Lecture 11

Ch. 10 Wellbore Stability
(11, 13 May 2020)

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Disclaimer

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- Materials in these slides cannot be used without the written consent from the instructor

Importance

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- Wellbore stability problems
  - Mechanical failure
  - Hole cleaning
  - Wellbore hydraulics
  - Drilling equipment
- Problems
  - Borehole instability can cause 5-10% of drilling cost (Fjaer et al., 2008). ~ billions $
  - Demand ↑ for more sophisticated well trajectories – highly deviated, horizontal, deep wells.
  - Environmental impact due to lost circulation
  - Safety issue too from kick/borehole blow out in petroleum industry
- Instability during drilling
  - Maintaining stability with optimal mud weight
- During production
  - Sand production
  - Collapse of well casing

Fjaer et al., 2008, Petroleum Related Rock Mechanics

Wellbore Stability
Basics

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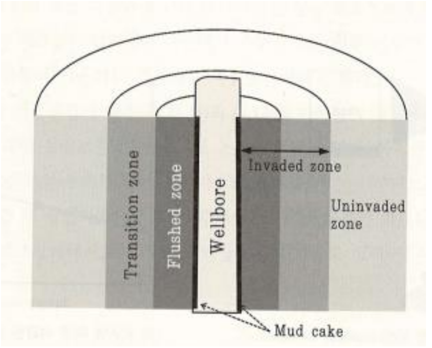
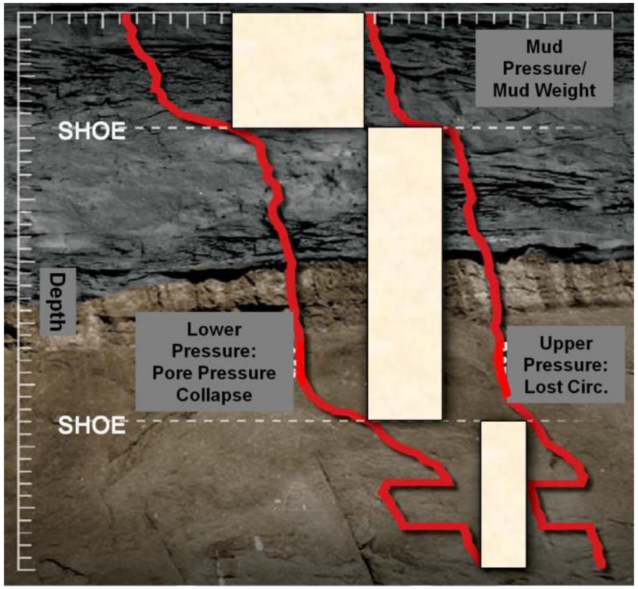
- Mud weight window
  - Difference between the minimum and maximum mud weight
  - Minimum mud weight: pore pressure to prevent well collapse
    - = pore pressure (to prevent inward flow while drilling)
    - Pore pressure to ensure stability
    - < pore pressure → underbalanced drilling
  - Maximum mud weight: lost circulation
    - = pressure to cause Lost circulation (or frac gradient)
    - Fracturing of borehole wall (tensile)
- Assumption of a perfect mud cake
  - Full difference between Pm and Pp



최종근, 해양시추공학, 2011



Frac gradient: pressure gradient necessary to hydraulically fracture

Itasca Short Course, 2011

Wellbore Stability
Issues

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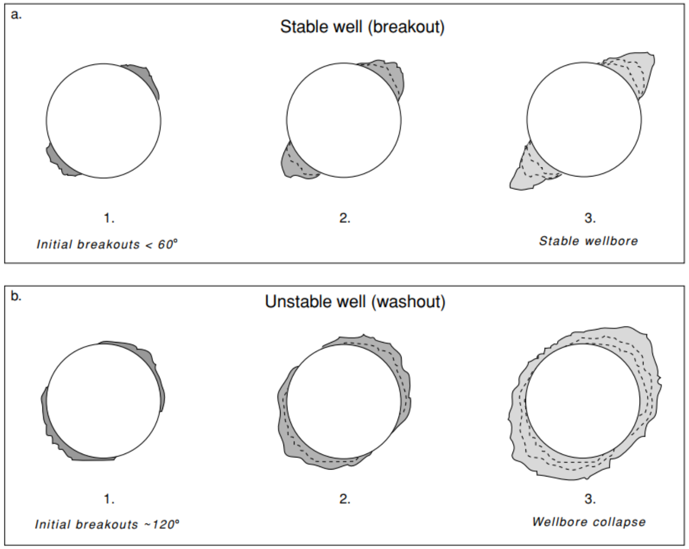
- Topics affecting wellbore stability
  - Influence of weak bedding planes (Rock Anisotropy)
  - Chemical effect on rock strength
  - Drilling with very high pore pressure (refer to the textbook)
  - Time dependent borehole failure

Mud cake: The residue deposited on a permeable medium when drilling fluid is forced against the medium under a pressure.

Preventing wellbore instability during drilling

- Instable well?
  - Washout with excessive breakout
  - Total volume of cuttings and failed materials cannot be circulated by mud →velocity of drilling mud decreases → reduces the ability to clean the cutting → cuttings and failed rock stick to the bottom hole assembly
- Stable well
  - Breakout angle of ~90° (empirical criterion) considered reasonable
  - Breakout deepen with time (not widen)
  - Breakout angle can be more conservative in
    - Horizontal well (more difficult to clean the well)



Zoback MD, 2007, Reservoir Geomechanics, Cambridge University Press

Preventing wellbore instability during drilling

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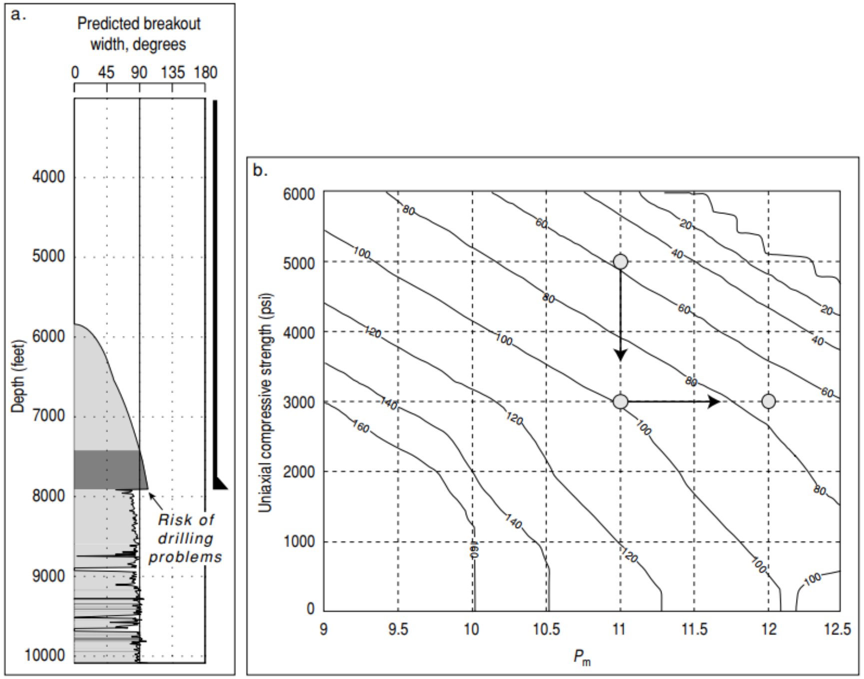
- Example
  - Geomechanical study allowed the identification of wellbore stability problem breakout width > 90° (7,500-7,900ft)
  - Casing was set
  - Geomechanical study was carried out after casing was set
  - Increasing Pm from 11 ppg to 12 ppg would have been possible
  - (message) appropriate geomechanical study save time and cost



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Preventing wellbore instability during drilling

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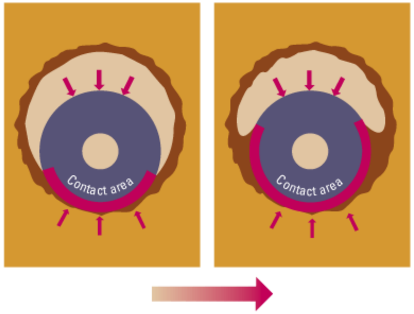
- Problem of raising mud weight
  - Inadvertent hydraulic fracturing
  - Lost circulation
  - Decreasing drilling rate (ROP)
  - Formation damage (due to mud infiltration)
  - Mud loss
  - Differential sticking (Condition in which Drilling string cannot be moved along the axis of the borehole)



Differential sticking. As time goes on the area becomes larger (Schlumberger oilfield glossary)

Preventing wellbore instability during drilling

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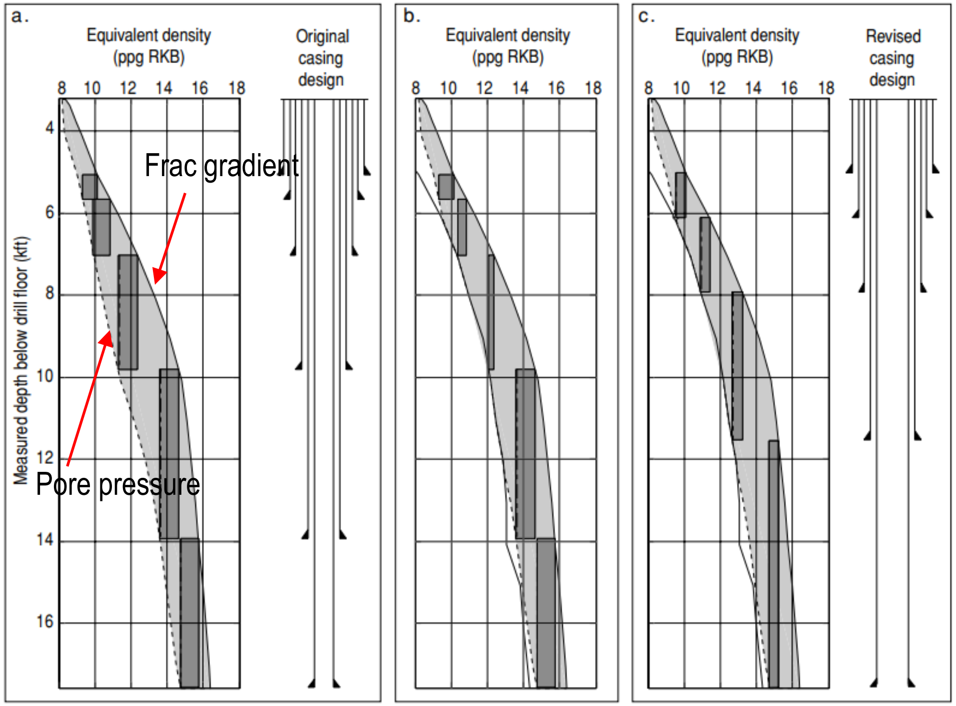
- Example
  - Original design: pore pressure ~ frac gradient
  - Two alternatives based on a previous well
  - Improved design 1:
    - lower bound increased
    - 6 casing strings
    - very small mud weight window
  - Improved design 2:
    - Adjust the windows
    - 5 casing strings
    - More economic



Why can't we just change p_m continuously?

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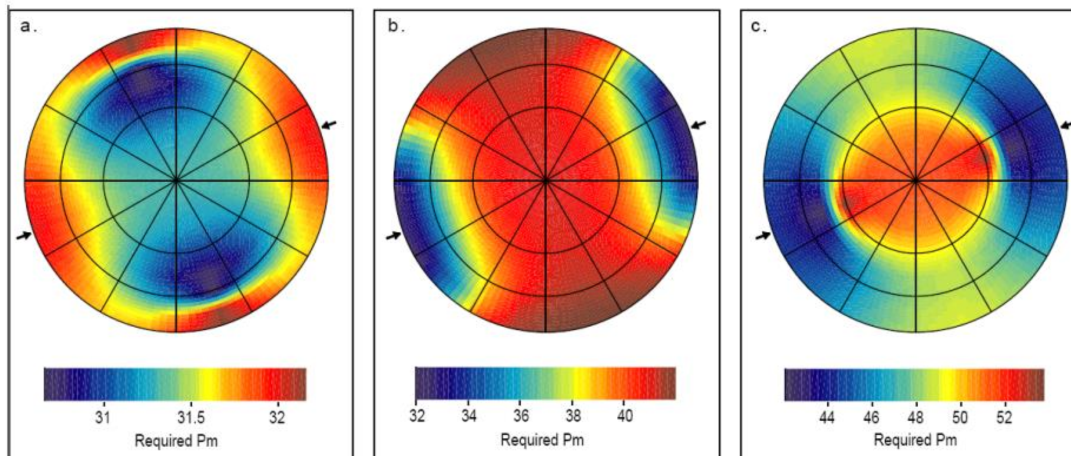
Preventing wellbore instability during drilling
Importance of well trajectory

- Effect of trajectory on the stability
  - Mud weight required to drill a stable well (bb angle < 30°)
  - Normal faulting: basically stable
    - Vertical well: pm ~ 30 Mpa
    - Deviated well: pm ~ 32 MPa
  - Strike-slip
    - High pm is necessary (40-42 Mpa: ~10.7 ppg)
    - Horizontal well to SHMax: most stable
  - Reverse fault
    - Vertical well most unstable: pm ~52 Mpa (13.7 ppg)
    - Horizontal well to SHMax: most stable



a	b	c
S_{Hmax} = 67 MPa	S_{Hmax} = 105 MPa	S_{Hmax} = 145 MPa
S_{hmin} = 45 MPa	S_{hmin} = 55 MPa	S_{hmin} = 125 MPa
S_v = 70 MPa	S_v = 70 MPa	S_v = 70 MPa
P_p = 32 MPa	P_p = 32 MPa	P_p = 32 MPa

C0=50 MPa

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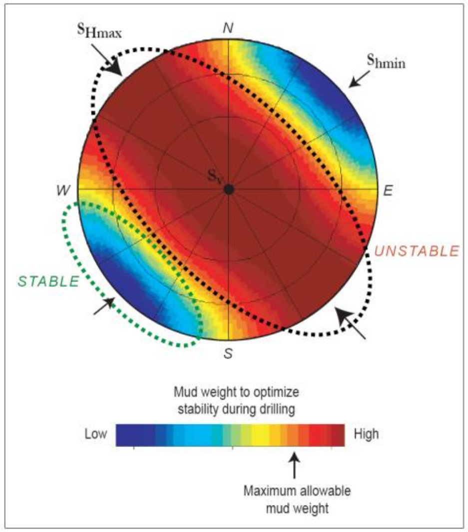
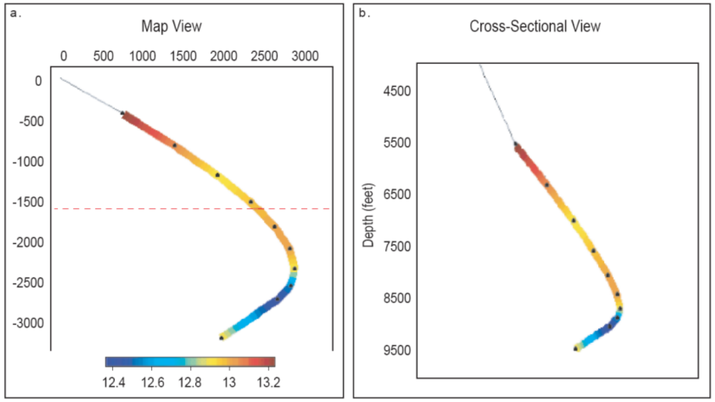
Preventing wellbore instability during drilling
Importance of well trajectory

- Example (Gulf of Mexico)
  - Build-and-hold trajectory
  - Initially drilling (in SouthEast) could not be continued and could not reach intended reservoir because the required pm was higher than the least principal stress
- Through geomechanical modeling;
  - Safer to drill southwest because of lower Shmin
  - By drilling to SouthEast + Southwest, drilling was feasible
  - With similar drilling length and deviation





Mud weight required to stability the borehole

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Preventing wellbore instability during drilling
Importance of well trajectory

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- Example

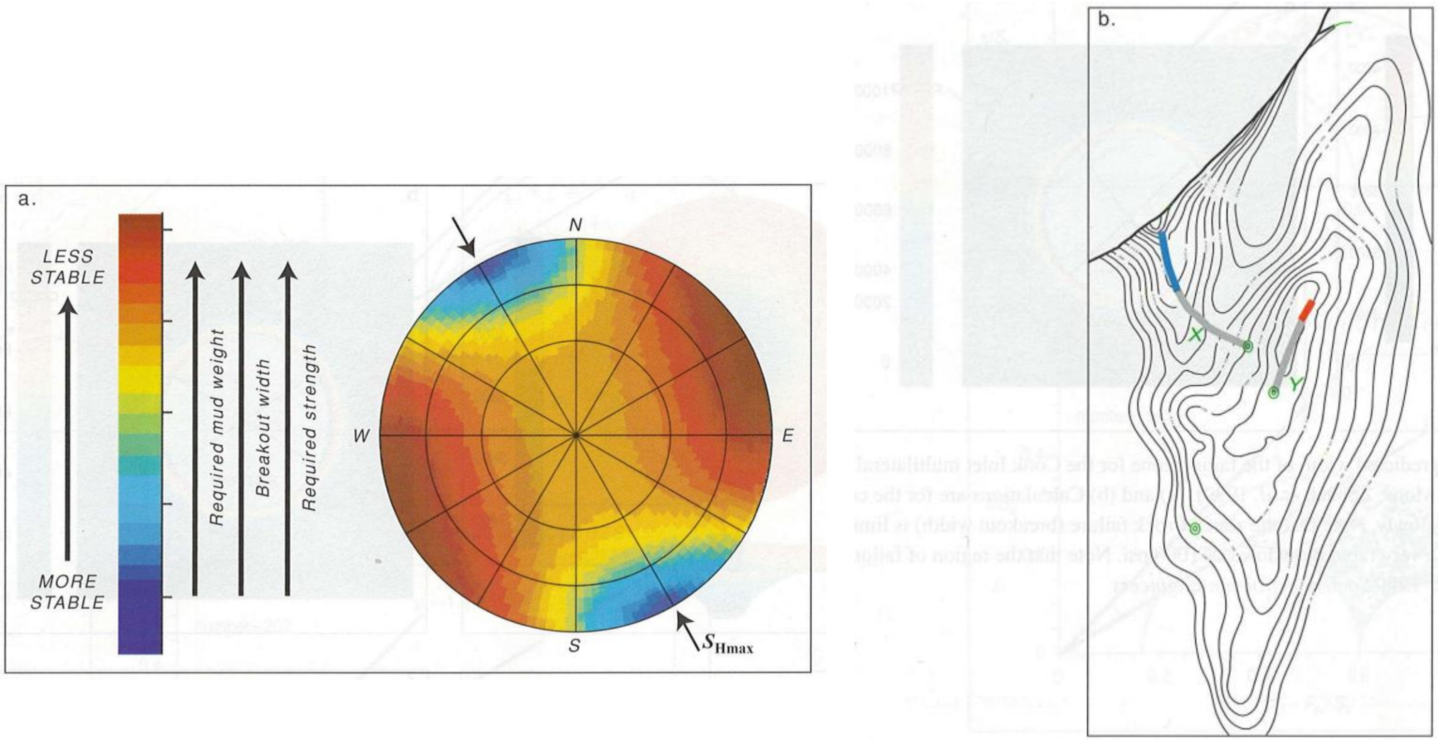

Figure 10.21. (a) Relative stability of multi-lateral wells drilled at various orientations in the Cook Inlet (modified from Moos, Zoback *et al.* 1999). Note that highly deviated wells drilled to the NW and SE are expected to be stable whereas those drilled to the NE and SW are not. (b) Following development of the analysis shown in (a) it was learned that well X (drilled to the NW) was drilled without difficulty whereas well Y (drilled to the NE) had severe problems with wellbore stability. *© 1999 Society Petroleum Engineers*

Zoback MD, 2007, Reservoir Geomechanics, Cambridge University Press

Preventing wellbore instability during drilling
Importance of well trajectory

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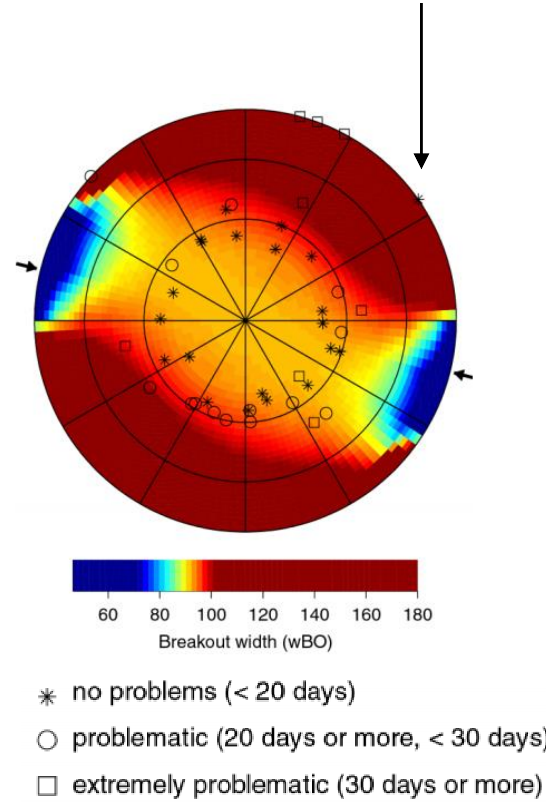
- Importance of well trajectory (compilation of data from Sub-Andean foreland basin in South America)
  - Drilling time < 20 days: Not problematic
  - Drilling time > 20 days: Problematic
  - Drilling time > 30 days: extremely problematic
- Predicted failure width and drilling time
  - Stability analysis shows stable vertical well
  - Instable horizontal well toward NNE-SSW (with largest breakout)
  - Stable well subhorizontal well parallel to SHmax in NW-SE
  - Drilling after this analysis was stable

with appropriate pm



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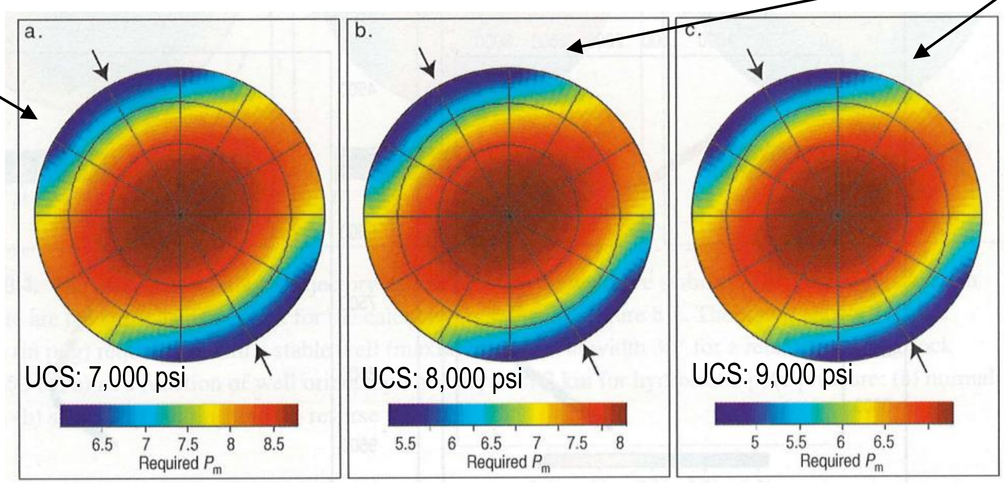
Preventing wellbore instability during drilling
Underbalanced drilling

- Underbalanced drilling
  - Mud weight < pore pressure
  - When there is potential for formation permeability damage
  - Can be a problem when rock strength is low or stress is high
    - When strength is higher, mud weight could be smaller

Lower mud weight can be a problem (sub-vertical wells, and deviated wells)

Hydrostatic (8.3ppg) or lower can be stable

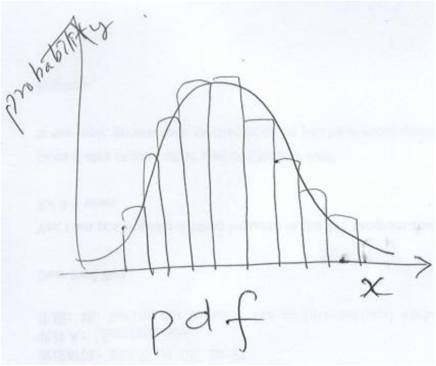


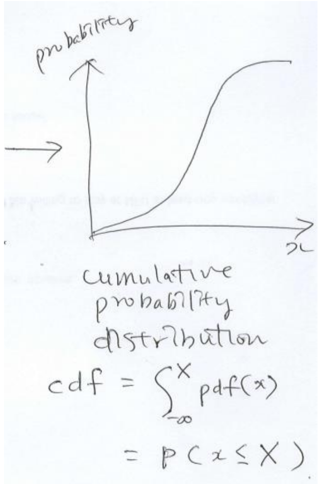
Notice the legend range change (not color)

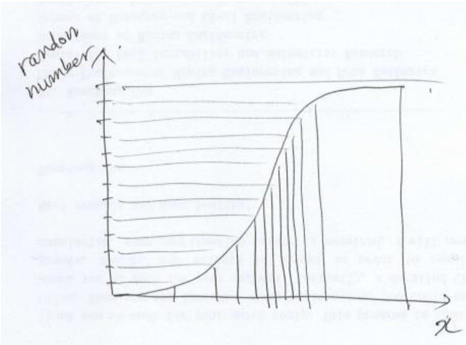
Zoback MD, 2007, Reservoir Geomechanics, Cambridge University Press

Quantitative Risk Assessment

- Monte Carlo simulation
  - Performs risk analysis by using a probability distribution (and cumulative probability distribution)
  - Probability density function & Cumulative probability density function
  - Generation of random number (sufficiently large numbers of generation is necessary)
  - Used widely in science and engineering







Quantitative Risk Assessment

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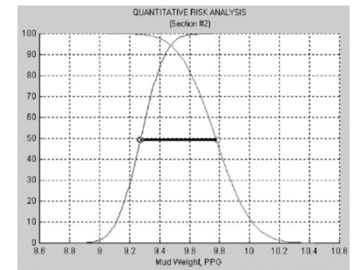
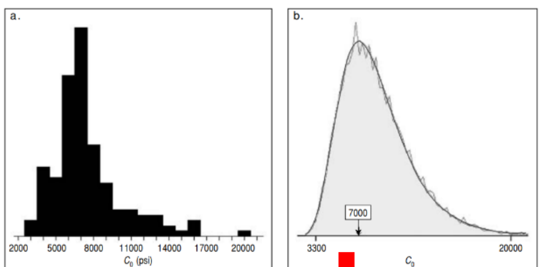
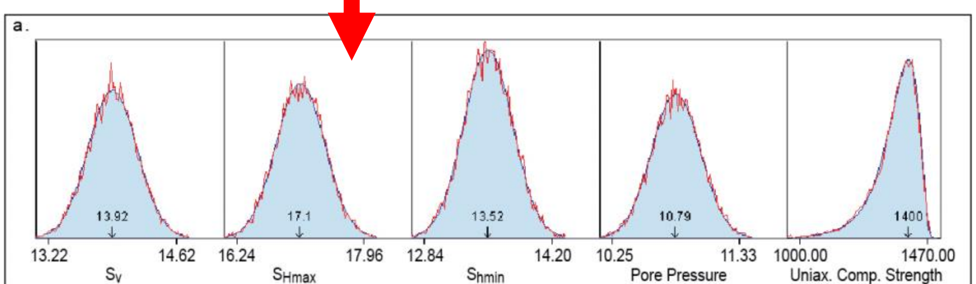
- Quantitative Risk Assessment
  - Input values for mud weight calculations involved significant uncertainties
  - Analysis has to be conducted by probabilistic approach
  - Input as probability density functions (PDF)
    → wellbore collapse & lost circulation pressure can be calculated



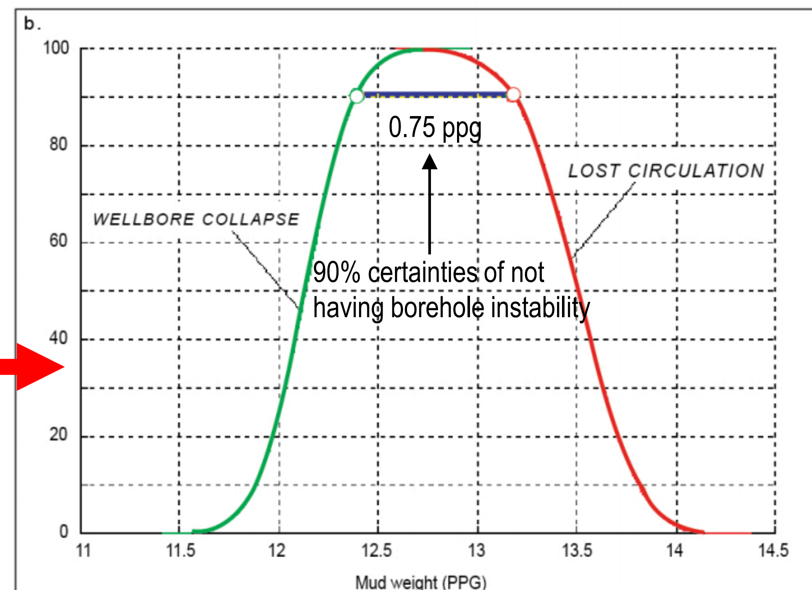
can be in a various forms



$$\sigma_{zz} = \sigma_{33} - 2\nu(\sigma_{11} - \sigma_{22})\cos 2\theta - 4\nu\sigma_{12}\sin 2\theta$$
$$\sigma_{\theta\theta} = \sigma_{11} + \sigma_{22} - 2(\sigma_{11} - \sigma_{22})\cos 2\theta - 4\sigma_{12}\sin 2\theta - \Delta P$$
$$\tau_{\theta z} = 2(\sigma_{23}\cos\theta - \sigma_{13}\sin\theta)$$
$$\sigma_{rr} = \Delta P$$



ppg psi



Zoback MD, 2007, Reservoir Geomechanics, Cambridge University Press

Quantitative Risk Assessment

- Sensitivity analysis reflecting importance (weighting) of input parameters
  - In this particular analysis, UCS turned out to be the most important
  - In fact, the variation of in situ stress could be wider depending upon the investigation

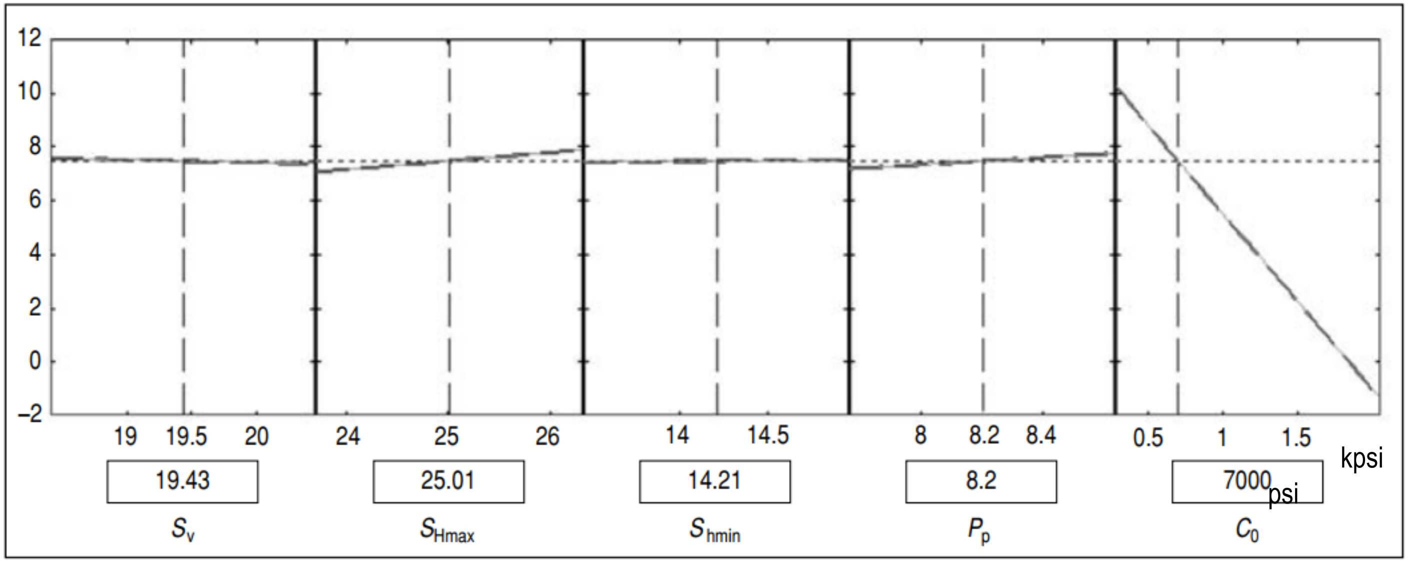


Figure 10.10. Response surfaces that illustrate the sensitivity of the mud weight predictions – expressed in ppg – associated with each parameter's uncertainty, as shown in Figure 10.9a (after Moos, Peska *et al.* 2003). *Reprinted with permission of Elsevier.*

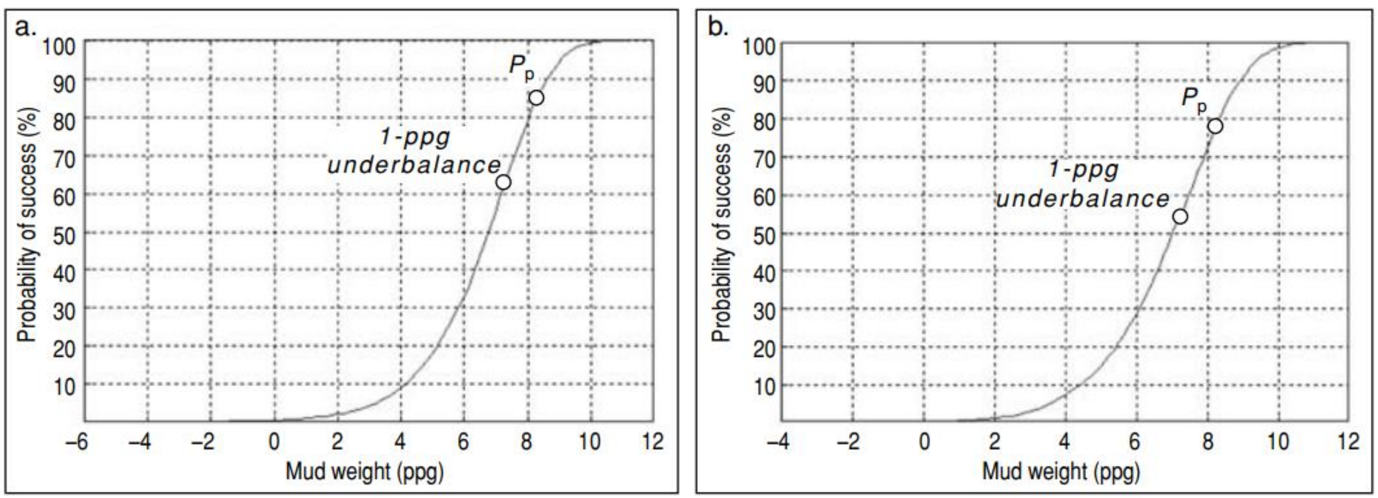
Zoback MD, 2007, Reservoir Geomechanics, Cambridge University Press

Quantitative Risk Assessment

- Probabilistic approach provide a more quantitative answer to the developers

Borehole breakout angle 60°

Borehole breakout angle 30°



Likelihood of successful drilling with given mud weights

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Role of Rock Strength Anisotropy
Rock Anisotropy

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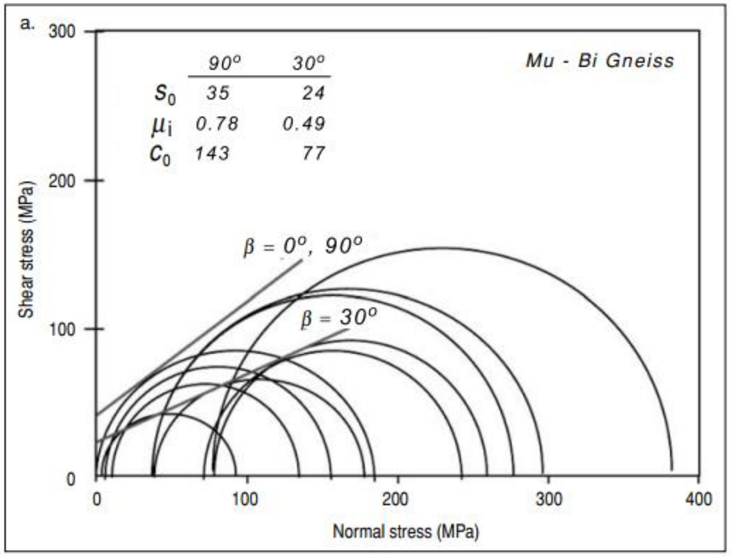
- Anisotropy of rock strength



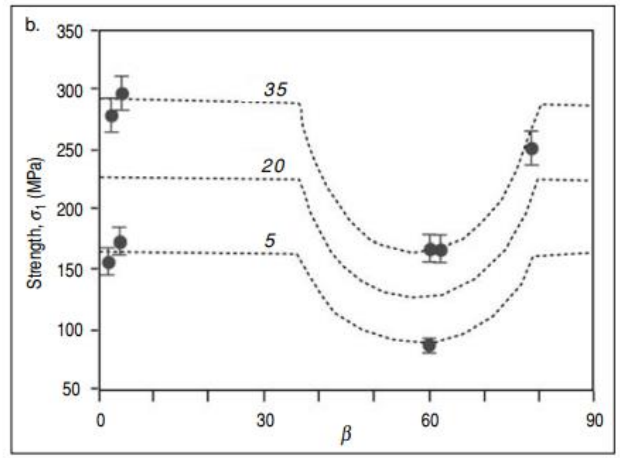
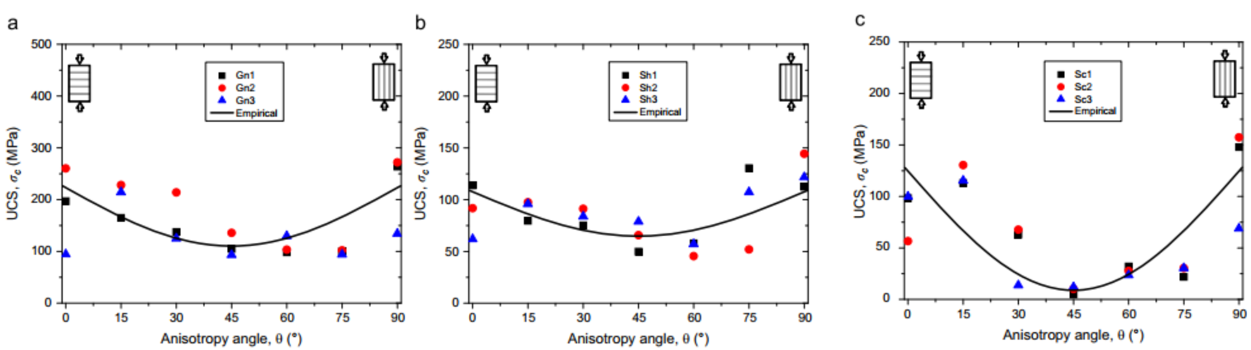


Figure 4.13. Fit of compressive strength tests to the theory illustrated in Figure 4.12 and defined by equation (4.33). Modified from Vernik, Lockner *et al.* (1992).



Cho JW, Kim H, Jeon S, Min KB, Deformation and strength anisotropy of Asan gneiss Boryeong shale, and Yeoncheon schist, IJRMMS, 2012;50:158-169.

Role of Rock Strength Anisotropy
Rock Anisotropy

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- Rock strength anisotropy can affect the stability
  - Due to the weak planes – double lobes are observed
- Situation of importance
  - Vertical drilling through steep bedding plane
  - Highly deviated well through near-horizontal bedding

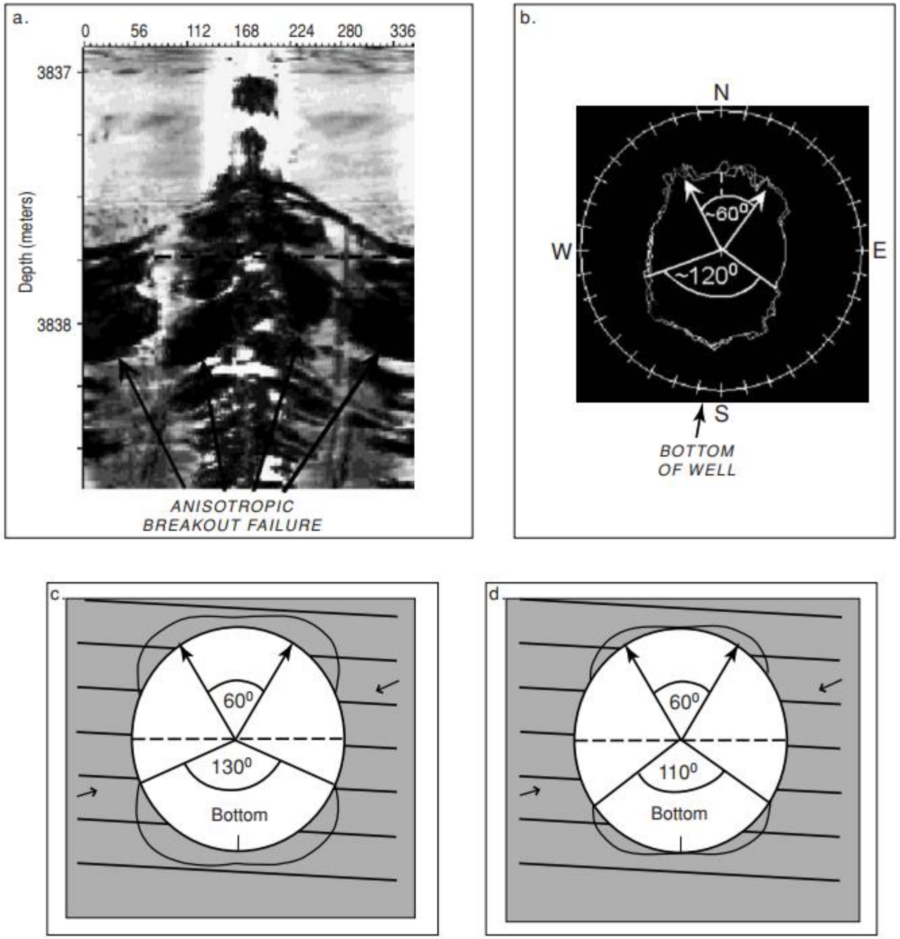

Figure 6.16. (a) Ultrasonic televiewer image of breakouts influenced by rock strength anisotropy associated with the presence of weak bedding planes cutting across a wellbore at a high angle. Note that there are four vertical bands of low reflectivity rather than two as shown in Figure 6.4. (b) Cross-sectional view of a breakout influenced by the presence of weak bedding planes shows a distinctive four-lobed shape. (c) This can be modeled by slip on bedding planes as the stress trajectories bend around the well. (d) When mud weight is increased, the size of the breakouts decreases.

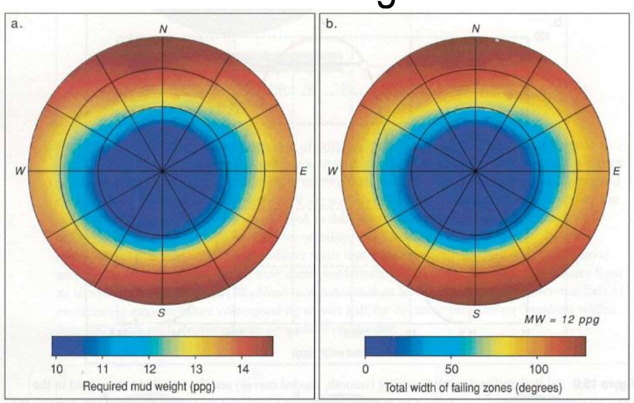

Figure 10.13. Drilling through sub-horizontal, weak bedding planes is only problematic in this case study when the wellbore deviation exceeds ~30°. Because there is little stress anisotropy, there are relatively minor differences in stability with azimuth. This can be seen in terms of the mud weight required to achieve an acceptable degree of failure (a) or the width of the failure zone at a mud weight of 12 ppg (b).

Sub-horizontal drilling can be problematic

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Role of Rock Strength Anisotropy
Rock Anisotropy

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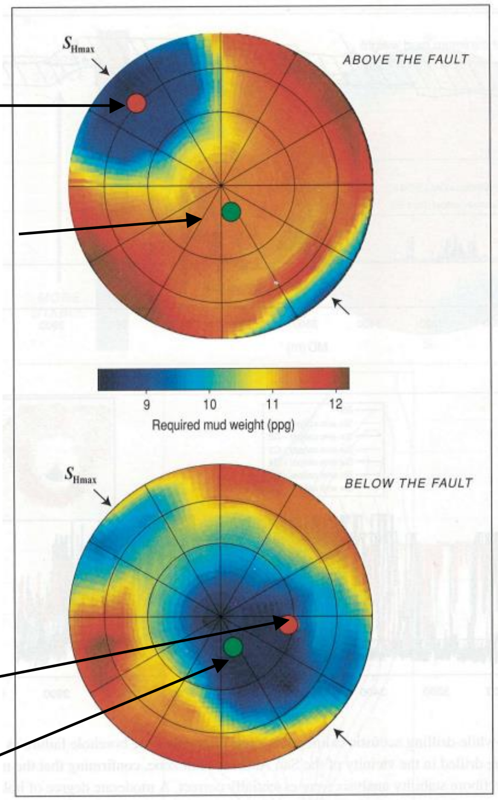
- Change of bedding planes

pole of bedding plane

Near vertical borehole



pole of bedding plane

Near vertical borehole

Figure 10.14. When bedding planes dip steeply, both the deviation and azimuth of wells have a strong effect on wellbore stability (similar to Willson, Last *et al.* 1999). (a) Wellbore stability diagram that shows the case above a fault at about 15,000 ft depth, where the bedding plane orientation (the red dot is the pole to the bedding planes) was such that drilling a near vertical well was quite problematic. Drilling orthogonal to the bedding planes (to offset the effect of bedding on strength) would require a steeply dipping well to the northwest. (b) Below the fault, the bedding orientation changes such that a near-vertical well is stable.

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Role of Rock Strength Anisotropy
Rock Anisotropy – Numerical Modeling

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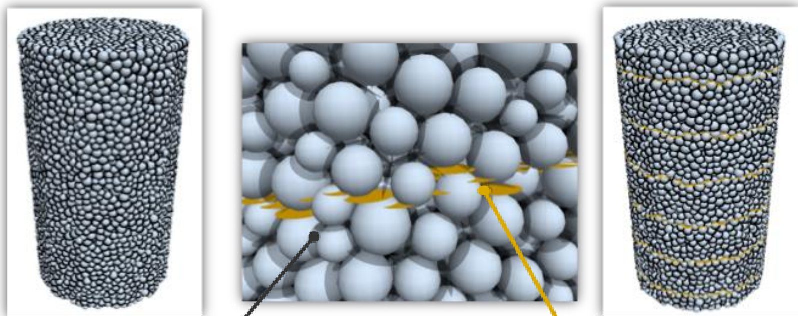
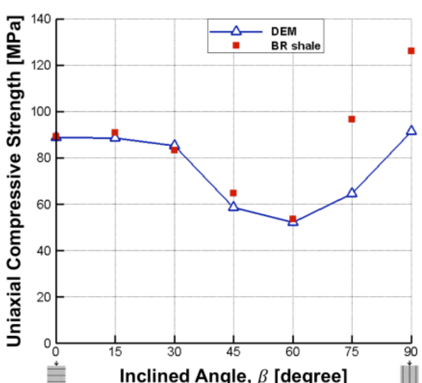
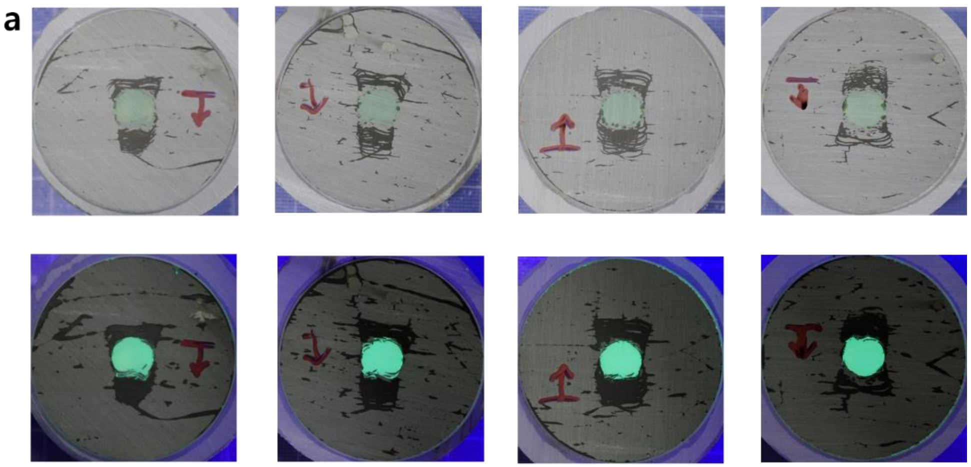
- Numerical modeling of rock anisotropy (Bonded-Particle & Smooth Joint Model)



	Bonded-particle model (parallel bonded contact)	Smooth joint model (smooth joint contact)
Micro elastic parameters	E_{pbm} (micro-elastic modulus)	$k_{n,sj}$ (micro-normal stiffness)
	$k_{s,pbm}/k_{n,pbm}$ (micro-stiffness ratio)	$k_{s,sj}$ (micro-shear stiffness)
Micro strength parameters	$\sigma_{t,pbm}$ (micro-tensile strength)	$\sigma_{t,sj}$ (micro-tensile strength)
	C_{pbm} (micro-cohesion)	C_{sj} (micro-cohesion)
	ϕ_{pbm} (micro-friction angle), μ_{pbm}	ϕ_{sj} (micro-friction angle), μ_{sj}



a



bottom cut 1 cut 2 top

b

cut 1 center cut 2

Hollow cylinder test with bedding plane 60° (sample from North Sea, Park, 2017)

Park B, Min KB*, Thompson N, Horsrud P, Three-dimensional bonded-particle discrete element modeling of mechanical behavior of transversely isotropic rock, Int J Rock Mech Min Sci, 2018, 110:120-132

Park B, 2018, Bonded-particle discrete element modeling of mechanical behavior of transversely isotropic rock, PhD Thesis, Seoul National University

Sand production

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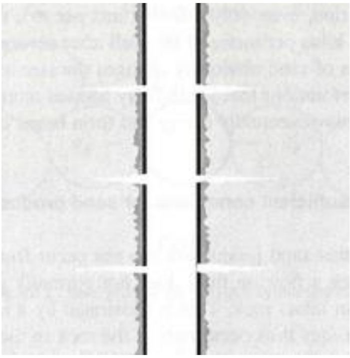
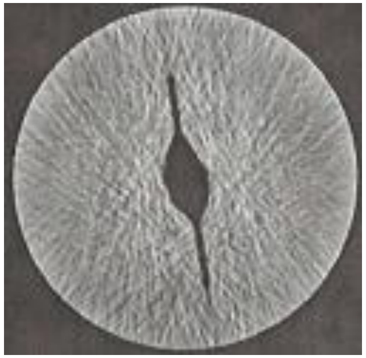
- Sand production (solid production)
  - Unintended byproduct of the hydrocarbon production
  - Solid particles follow the reservoir fluid
  - Usually in unconsolidated sand(stone) reservoir
  - From a few g/m3 ~ to a complete filling of borehole (catastrophe)
  - Closely related to stress induced damage around the perforation
- Problem
  - Erosion of the production equipment due to quartz grains (safety, economy)
  - Wellbore may be abandoned
  - Disposal of polluted sand at the rig
- Chalk production
  - Permeability of chalk is lower, ~ mD



Schematics of perforation (Fjaer et al., 2008)



CT scan image of failure from cylindrical perforation in a sand production test (Fjaer et al., 2008)

Fjaer et al., 2008, Petroleum Related Rock Mechanics, Elsevier

Chalk: Porous marine limestone composed of fine-grained remains of microorganisms with calcite shells (Schlumberger oilfield dictionary)

Sand production

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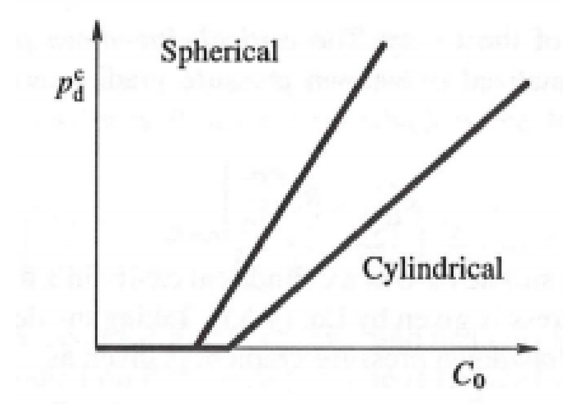
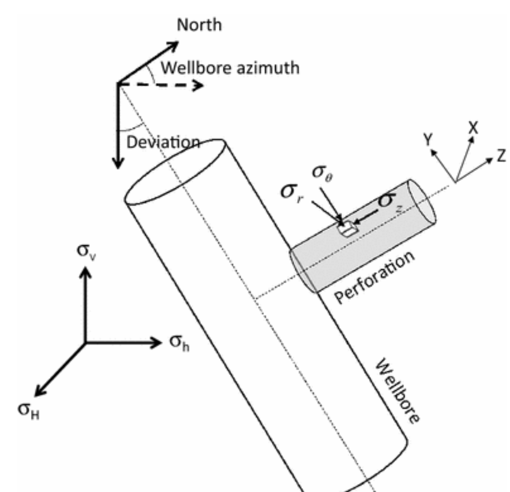
- Drawdown
  - $p_d = p_p - p_w$
  - p_d: drawndown
  - p_p: pore pressure (reservoir pressure)
  - p_w: well pressure(bottomhole flowing pressure)
  - p^c_d: Critical drawdown for sand production:
- Possible solution
  - Presence of breakout, direction of perforation, …
  - A more comprehensive analysis is necessary considering the shape of the perforation
  - Numerical analysis can be used to address the issue of sand production



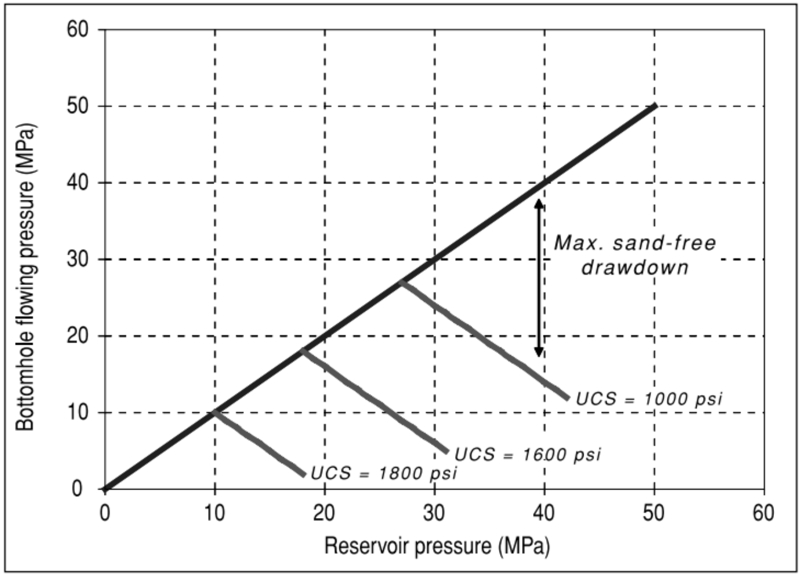
Critical drawdown for sand production and UCS (and shape of cavity formed by sand production)



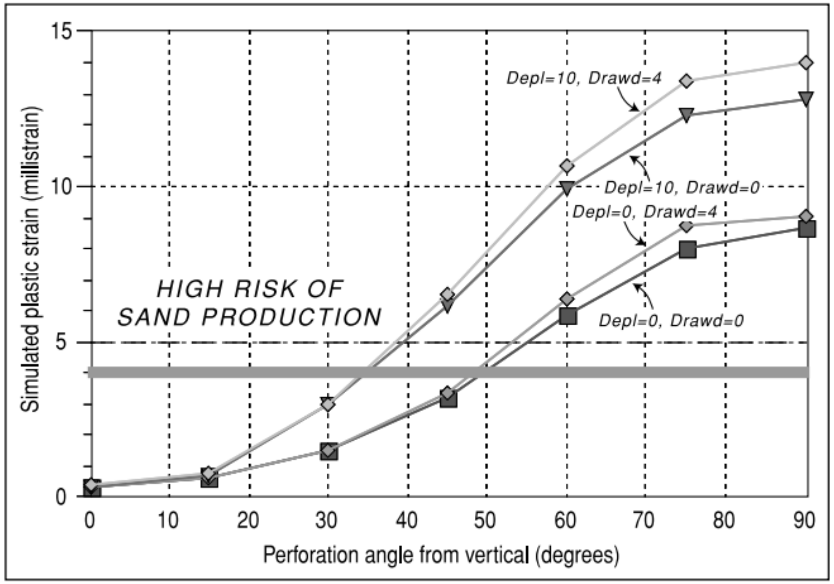
Full shape can be modeled numerically for stress analysis

Sand production

- Reservoir pressure vs. Bottomhole flowing pressure
  - Uncased well
  - Stronger formation can have more drawdown
  - With depletion (decrease of reservoir pressure), critical drawdown gets smaller



- Influence of varying deviation and orientations of perforations
  - Calculation of plastic strain from numerical modeling (critical ~0.5%)
  - As drawdown and depletion continues, sand production at another deviated wells



Zoback MD, 2007, Reservoir Geomechanics, Cambridge University Press

Chemical Effect - Mud/rock interaction

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- Chemical interactions between drilling mud and clay-rich (shaley) rocks can affect rock strength and local pore pressure
  - ← Shales tends to be more unstable than sand or carbonates
  - Oil has perfect membrane efficiency and prevents ion exchange. But oil-based mud is expensive and has regulatory restrictions
- Three factors;
- Relative salinity of the drilling mud vs. formation pore fluid
  - Water activity A_m (inversely proportional to salinity)> Activity of formation fluid (A_w) → osmosis diffusion (transfer of water from regions of low salinity to regions of high salinity) → formation pore pressure increase
- Membrane efficiency (change in pore pressure is limited by this)
  - How easily ions can pass from the drilling mud into the formation
- Ion exchange capacity is important for replacement of cations
  - Mg^{++} by Ca^{++}, Na^{++} by K^{+} weakens the shale

Chemical Effect - Mud/rock interaction

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- Magnitude of pore pressure generated by osmotic diffusion

$$\Delta P = E_m \times ({}^{RT}/_{V}) \times \ln(A_p/A_m) \quad (10.1)$$

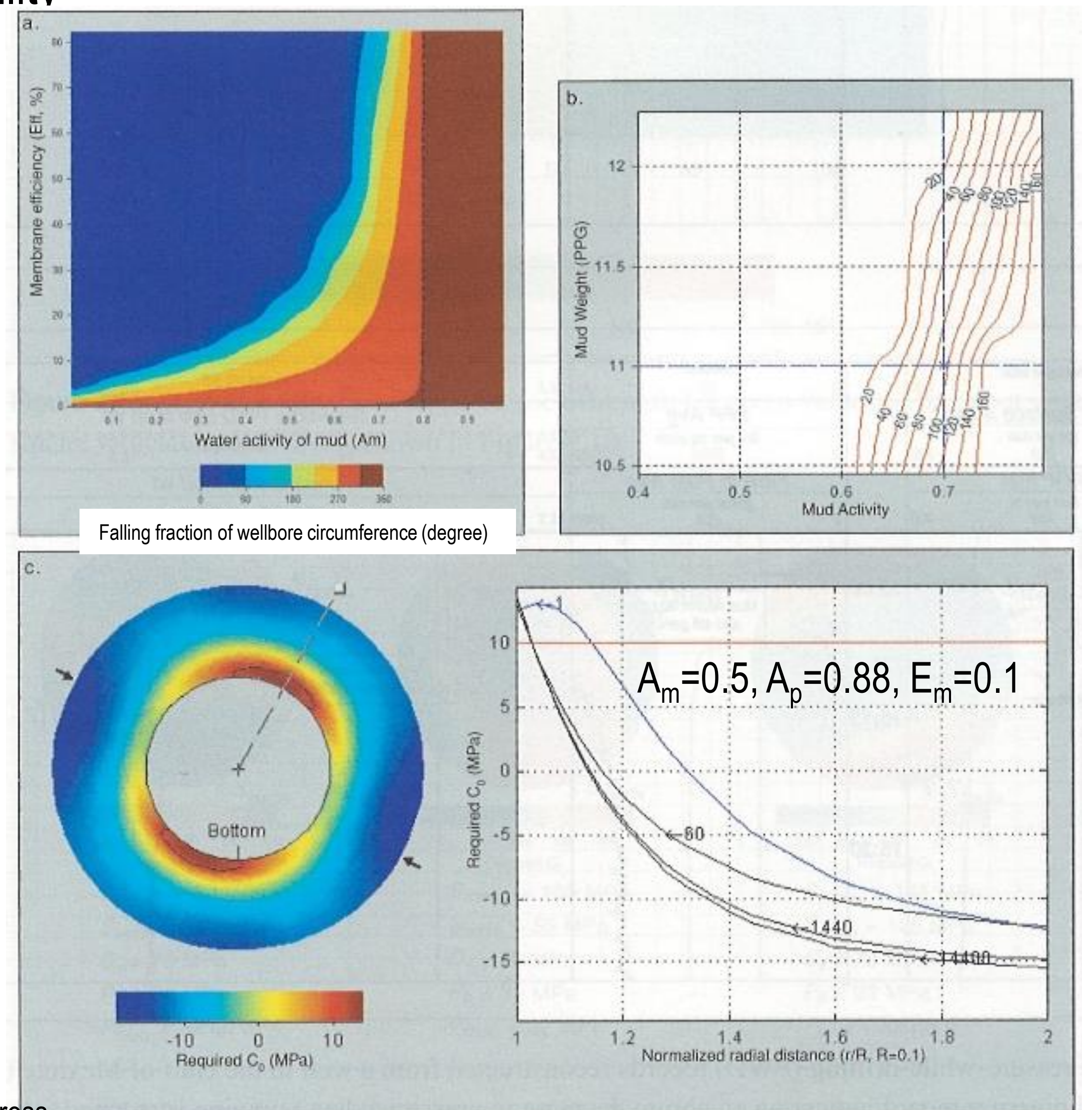
  - Activity of fluid: ratio of the vapor pressure above pure water to the vapor pressure above the solution being tested
    - Inversely proportional to salinity
    - Activity of mud (Am) ~ 0.8-0.9
    - Typical shale (Ap)~ 0.75-0.85
  - Δp is (-) → water will be drawn into the shale
  - E_m: membrane efficiency (%)
  - R: Gas constant, T: Temperature (Kelvin), V: molar volulme of the water (liters/mole)
  - A_p: pore fluid activity
  - A_m: mud activity
- $A_m < A_p$: virtual excess mud pressure
- $A_m > A_p$: virtual underbalance

Chemical Effect - Mud/rock interaction

- Chemical effect and wellbore stability

$$\Delta P = E_m \times (^{RT}/_V) \times \ln(A_p/A_m)$$

- Membrane efficiency (E_m)
  - Increasing E_m dramatically improve stability at intermediate A_m value
- Water activity of mud
  - Wellbore is very unstable with high A_m
- Mud weight increase can be used to offset the weakening by chemical effect
- When mud is more saline than formation, wellbore becomes more stable with time

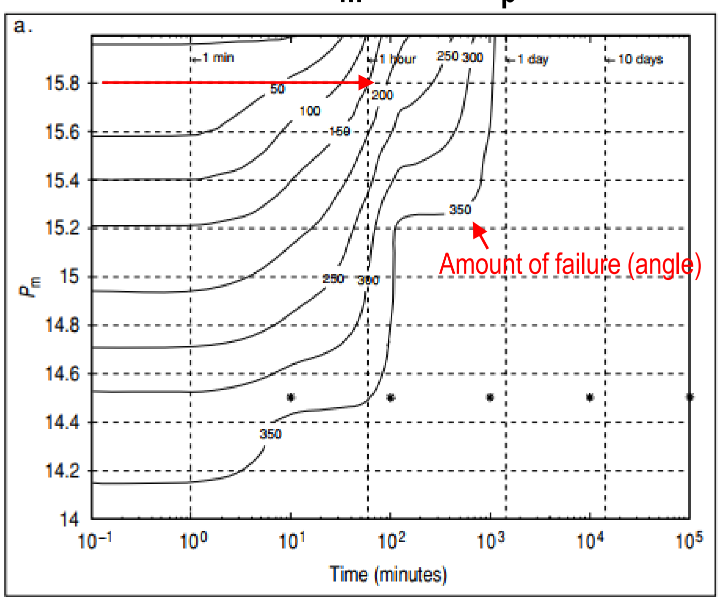


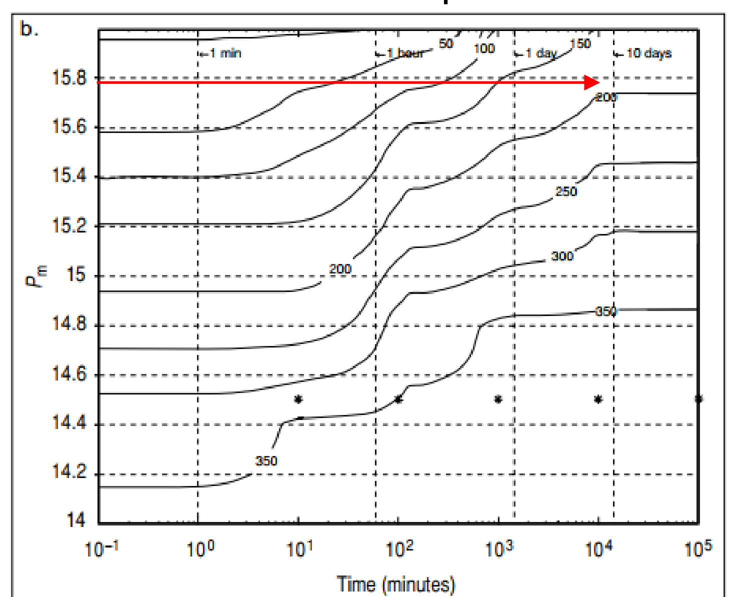
Zoback MD, 2007, Reservoir Geomechanics, Cambridge University Press

Chemical Effect - Mud/rock interaction

- Time dependent borehole stability due to chemical effect
  - Chemoelastic and poroelastic behavior
  - Selection of mud weight considering mud activity is necessary
  - Lowering Am allow lowering of mud weight with extended working time

A_m= 0.9, A_p=0.8 → A_m= 0.7, A_p=0.8





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Time dependent wellbore failure

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- SAFOD (San Andreas Fault Observatory at Depth) borehole (~4 km)
  - Arkosic sandstone with interbedded shale
  - Comparison of LWD and logging after 5 weeks → Significant deterioration of borehole (enlargement on the top)
- Reason?
  - Mud-rock interaction? But there are arkosic rock.
  - Mud penetration into the formation (after shutting off) with fractures
  - Keyseat could also have occurred
  - Artifact of logging tool near the bottom in the deviated well

Measured Depth (MD):measured along the path of the borehole
True Vertical Depth (TVD): absolute vertical distance between the datum and the point in the wellbore

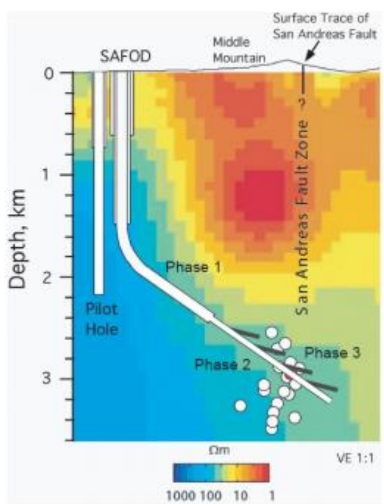
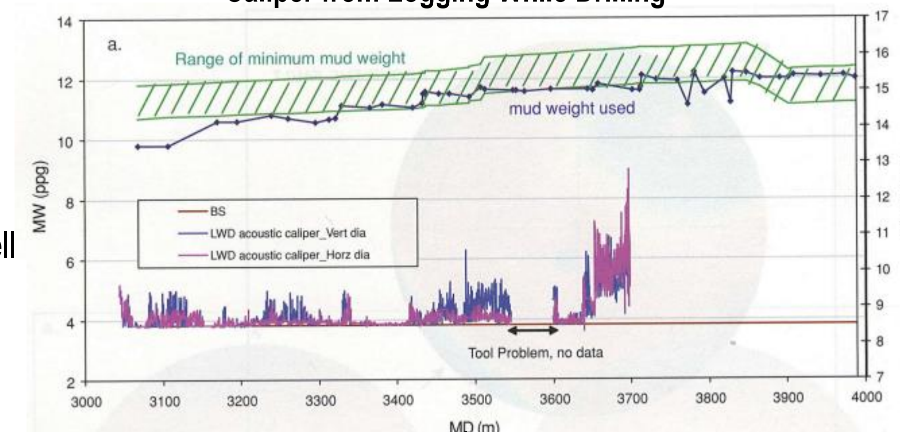


Fig. 1: The SAFOD well trajectory superimposed on electrical resistivity structure determined from inversion of active source magnetotelluric data.[1, 27] The locations of the target earthquakes (after Thurber et al.[1]) are shown approximately in this cartoon.

Paul, P. K., & Zoback, M. D., 2006. Wellbore Stability Study for the SAFOD Borehole Through the San Andreas Fault. SPE 102781

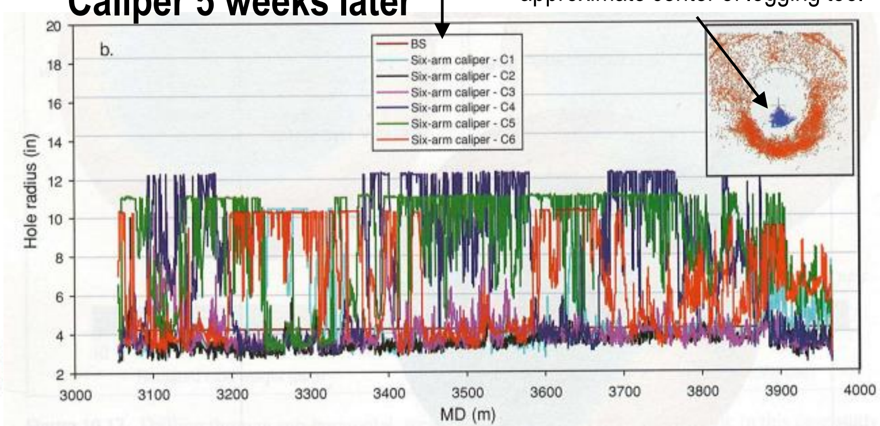
Arkosic rock: sandstone containing at least 25% feldspar.

Caliper from Logging While Drilling



Caliper 5 weeks later

approximate center of logging tool



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