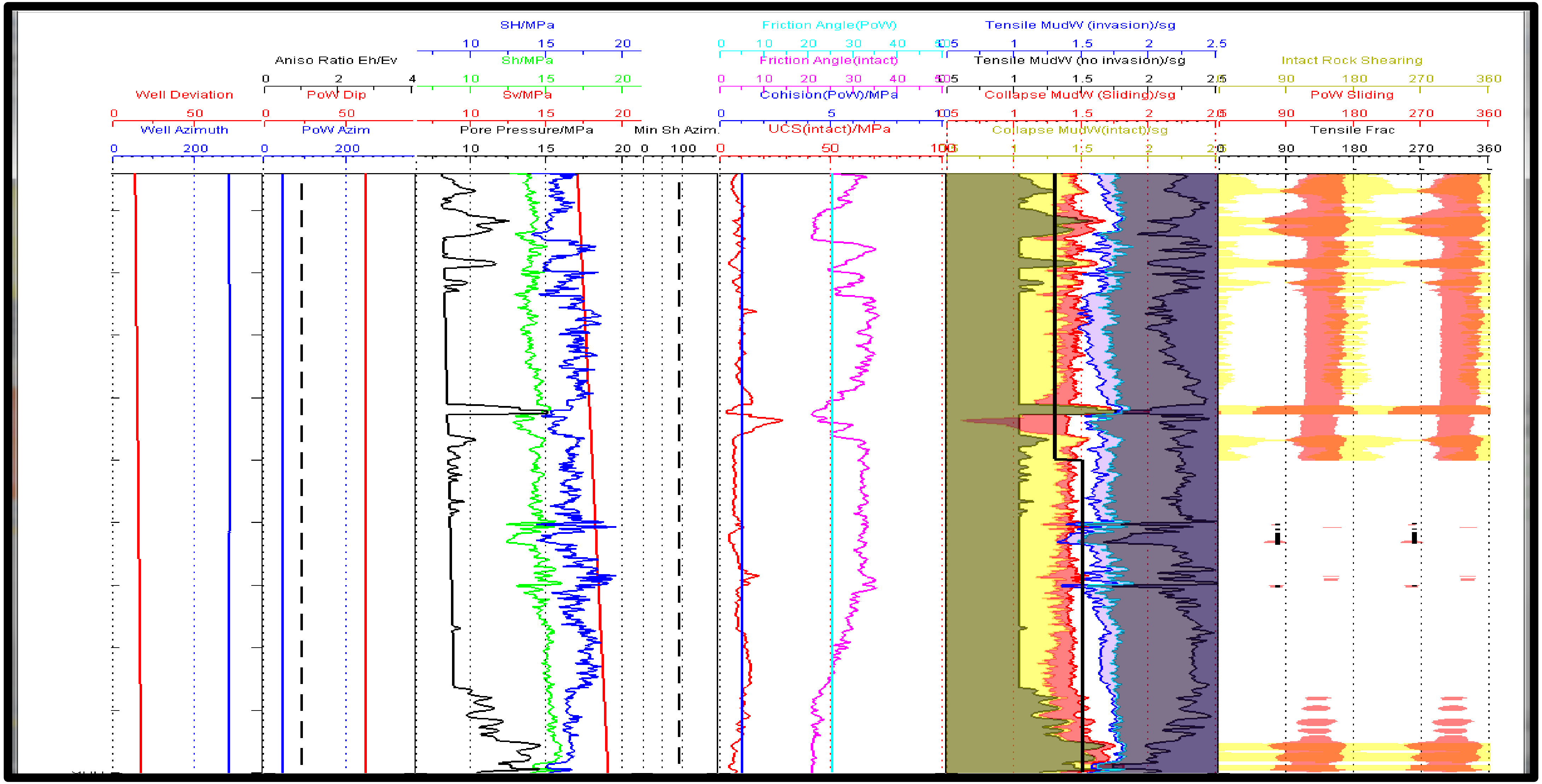
Schlumberger

WBS with PoW Model (PoW dip 0 – 30 – 45 – 60 – 75 - 85)



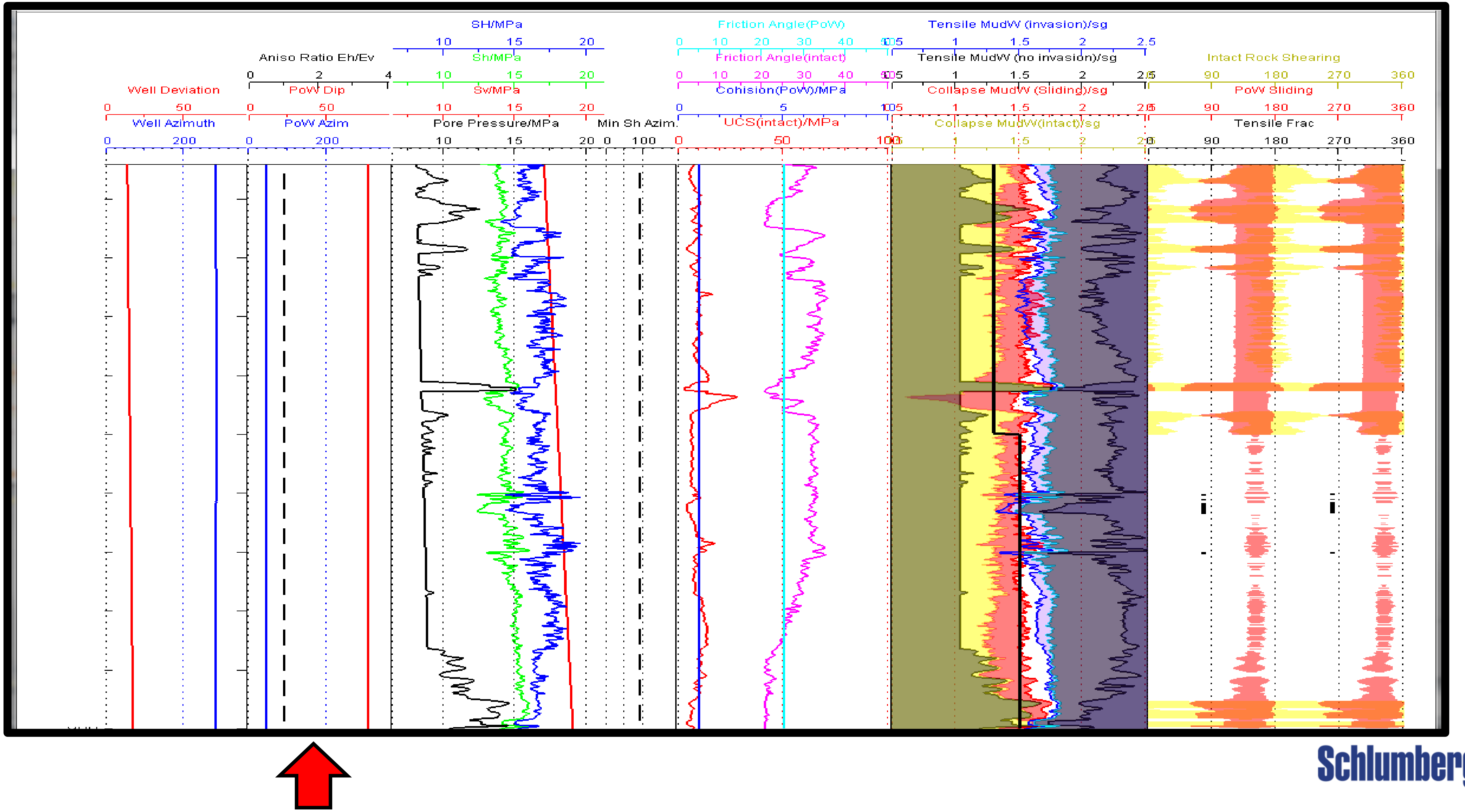
Schlumberger

WBS with PoW Model (PoW dip 0 – 30 – 45 – 60 – 75 - 85)



Schlumberger

WBS with PoW Model (PoW dip 0 – 30 – 45 – 60 – 75 - 85)



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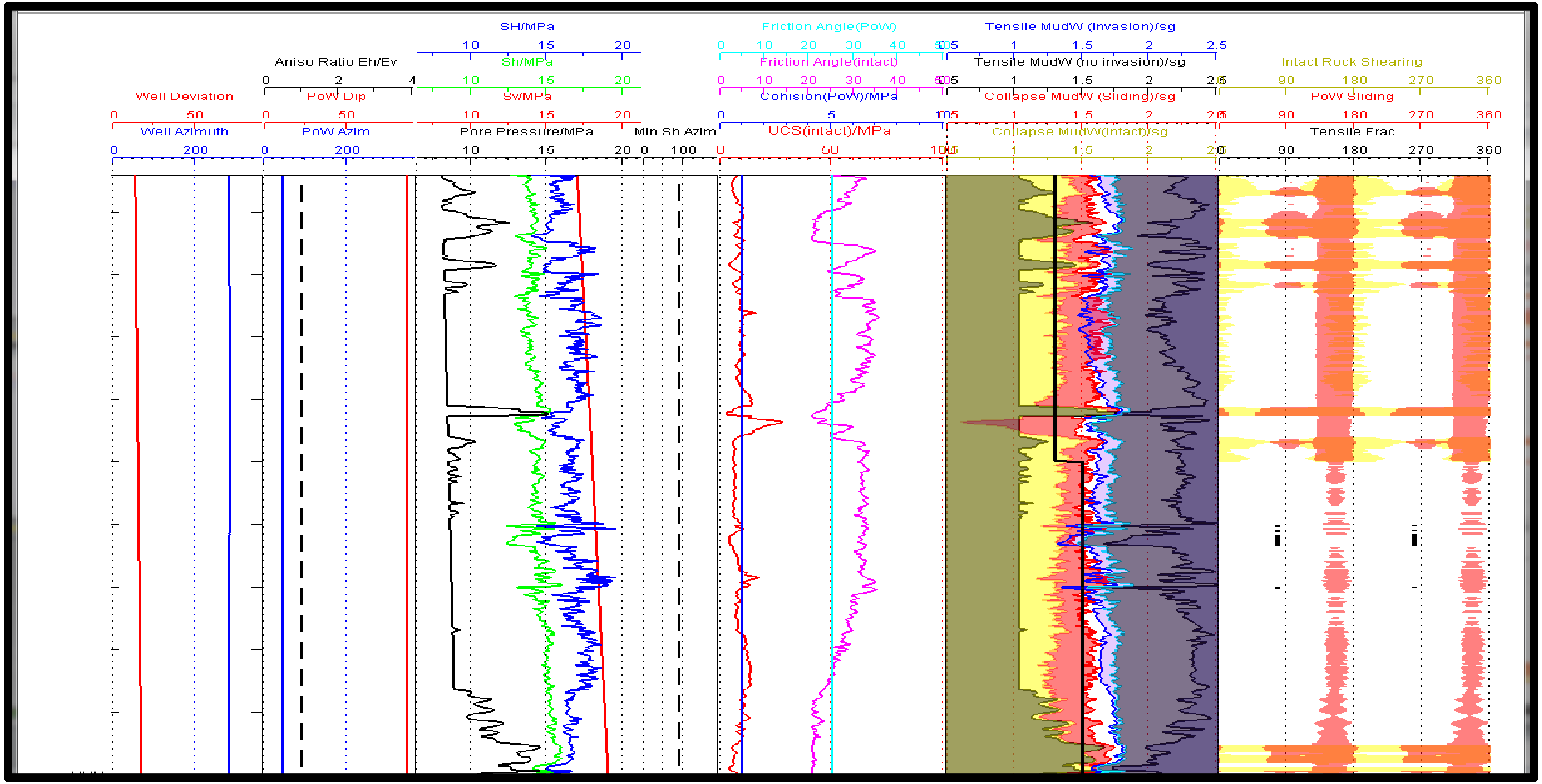
WBS with PoW Model (PoW dip 0 – 30 – 45 – 60 – 75 - 85)



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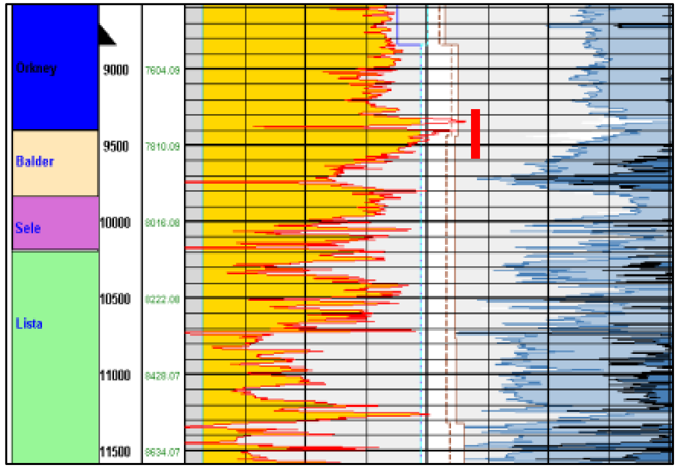
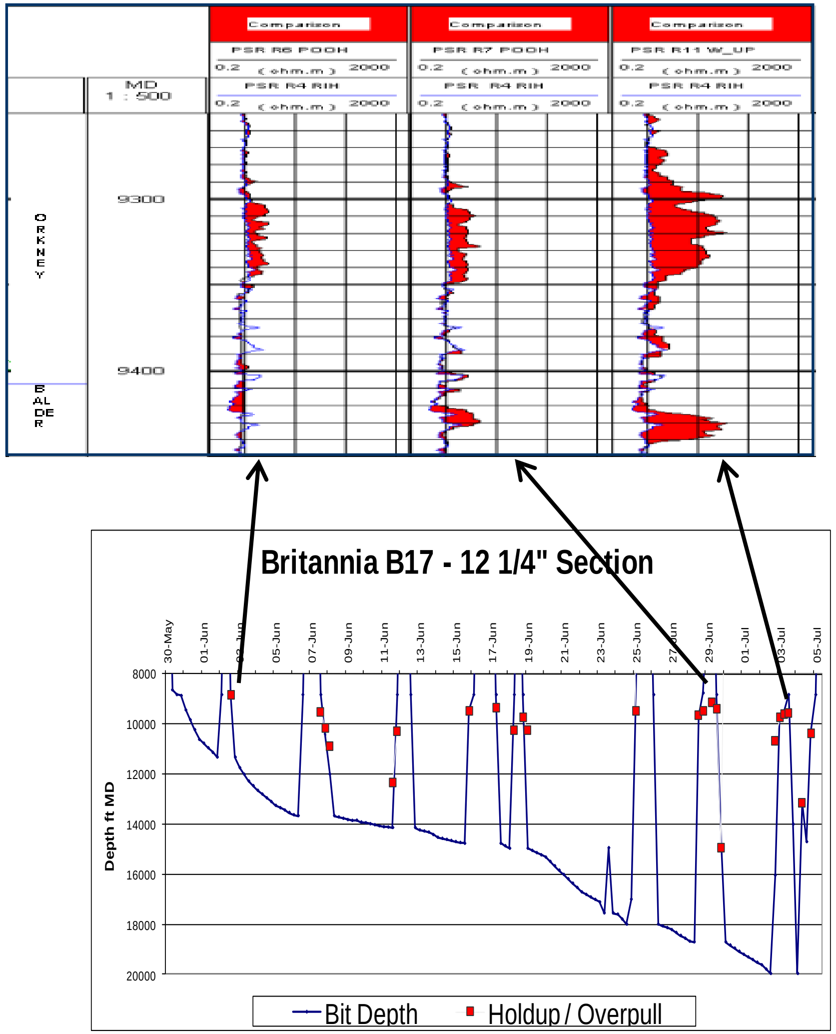
Unconventional failures: time dependent behaviour





- Pre-drill analysis identified likely shear failure, 9300′-9400′
- Time lapse monitoring with CDR, showed progressive hole enlargement
- Drillers tripped through this identified section carefully to avoid unnecessary disturbance
- Minimal breakout maintained for 25 days, after 30 days significant enlargement and cavings production. One further trip to complete section ready to case
- Tight hole plotted on time vs. depth plot shows troublesome depths

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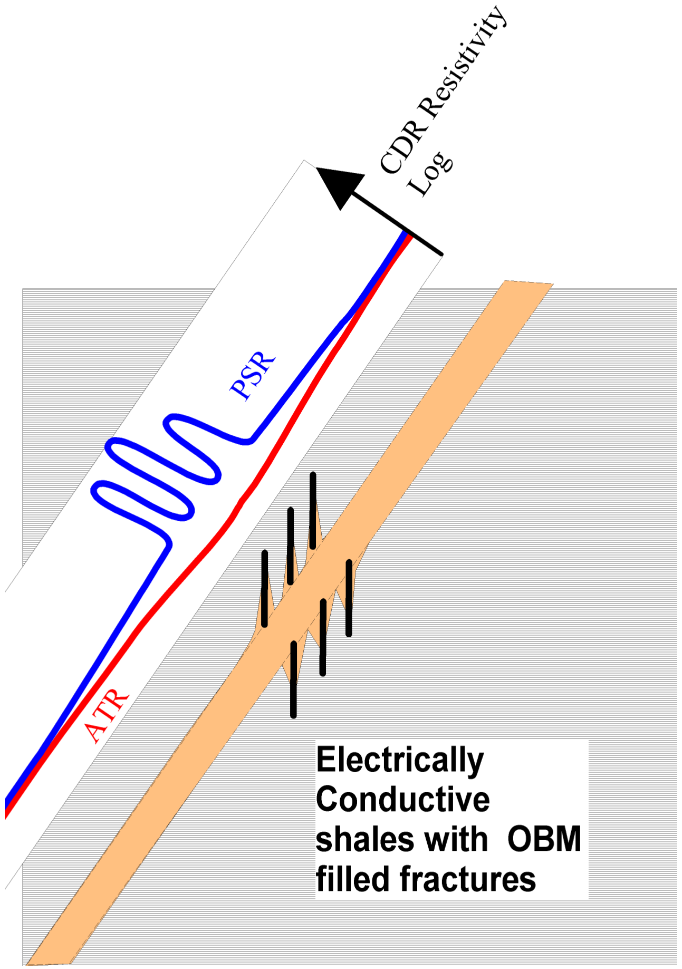
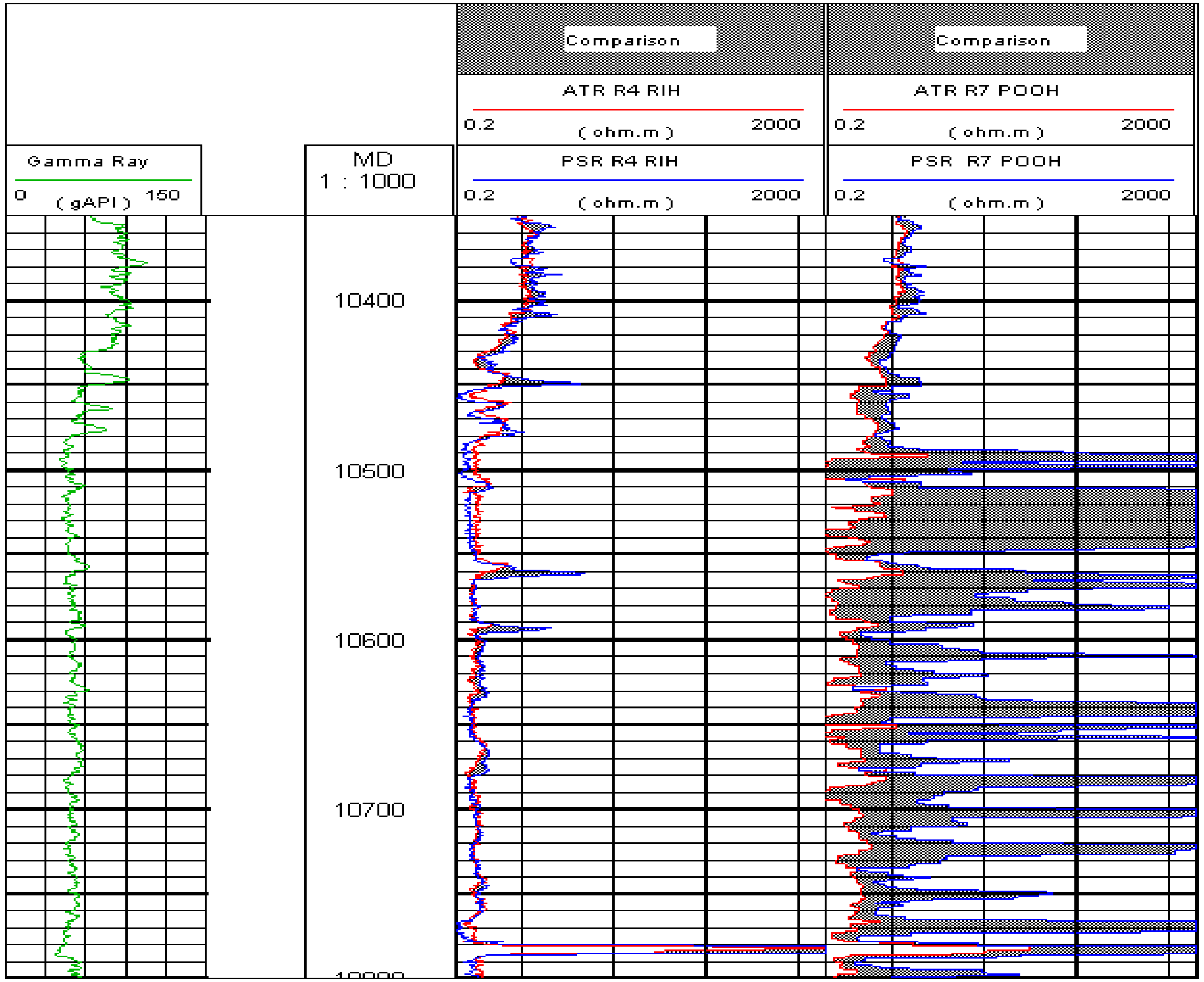
Unconventional failures: time dependent behaviour





While drilling data

15 days after drilling

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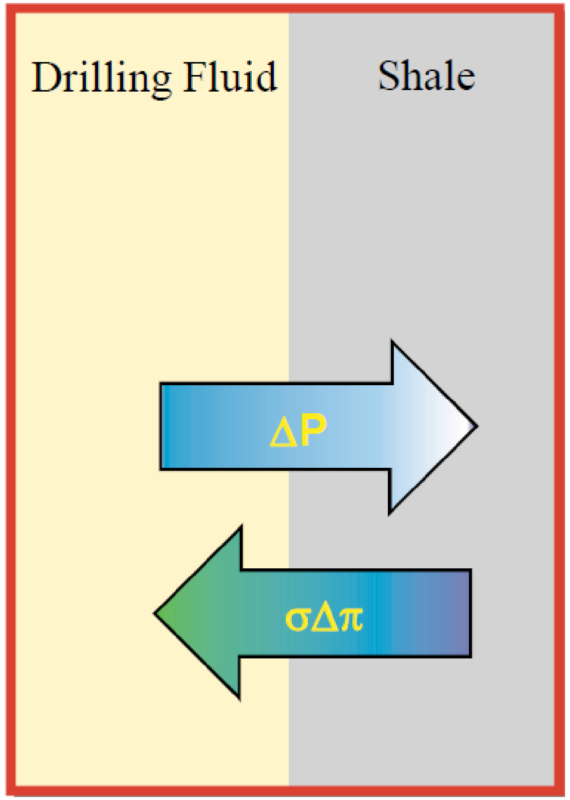
Unconventional failures: time dependent behaviour



Mud pressure penetration P_p increases, mud support decreases, swelling, unstable conditions

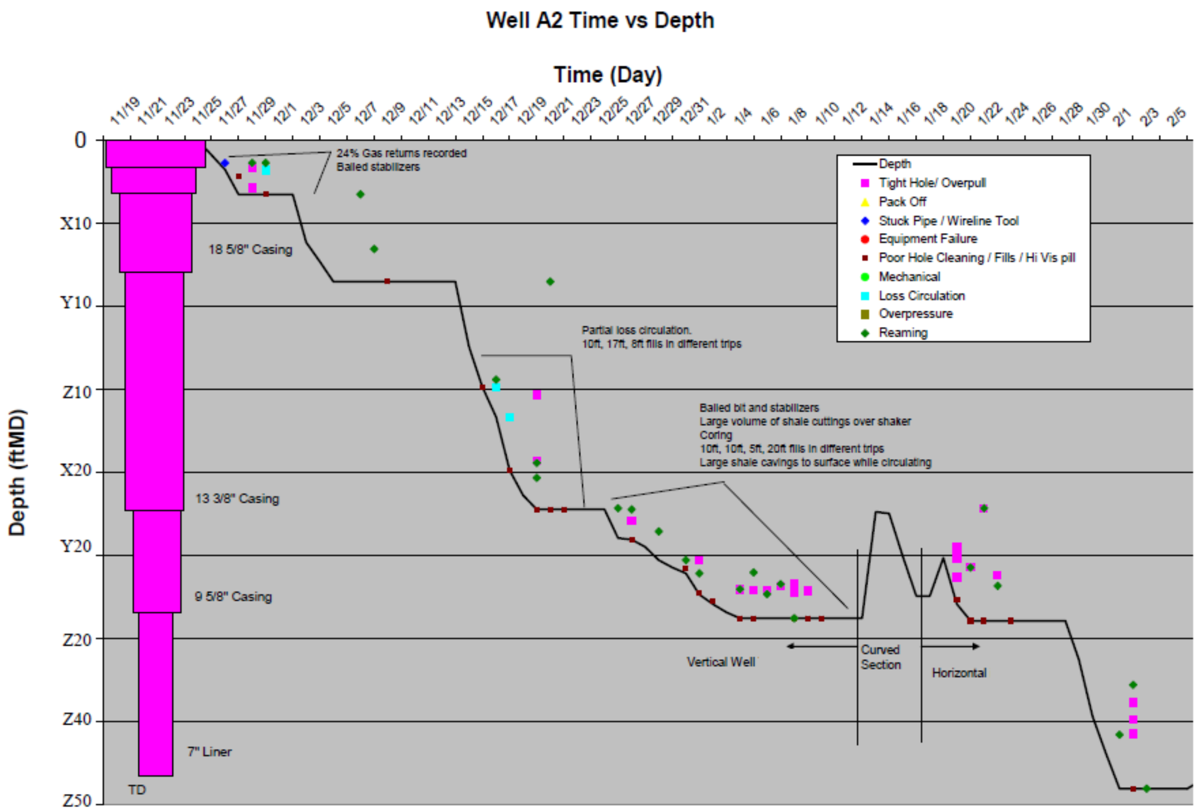
Chemical potential mechanism due to osmotic outflow (low mud activity, i.e. high salt concentration), P_p decreases, stable conditions

After Chee et al., 2009 (SPE 126052)

Shale STability Analysis (SSTA)

- Petrophysical and chemical properties of formations (cores)
- Properties of drilling fluids
- Overbalance pressure
- Formation temperature

Unconventional failures: time dependent behaviour



Offset well

Table 1: Petrophysical and chemical properties of cores, cavings and cuttings of Wara Shale

Sample No.	Average Total Clay (%)	Porosity (%)	Permeability (nano-Darcy)	Shale Activity	Membrane Efficiency (%)		
					Bentonite Mud	$CaCl_2$ Polymer Mud	Mud A
Wara-1	50.3	9.32	33.35	0.916	25.4	25.4	31.8
Wara-2	23.0	13.31	40.99	0.916	19.6	-	24.5
Wara-3	65.4	7.11	29.14	0.916	28.7	28.7	35.9
Wara-4	27.0	12.73	39.87	0.916	-	-	25.5

Table 3: Properties of drilling fluids used in offset wells

Mud Type	Adhesion (dyne/cm)	Kinematic Viscosity (cStoke)	Membrane Efficiency (%)	Salt Concentration (wt%)	Water Activity
$CaCl_2$ Polymer Mud	58.6	Temperature Dependent (0.90 – 0.97)	Pore Size Distribution Dependent (20.9 – 28.7%)	15.8% $CaCl_2$	0.89
				20.0% $CaCl_2$	0.84
Bentonite Mud	58.6	Temperature Dependent (0.83 – 0.96)	Pore Size Distribution Dependent (19.6 – 31.6%)	3.5% – 4.9% NaCl	0.97 – 0.98
KCL Polymer	58.6	Temperature Dependent (0.76 – 0.77)	Pore Size Distribution Dependent (13.8 – 24.7%)	12.8% KCl	0.94

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Unconventional failures: time dependent behaviour

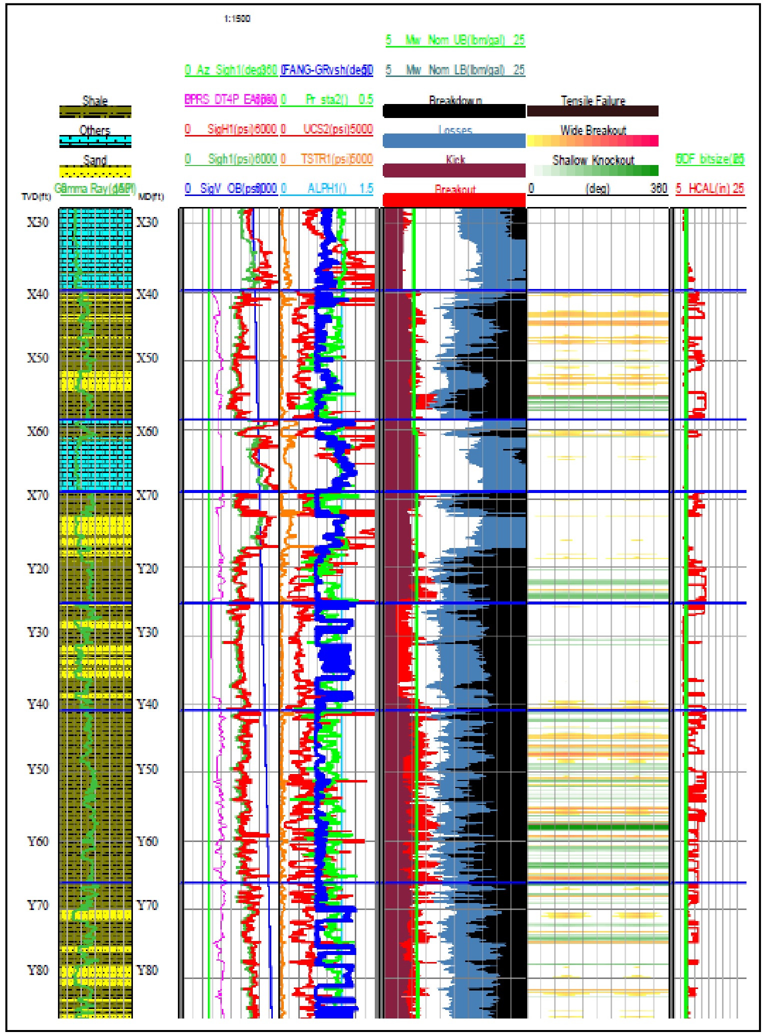

Table 4: Summary of back-analysis of time-dependent wellbore instability events in Wara Shale

Well	Depth (ftMD)	Mud Type	Mud Activity	Mud Weight Used (ppg)	Openhole Duration (Day)	Hole Enlargement (% of Wellbore Diameter)	Calculated Pore Pressure Change After Maximum Exposure Duration		
							Mud Pressure Penetration Pore Pressure Change (psi)	Chemical Potential Mechanism Pore Pressure Change (psi)	Total Pore Pressure Change (psi)
A1	X22	$CaCl_2$ Polymer (15.8%$CaCl_2$)	0.89	9.7	4	4.7%	257.1	-88.5	168.7
A1	X37	$CaCl_2$ Polymer (15.8%$CaCl_2$)	0.89	9.7	4	8.2%	237.6	-103.0	134.6
A2	X58	Bentonite (3.5% NaCl)	0.98	9.4	3	15.0%	138.4	330.7	469.0
A2	X59	Bentonite (3.5% NaCl)	0.98	9.4	3	34.0%	131.8	330.7	462.5
A2	X42	Bentonite (3.5% NaCl)	0.98	9.4	3	7.0%	287.2	285.7	572.9
A2	X43	Bentonite (3.5% NaCl)	0.98	9.4	3	40.0%	125.3	203.0	328.4
A2	X44	Bentonite (3.5% NaCl)	0.98	9.4	3	8.4%	172.3	330.7	503.0

Wara Shale Activity: 0.916

Positive net change indicates that pore pressure increases with time in the formation

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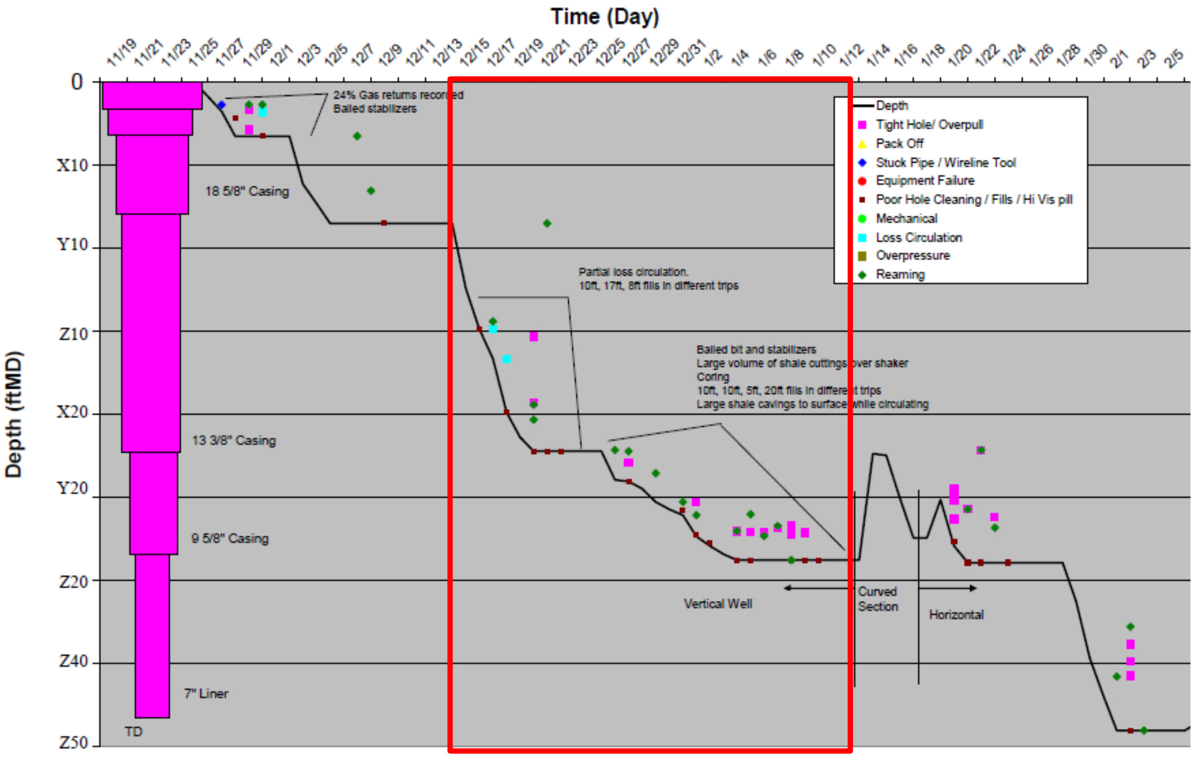
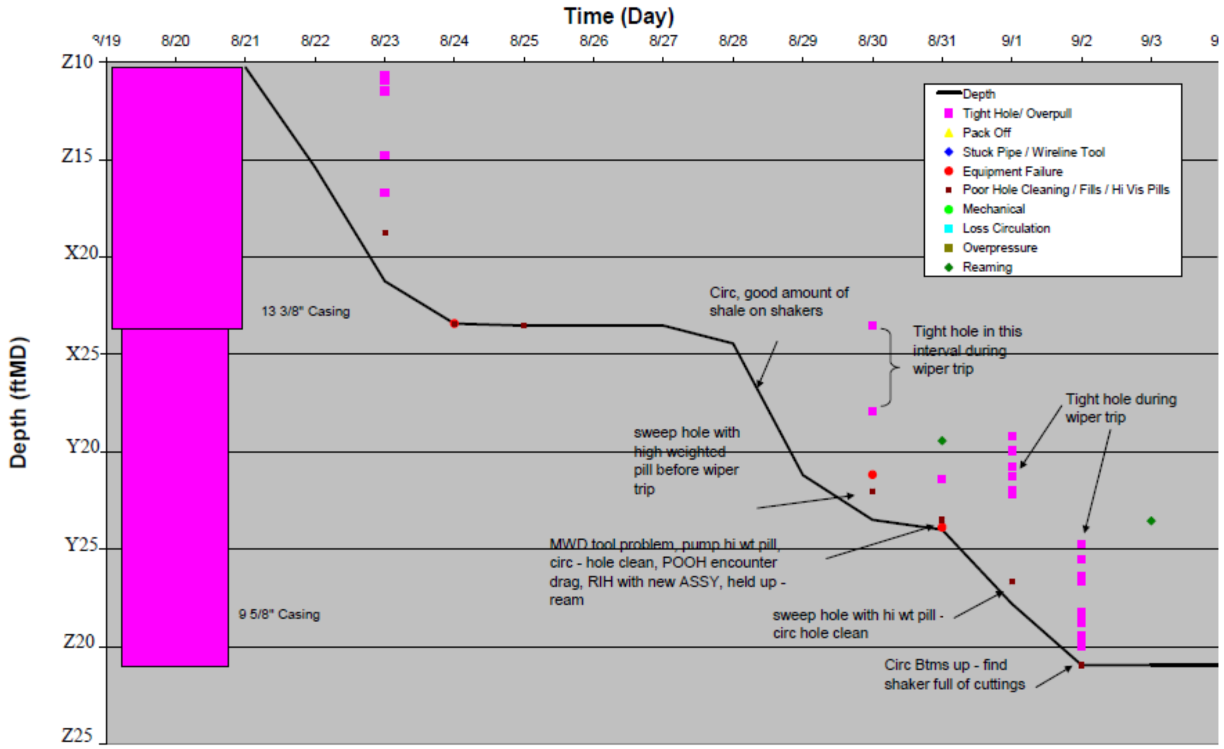
Unconventional failures: impact on NPT



Offset well : **28 days** (13 3/8" and 9 5/8")

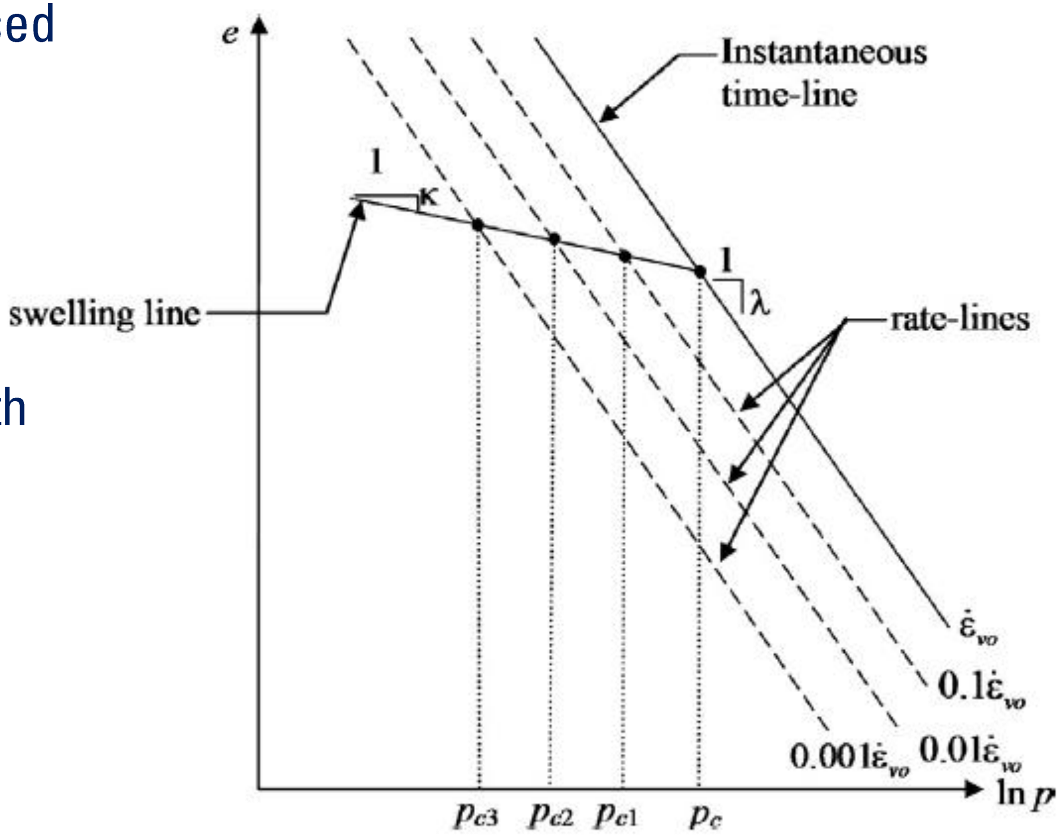


Planned Well :**13 days** (13 3/8" and 9 5/8")

Planned Well	Formation	Recommended Mud Weight (ppg)	Recommended Salinity for Water-based Mud A & B	Mud Weight Used During Drilling (ppg)
A3	Ahmadi Shale	11.0	15.0 – 15.5% KCl	10.5
	Wara Shale	11.5	14.0 – 14.5% KCl	11.5 – 11.7

Unconventional failures: partial saturation

- Time exposure to water based mud due to coring increased water saturation
- Rock exhibits stress-strain-strain rate behaviour (isotach behaviour) – Suklje (1957)
- Yield stress is rate dependent (yield stress increases with increasing strain rate)
- Rate dependency is a function of saturating fluid (strain rate increases with increasing fluid saturation)
- This behaviour doesn't impact only drilling, reservoir stimulation in shales induces a similar effect → swelling, creep, fracture closing



After De Gennaro & Pereira, 2013 (Computers & Geotechnics 54)

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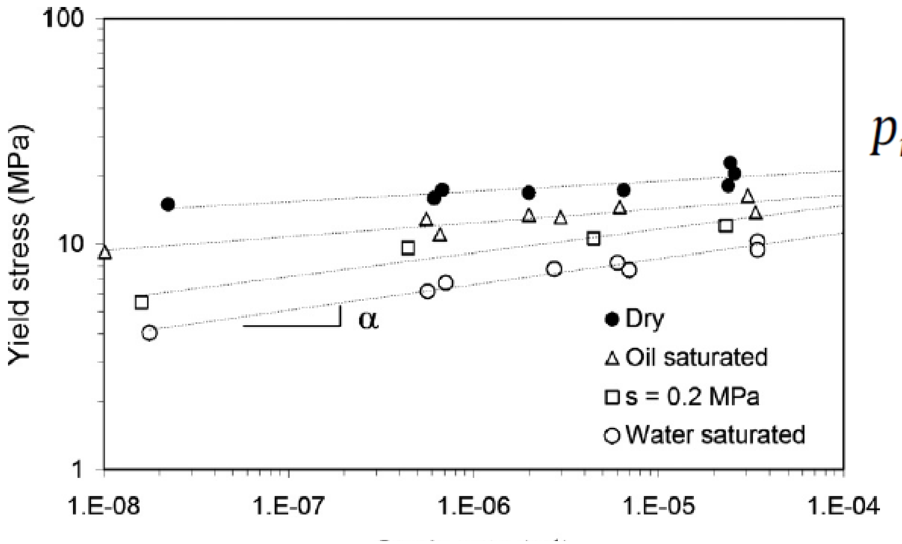
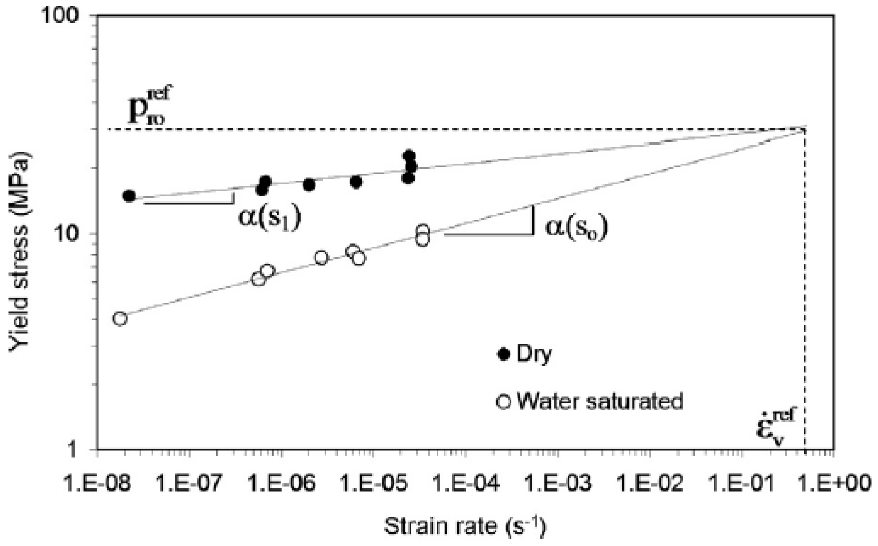
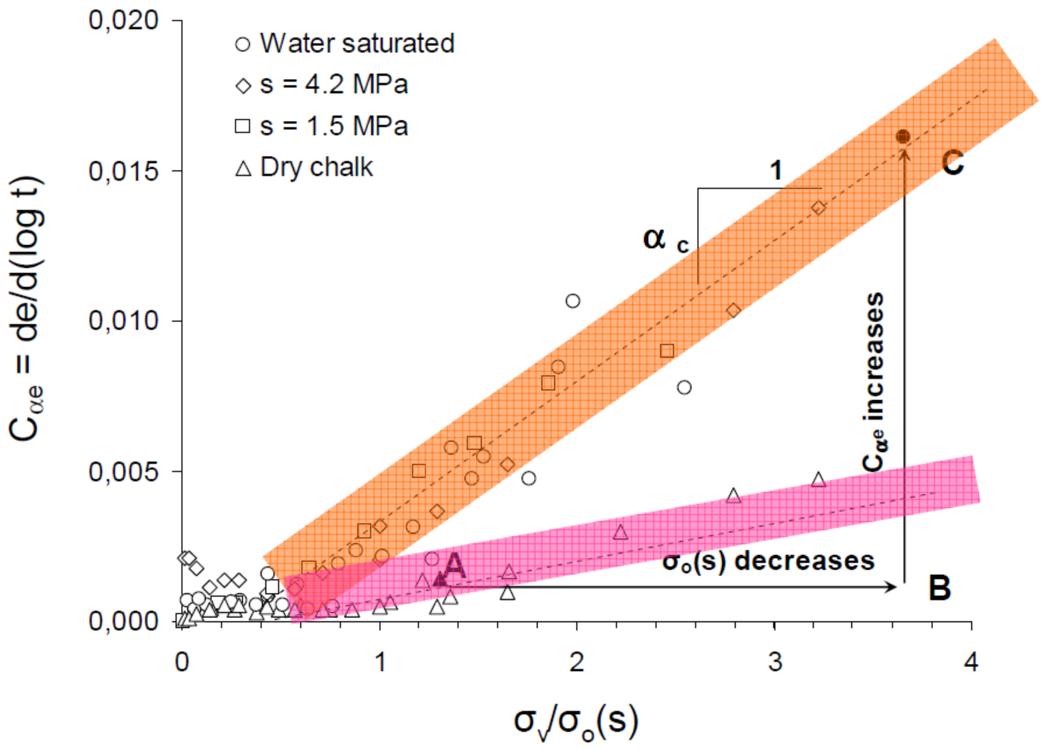
Unconventional failures: viscoplasticity & partial saturation





$$p_{ro}(\dot{\varepsilon}_v) = p_{ro}^{ref}\left(\frac{\dot{\varepsilon}_v}{\dot{\varepsilon}_v^{ref}}\right)^{\alpha(s)}$$

- Extended plastic hardening (rate hardening)
  Dragon & Mroz (1979), Lemaitre & Chaboche (1985)
- Cam-clay partially saturated models family
  Alonso & Gens (1990)



Data after Priol et al., 2007 (Springer Proc. Physics 112)

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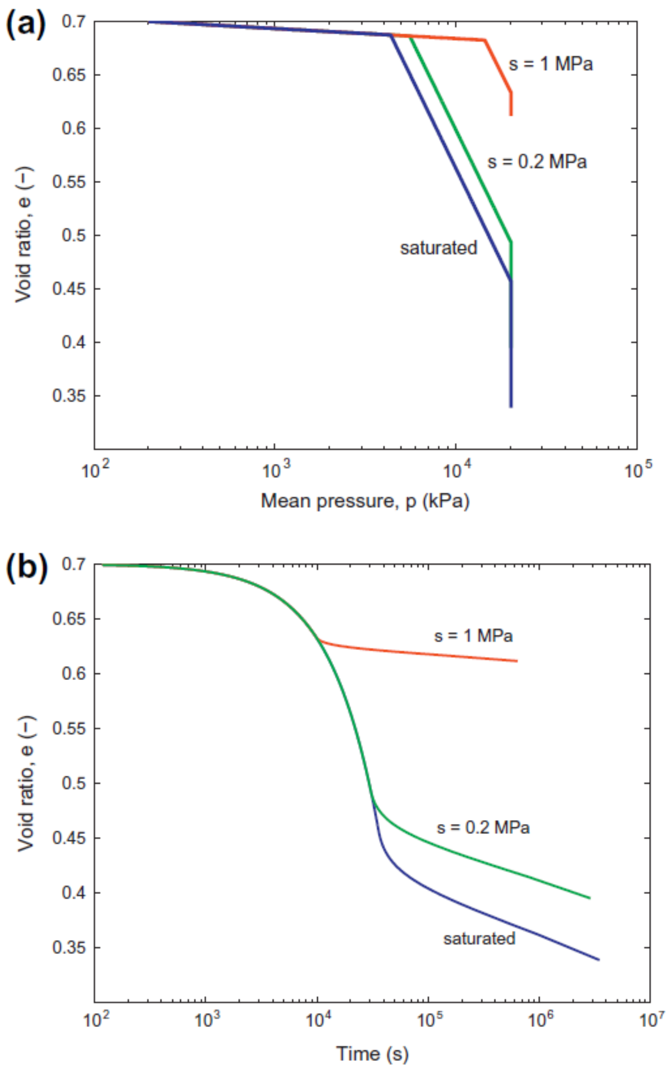
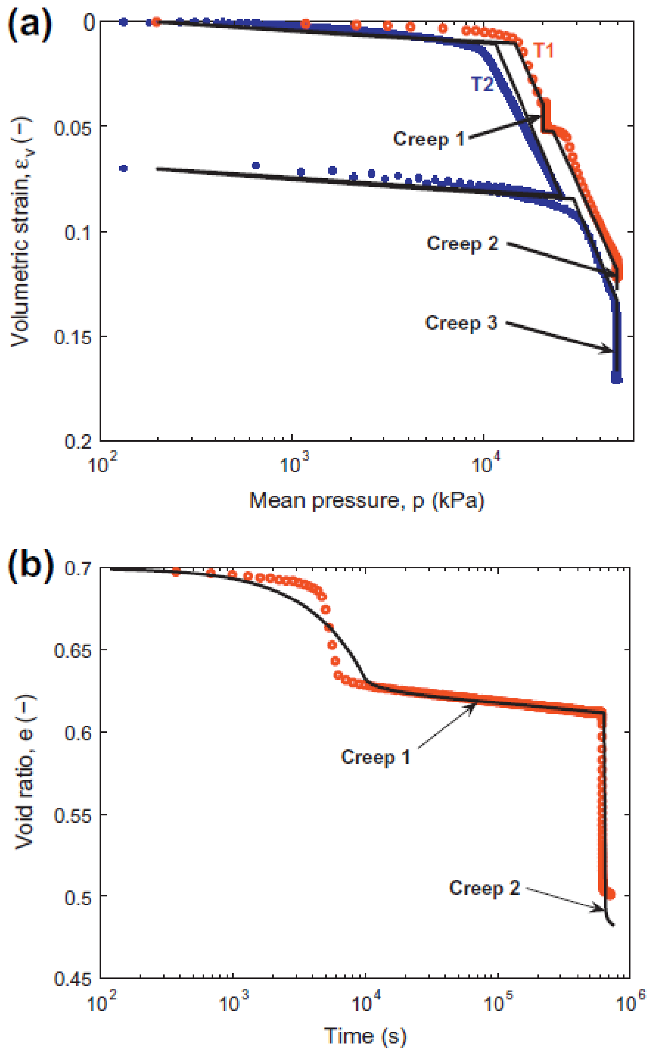
Unconventional failures: viscoplasticity & partial saturation



Model



Model + Experiment

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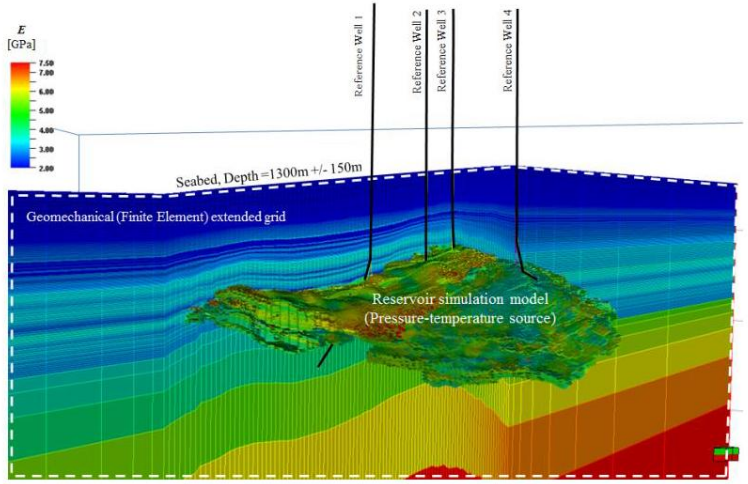
What's next? 3D seismic geomechanics and wellbore and casing integrity analysis

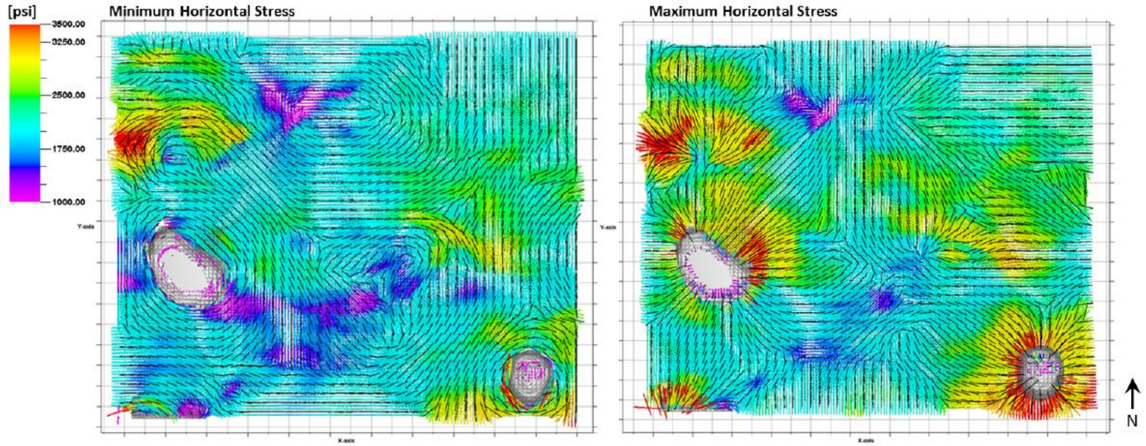
- State of stress underground is generally more complex than the simple scheme addressed by the well centric approach:
  - ✓ *Challenging environments – deep water, HPHT, tectonic areas, salt*
  - ✓ *More complex well geometries – extended reach, multi-lateral, high dogleg*
  - ✓ *Recovery – depleted fields, shale gas drilling*

- Advanced 3D modelling is often mandatory

- Applications are numerous, wellbore and casing integrity analysis are just some



After Onaisi et al., 2015 (ARMA)



After Rodriguez-Herrera et al., 2014 (EAGE Dubai)

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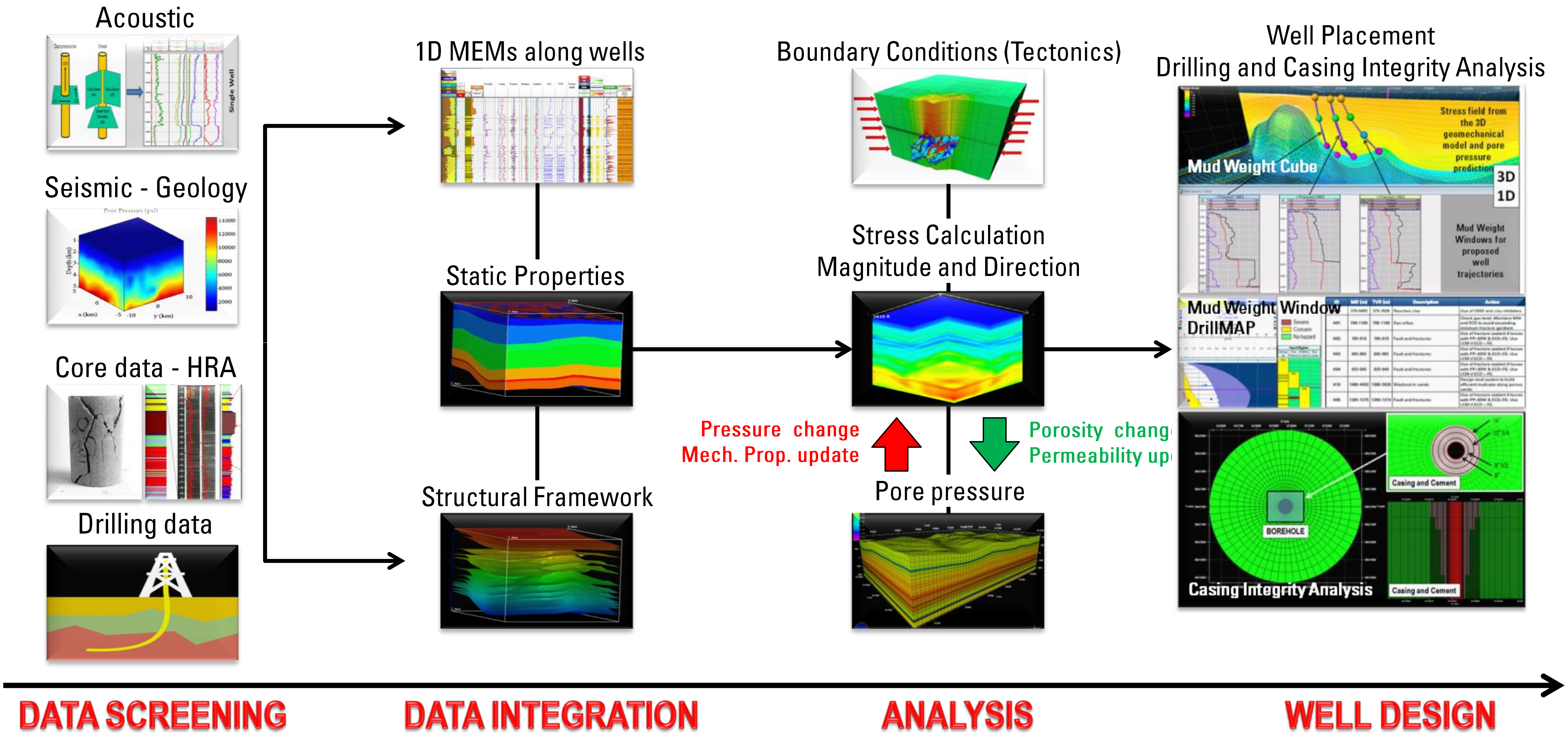
3D seismic geomechanics and casing integrity analysis



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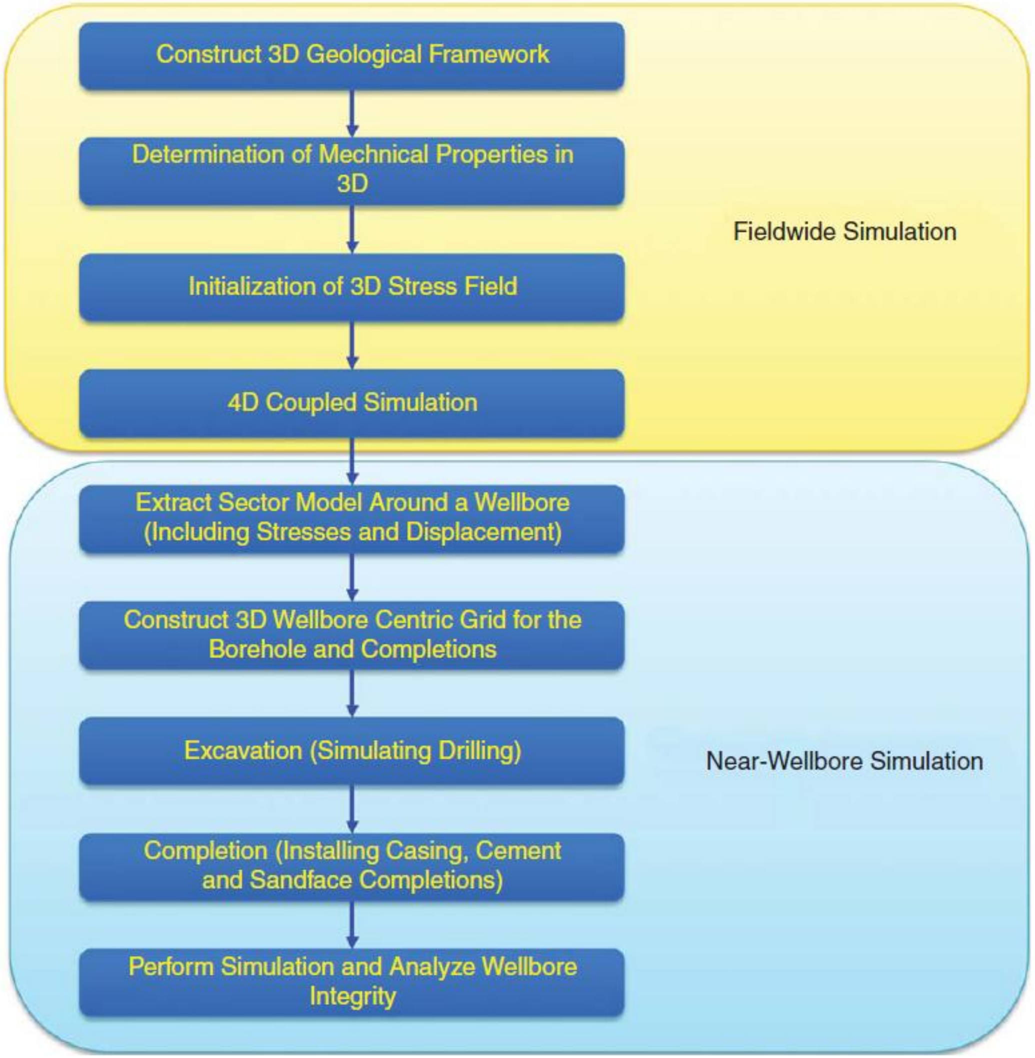
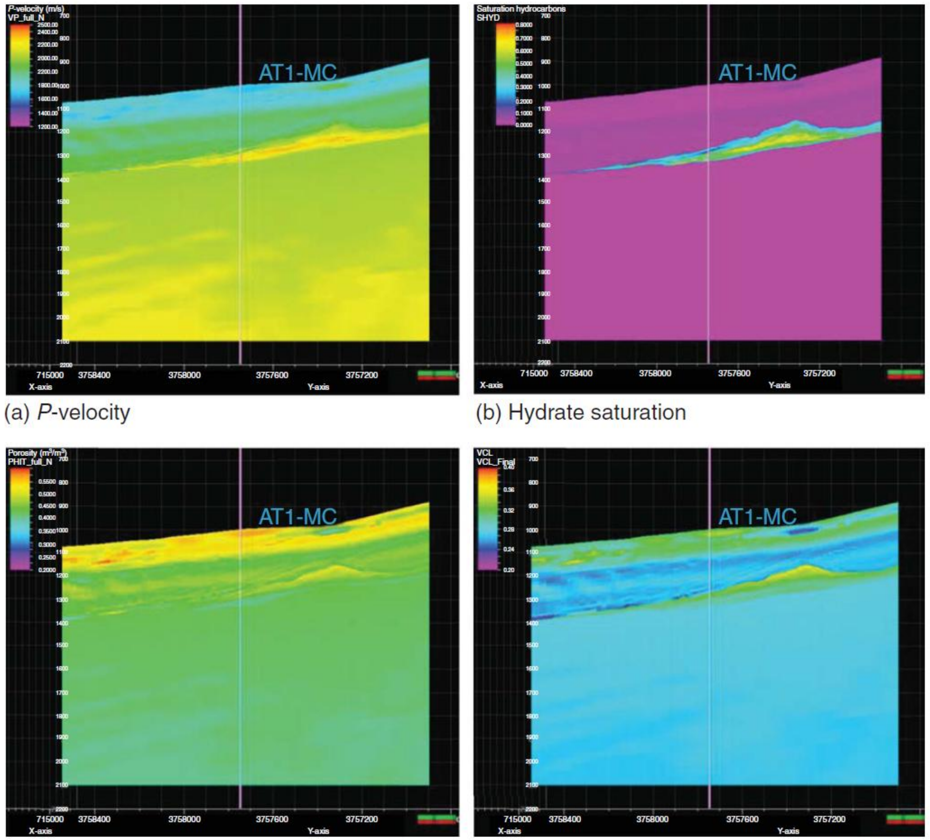
Example from Deepwater Nakai Trough



Well integrity evaluation for methane-hydrates production

- Detection and estimation of gas hydrates saturation using rock physics and seismic inversion
  Dai et al., 2004 (The Leading Edge)



(a) *P*-velocity (b) Hydrate saturation (c) Porosity (d) vcl

After Qiu et al., 2015 (SPE Drilling and Completion)

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Well integrity evaluation for methane-hydrates production

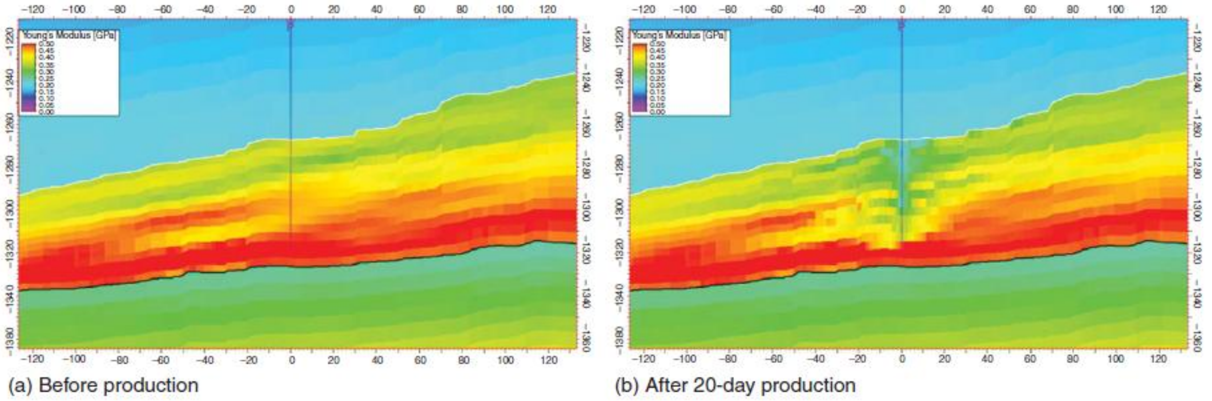

Fig. 7—Young's modulus before and after 20-day production.

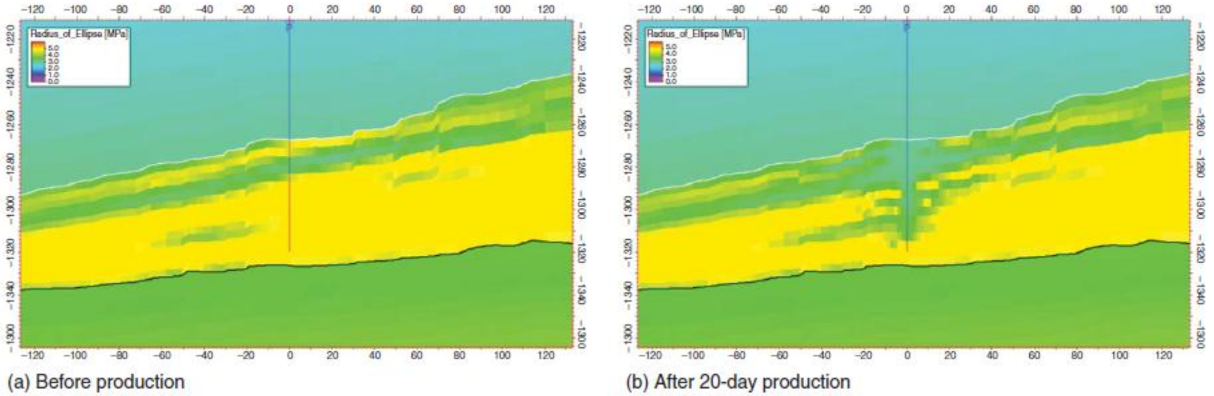

Fig. 8—The *pc*0 before and after 20-day production.

- Correlations derived to determine mechanical properties from petrophysical properties, seismic velocity, hydrates saturation, overburden stress
- Hydro-mechanical coupled effects of hydrates production simulated by a third party methane-hydrate production simulator coupled to Schlumberger geomechanical simulator (1-way or explicit coupling)
- Degradation of mechanical properties due to hydrate dissociation (stiffness & strength) correlated to hydrates saturation and mean effective stress change
  Sultan et al., 2012 (Geotechnique 62(9))

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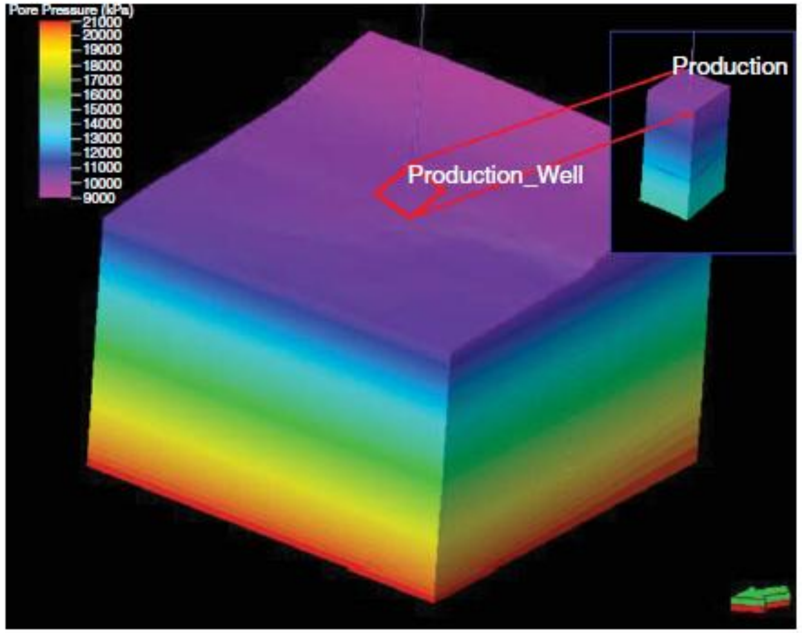
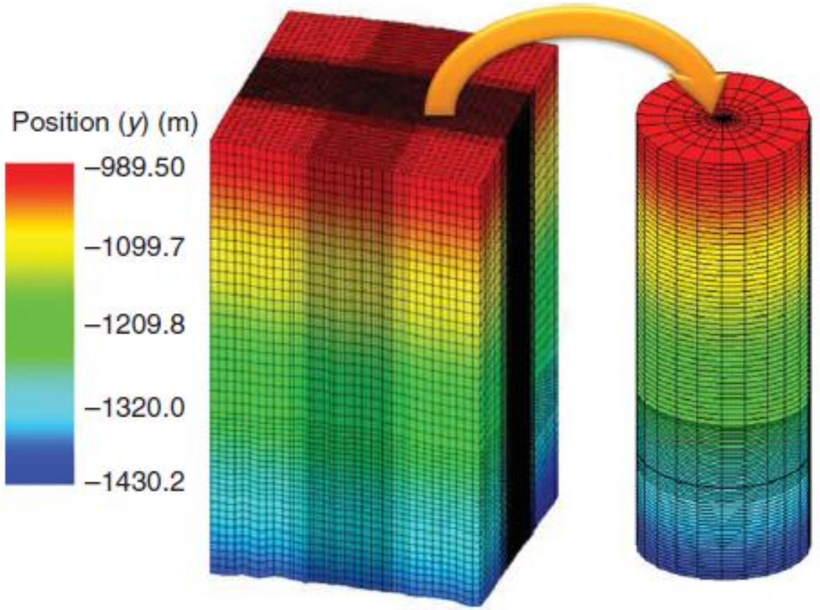
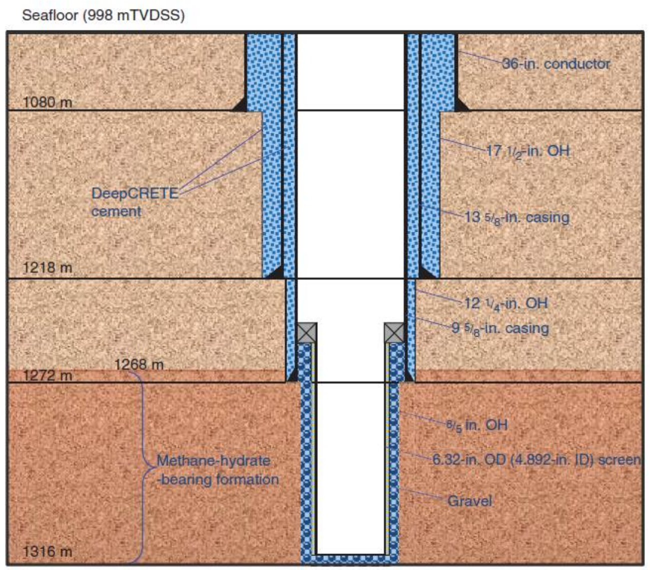
Sector model



Full Model



Sector Production Well



Schematic Completion

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Cement-Casing integrity analysis

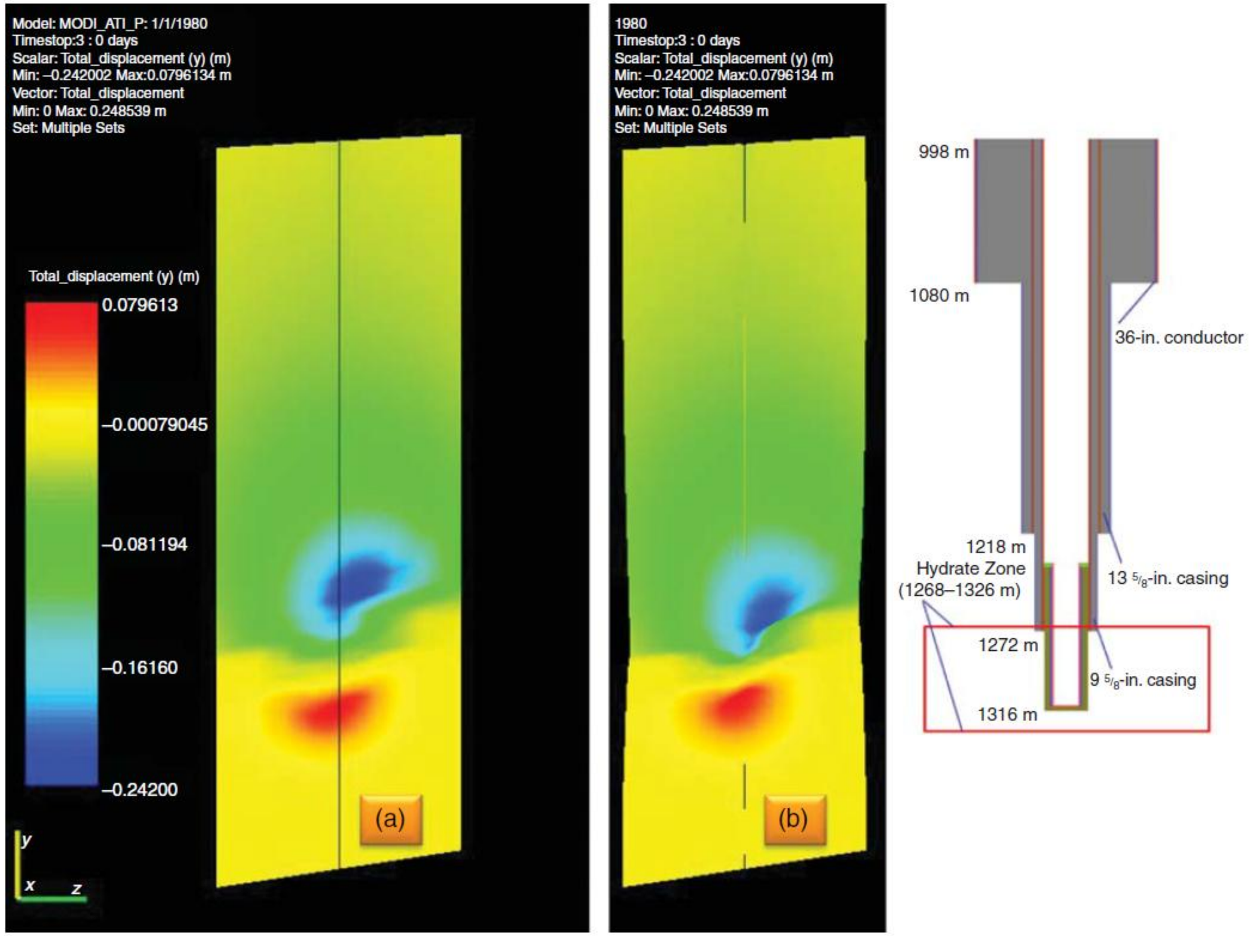

Fig. 18—Vertical-displacement distribution in cross section (*Y–Z*) after production: (a) on original geometry and (b) on deformed grid.

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Cement-Casing integrity analysis

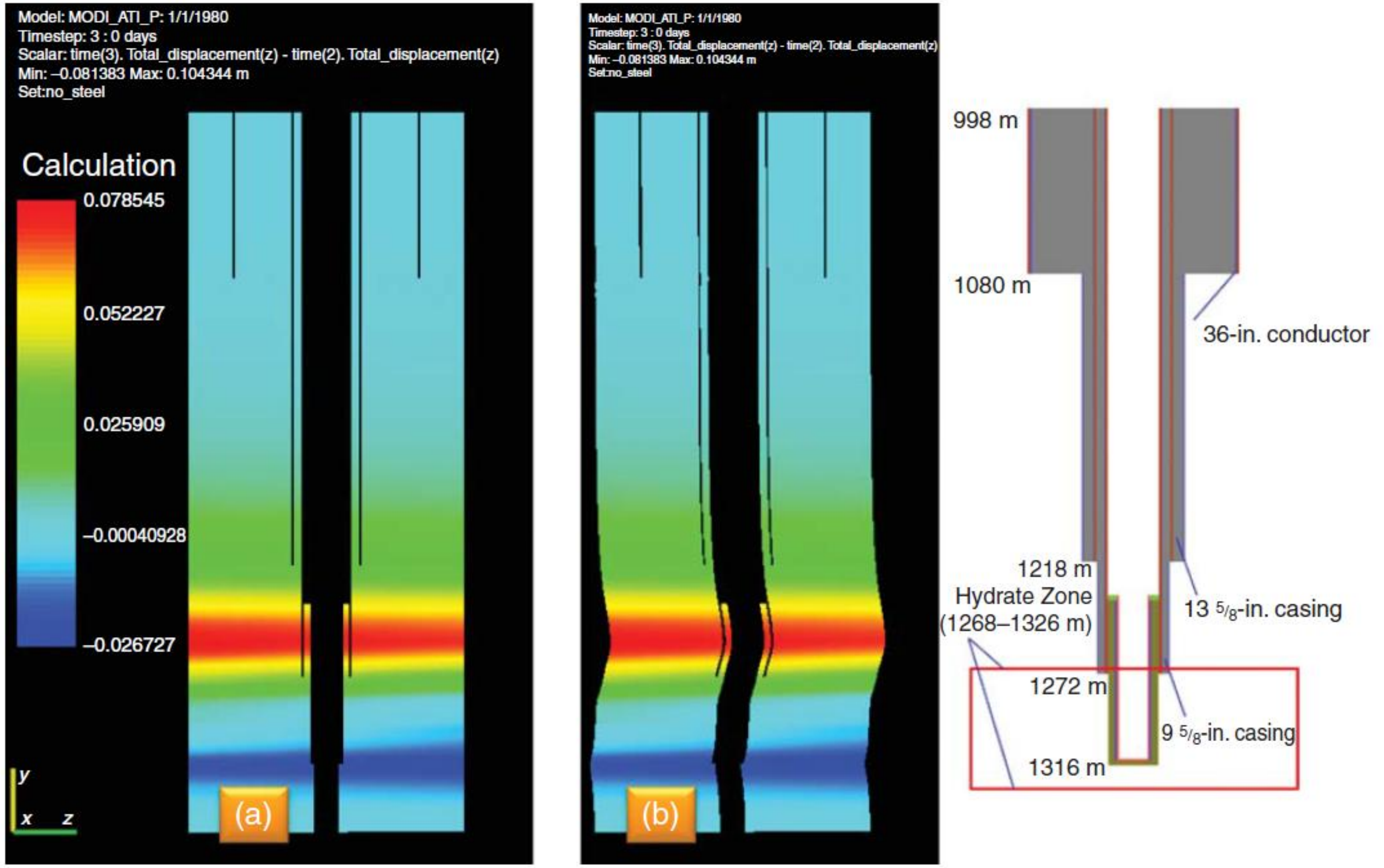

Fig. 19—Horizontal displacement (*ZZ*) distribution: (a) on the original grid geometry and (b) on deformed grid in the near-wellbore region.

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Cement-Casing integrity analysis

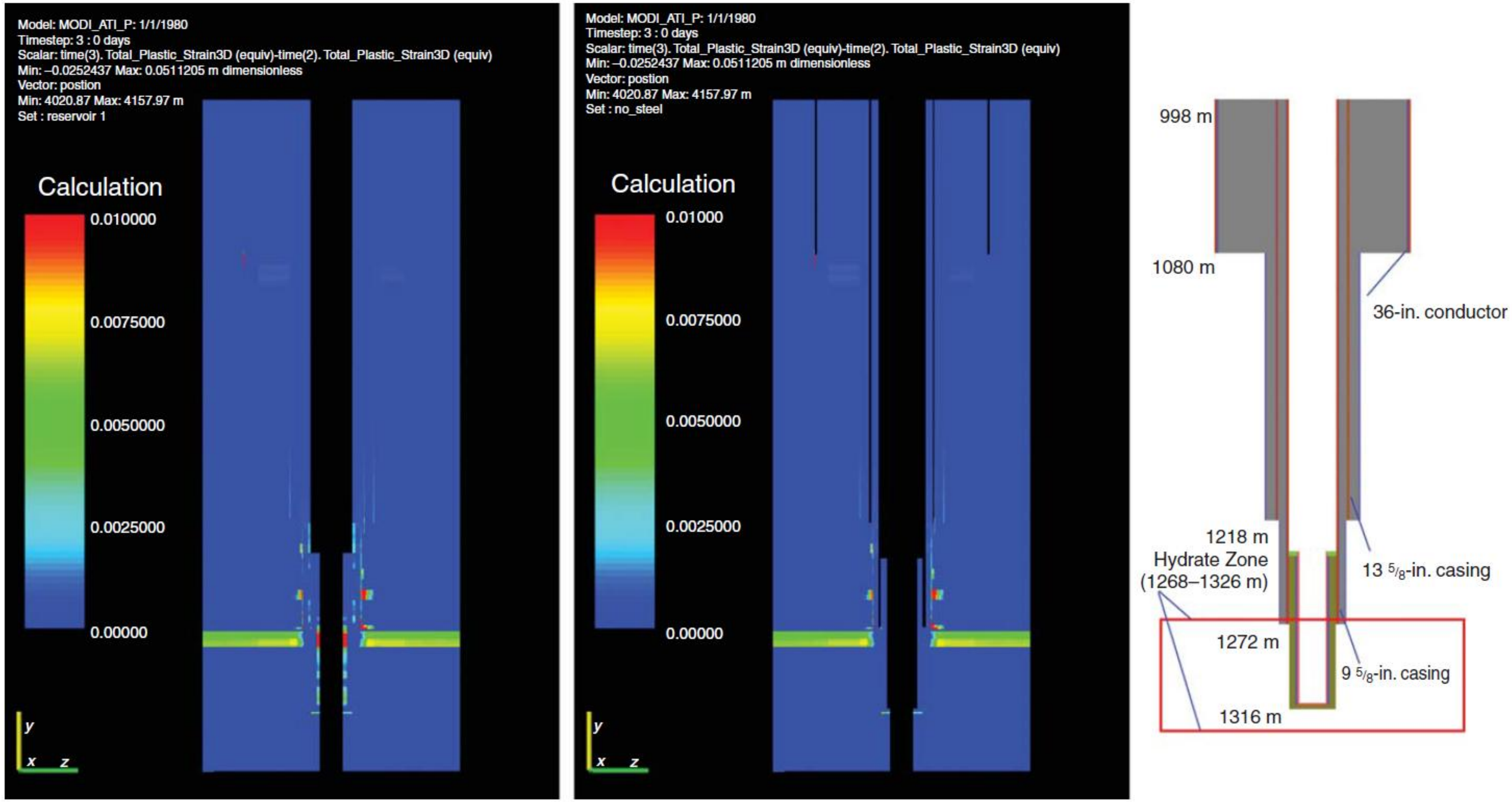

Fig. 21—Equivalent plastic strain after 20-day production: (a) including casing results; (b) excluding casing results.

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Concluding remarks

- The proposed integrated geomechanics workflows enhances reservoir characterization and cross-discipline capabilities.
- Access to data for validation is essential, this is often a major missed information
- Solutions need to comply often, if not always, with operational needs: fast implementation, simplicity, scalability; all this while ensuring sound technical solutions.
- Operational needs are often conflicting with natural complexity of the problem, especially for drilling

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