Lecture 10

Ch. 8 Wellbore failure and stress determination in deviated wells (6 May 2020)

Ki-Bok Min, PhD

Professor
Department of Energy Resources Engineering
Seoul National University

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

Importance

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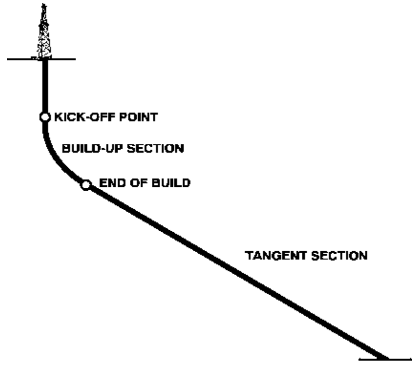
- Many boreholes are horizontal, highly deviated from vertical or have complex trajectories
- Difficulties
  - Four-arm calipers track key seats in deviated borehole
  - Breakout/DITF direction different from vertical well
  - Pattern of DITF occur in en echelon at an angle to the wellbore axis. Hard to distinguish with natural fractures
- Extend the theory developed in vertical well to arbitrary orientation
  - borehole breakout and drilling induced tensile fracture (DITF)
  - Assume S1, S2, S3 are in horizontal and vertical direction (however, this condition can be relaxed)



https://www.netwasgroup.us/engineering-4/workbook.html

State of stress surrounding an arbitrarily deviated well

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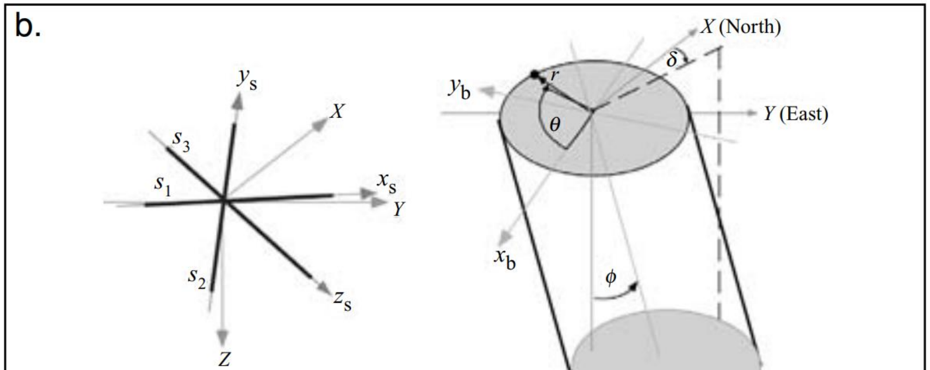
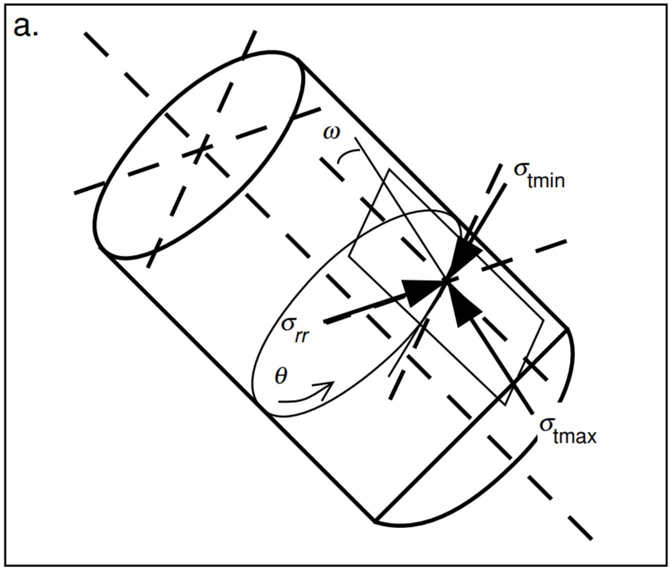
- Principal stresses are not aligned with the wellbore axis
  - Geographic coordinate: X, Y and Z
  - Stress coordinate: x_s, y_s and z_s
  - Wellbore coordinate: x_b, y_b and z_b
  - σ_{tmin} & $\sigma_{tmin:}$ principal stresses acting in a plane tangential to the wellbore wall
  - ω: angle between the axis of the wellbore and plane normal to σ_{tmin}
  - Θ: measured from the bottom in clockwise direction



Rotation Angle	Geographic	Stress
α	X (N)	x_s
β	Y (E)	y_s
γ	Z (Down)	z_s



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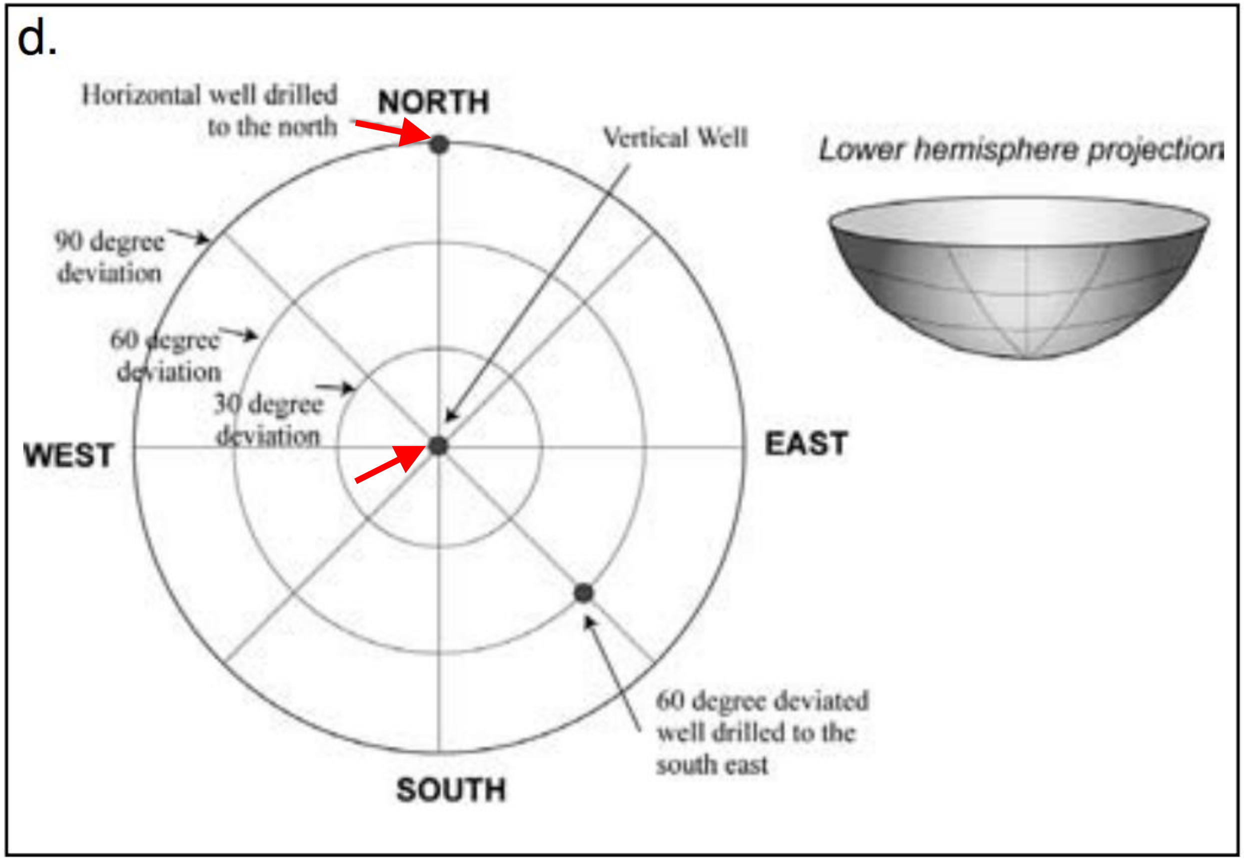
State of stress surrounding an arbitrarily deviated well

- Orientation of deviated borehole in stereonet
  - Vertical, horizontal and arbitrarily oriented borehole



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State of stress surrounding an arbitrarily deviated well

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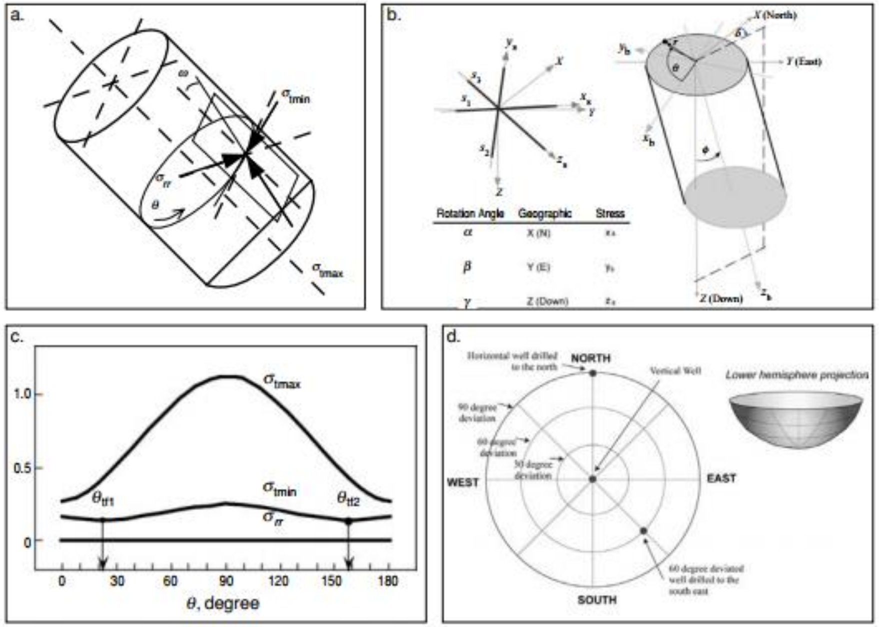
- Borehole breakout and DITF location and pattern is more complex in deviated well
  - Position of BB:
  - magnitude and orientation of principal stresses + borehole orientation



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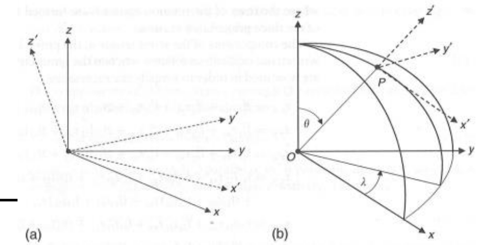
State of stress surrounding an arbitrarily deviated well



- Transformation from stress coordinate system (x_s, y_s and z_s)→ Global coordinate system (X, Y and Z)→ wellbore coordinate system (x_b, y_b and z_b)

$$\mathbf{S}_s = \begin{pmatrix} S_1 & 0 & 0 \\ 0 & S_2 & 0 \\ 0 & 0 & S_3 \end{pmatrix} \quad (8.1)$$

To rotate these stresses into a wellbore coordinate system we first need to know how to transform the stress field first into a geographic coordinate system using the angles α, β, γ (Figure 8.1c). This is done using

$$\begin{pmatrix} x_s \\ y_s \\ z_s \end{pmatrix} = \mathbf{R}_s \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad (8.2)$$

where,

$$\mathbf{R}_s = \begin{pmatrix} \cos\alpha\cos\beta & \sin\alpha\cos\beta & -\sin\beta \\ \cos\alpha\sin\beta\sin\gamma - \sin\alpha\cos\gamma & \sin\alpha\sin\beta\sin\gamma + \cos\alpha\cos\gamma & \cos\beta\sin\gamma \\ \cos\alpha\sin\beta\sin\gamma + \sin\alpha\sin\gamma & \sin\alpha\sin\beta\cos\gamma - \cos\alpha\sin\gamma & \cos\beta\cos\gamma \end{pmatrix} \quad (8.3)$$

To transform the stress field from the geographic coordinate system to the borehole system, we use

$$\begin{pmatrix} x_b \\ y_b \\ z_b \end{pmatrix} = \mathbf{R}_b \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad (8.4)$$

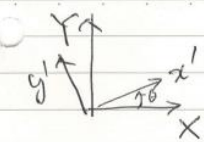
where,

$$\mathbf{R}_b = \begin{pmatrix} -\cos\delta\cos\phi & -\sin\delta\cos\phi & \sin\phi \\ \sin\delta & -\cos\delta & 0 \\ \cos\delta\sin\phi & \sin\delta\sin\phi & \cos\phi \end{pmatrix} \quad (8.5)$$

With $\mathbf{R}_s$ and $\mathbf{R}_b$ defined, we can define the stress first in a geographic, $\mathbf{S}_g$, and then in a wellbore, $\mathbf{S}_g$, coordinate system using the following transformations

$$\mathbf{S}_g = \mathbf{R}_s^{\mathrm{T}}\mathbf{S}_s\mathbf{R}_s$$
$$\mathbf{S}_b = \mathbf{R}_b\mathbf{R}_s^{\mathrm{T}}\mathbf{S}_s\mathbf{R}_s\mathbf{R}_b^{\mathrm{T}} \quad (8.6)$$

$$R = \begin{pmatrix} \cos(x',x) & \cos(x',y) \\ \cos(y',x) & \cos(y',y) \end{pmatrix} = \begin{pmatrix} \cos\theta \cdot & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$



$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} X \\ Y \end{pmatrix}$$

R : direction cosine.

3D

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = R \begin{pmatrix} X \\ Y \end{pmatrix}$$

$$R = \begin{pmatrix} \cos(x',x) & \cos(x',y) & \cos(x',z) \\ \cos(y',x) & \cos(y',y) & \cos(y',z) \\ \cos(z',x) & \cos(z',y) & \cos(z',z) \end{pmatrix}$$

$$\begin{pmatrix} \tau_{x'x'} & \tau_{x'y'} \\ \tau_{y'x'} & \tau_{y'y'} \end{pmatrix} = R \begin{pmatrix} \tau_{xx} & \tau_{xy} \\ \tau_{xy} & \tau_{yy} \end{pmatrix} R^T$$

$$\tau' = R \tau R^T$$

$$\begin{pmatrix} x_s \\ y_s \\ z_s \end{pmatrix} = R_s \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \rightarrow \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = R_s^T \begin{pmatrix} x_s \\ y_s \\ z_s \end{pmatrix}$$

(8.2)

$$S_g = R_s^T \cdot S_s (R_s^T)^T = R_s^T S_s R_s$$

$$\begin{pmatrix} x_b \\ y_b \\ z_b \end{pmatrix} = R_b \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \rightarrow S_b = R_b \cdot S_g \cdot R_b^T = R_b R_s^T S_s R_s \cdot R_b^T$$

(8.4) (8.6)

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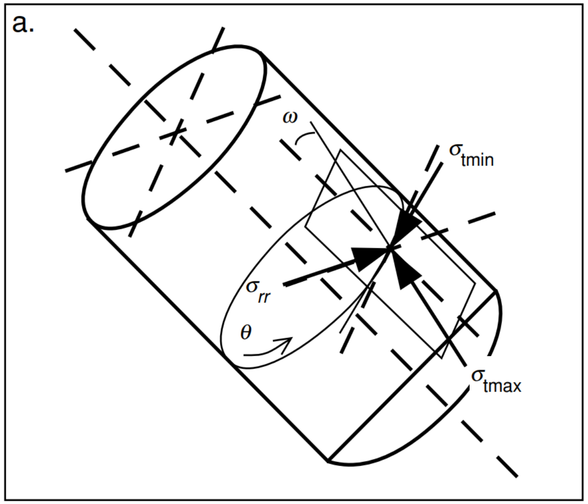
State of stress surrounding an arbitrarily deviated well

- Stresses acting at the borehole wall

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

and Zoback (1995). The principal effective stresses around the wellbore are given by

$$\sigma_{\mathrm{tmax}} = \frac{1}{2}\left(\sigma_{zz} + \sigma_{\theta\theta} + \sqrt{(\sigma_{zz} - \sigma_{\theta\theta})^2 + 4\tau_{\theta z}^2}\right)$$
$$\sigma_{\mathrm{tmax}} = \frac{1}{2}\left(\sigma_{zz} + \sigma_{\theta\theta} - \sqrt{(\sigma_{zz} - \sigma_{\theta\theta})^2 + 4\tau_{\theta z}^2}\right)$$



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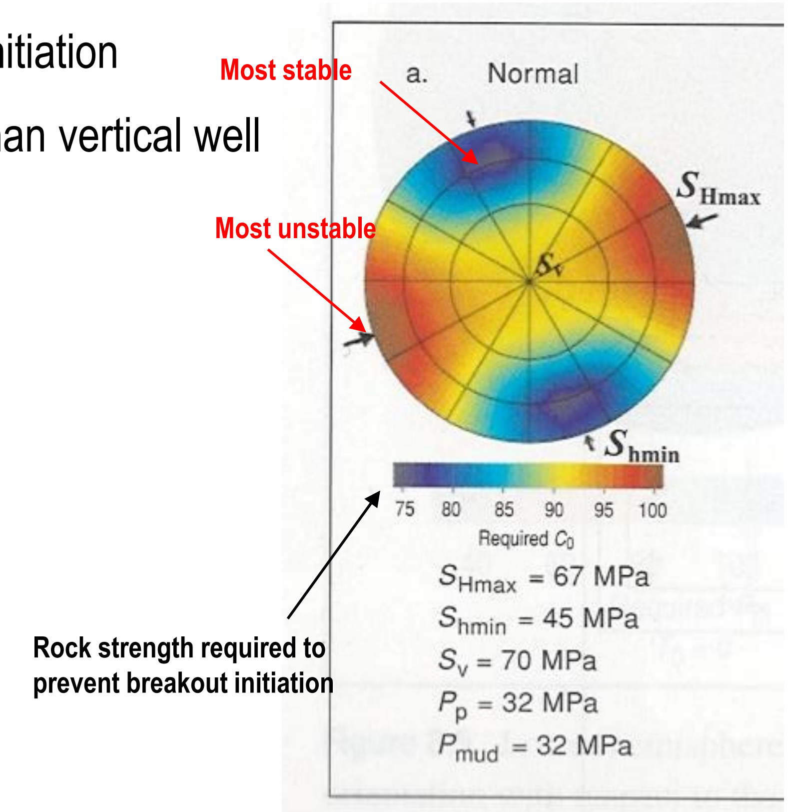
Failure of arbitrarily deviated wells

- Tendency for the initiation of *wellbore breakout* in wells of different orientations for normal, strike-slip and reverse faulting stress regimes (3.2 km)
- Normal faulting stress regime
  - Deviated holes in S_{Hmax} are more likely for BB initiation
  - Wells highly deviated in S_{hmin} are more stable than vertical well



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Failure of arbitrarily deviated wells

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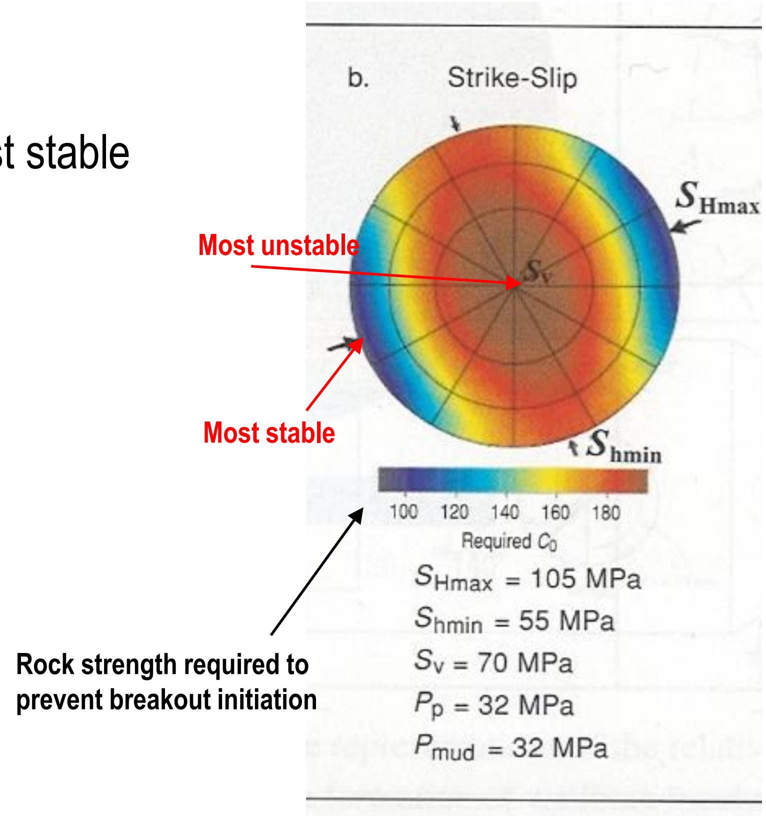
- Tendency for the initiation of *wellbore breakout* in wells of different orientations for normal, strike-slip and reverse faulting stress regimes (3.2 km)
- Strike-slip faulting stress regime
  - Vertical holes are more likely for BB initiation
  - Horizontal wells drilled in S_{Hmax} direction are most stable



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Failure of arbitrarily deviated wells

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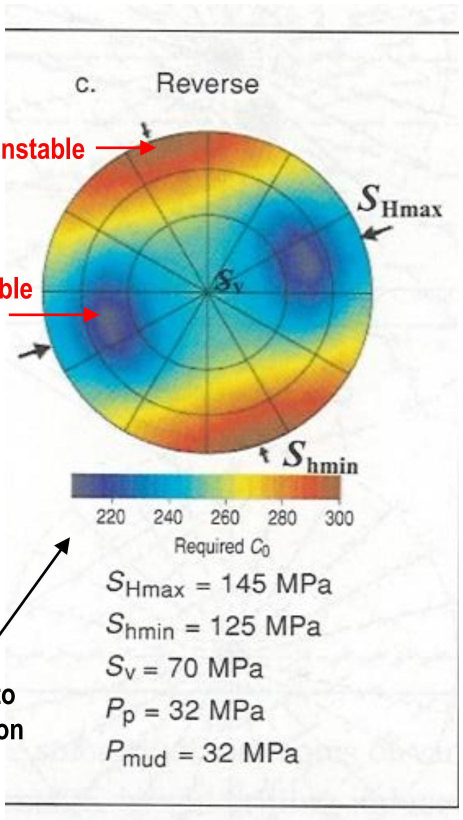
- Tendency for the initiation of *wellbore breakout* in wells of different orientations for normal, strike-slip and reverse faulting stress regimes (3.2 km)
- Reverse faulting stress regime
  - Horizontal wells drilled in S_{hmin} direction are most unstable
  - Subhorizontal holes in S_{Hmax} direction are more stable

Most unstable

Most stable



Rock strength required to prevent breakout initiation

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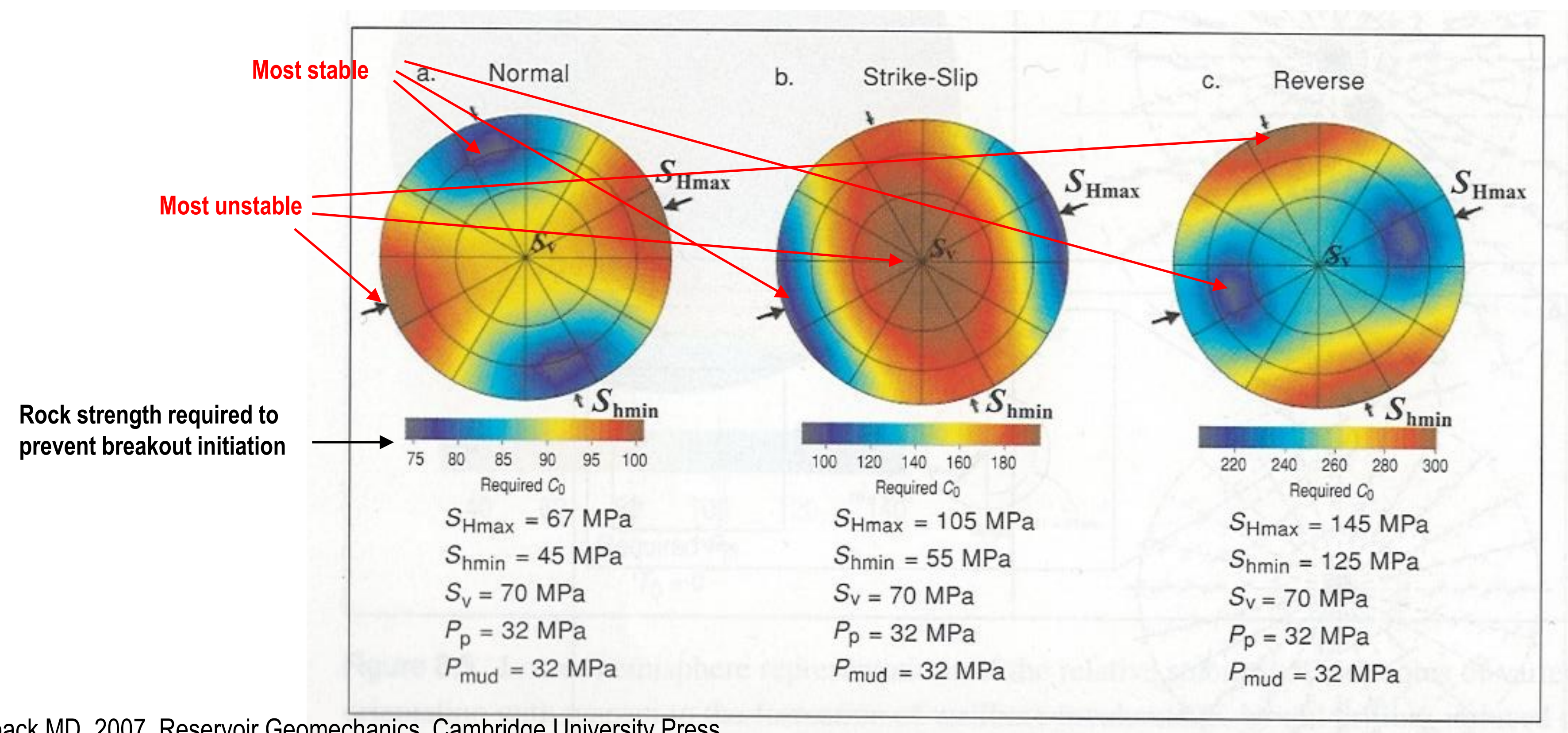
Failure of arbitrarily deviated wells
wellbore breakout

- General observation
  - Stability: reverse faulting(least stable) < strike-slip < normal faulting (most stable)
    - Simply because stresses are highest in reverse faulting
  - Although stable well is not necessarily to prevent borehole breakout



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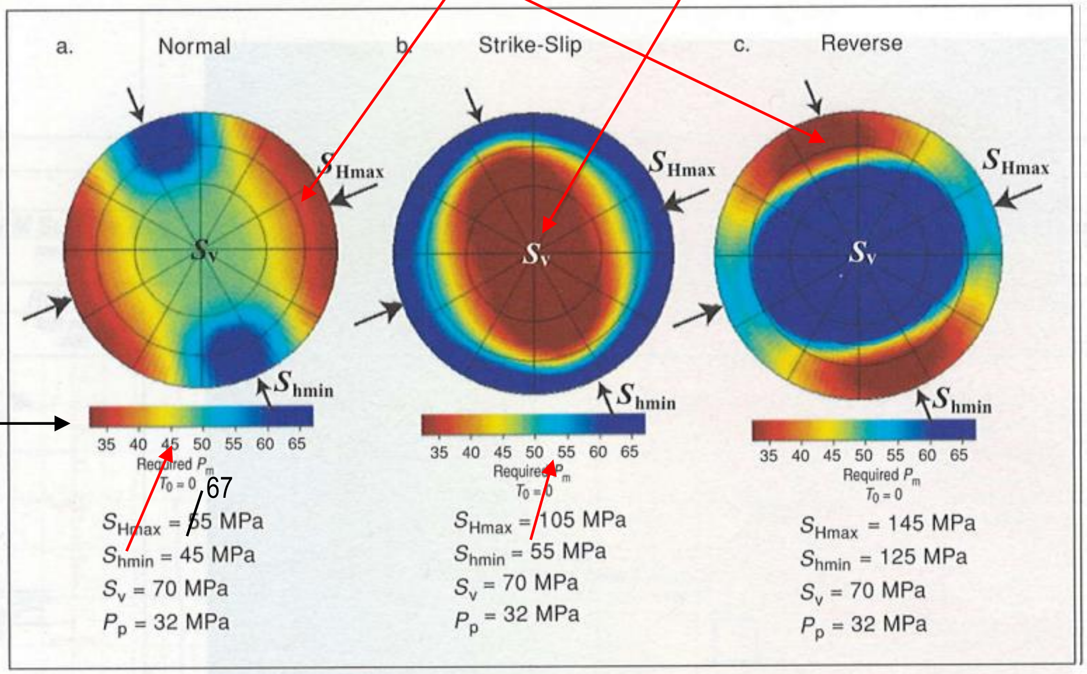
Failure of arbitrarily deviated wells
Tensile fractures

- Tendency for the initiation of *tensile fractures* in wells of different orientations for normal, strike-slip and reverse faulting stress regimes
  - In normal faulting & strike slip, extremely high mud weight is required for tensile fracture. May cause lost circulation
  - Strike-slip: wells deviated <30° are expected to cause tensile fractures
  - NF/RF: tensile fractures expected in highly deviated wells

Mud weight required to induce tensile fractures



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Failure of arbitrarily deviated wells
Borehole breakout & tensile fractures (traces)

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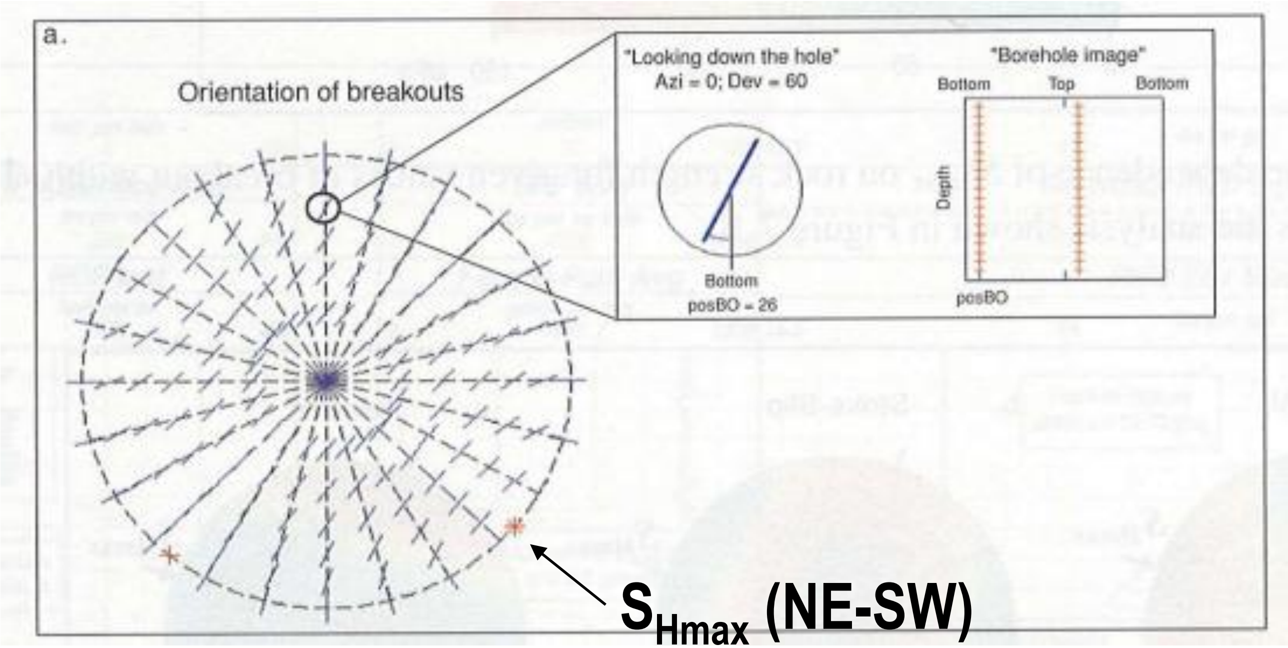
- Borehole breakout
  - Deviation to the NE or SW → BB on top and bottom of the well
  - Deviation to the NW or SE → BB on sides of the well
  - Looking-down-the-well convention. posBO: orientation of BB



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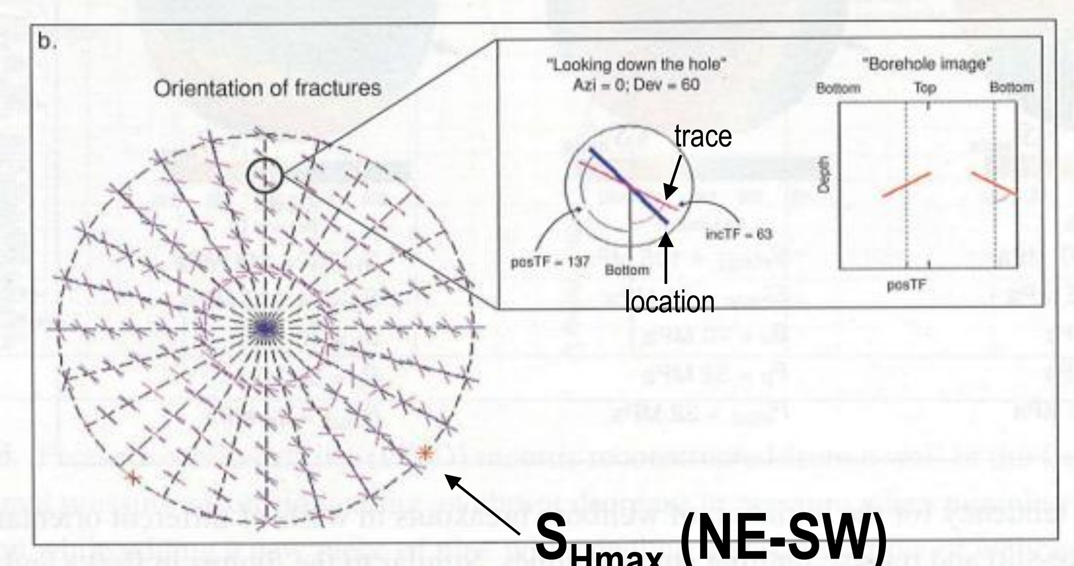
Failure of arbitrarily deviated wells
Borehole breakout & tensile fractures (traces)

- Drilling induced tensile fractures (DITF)
  - posTF: position of tensile fracture around the borehole circumference
  - incTF: orientation of fracture trace wrt borehole axis
  - DITF in deviated well occur as *en echelon* pairs of fractures inclined to the wellbore wall at the angle ω
  - Relationship with hydraulic fracturing propagation? – eventually become perpendicular to the least principal stress



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en echelon: Describing parallel or subparallel, closely-spaced, overlapping or step-like minor structural features in rock, such as faults and tension fractures, that are oblique to the overall structural trend (Schlumberger oilfield dictionary)

Failure of arbitrarily deviated wells
Borehole breakout & tensile fractures (traces)

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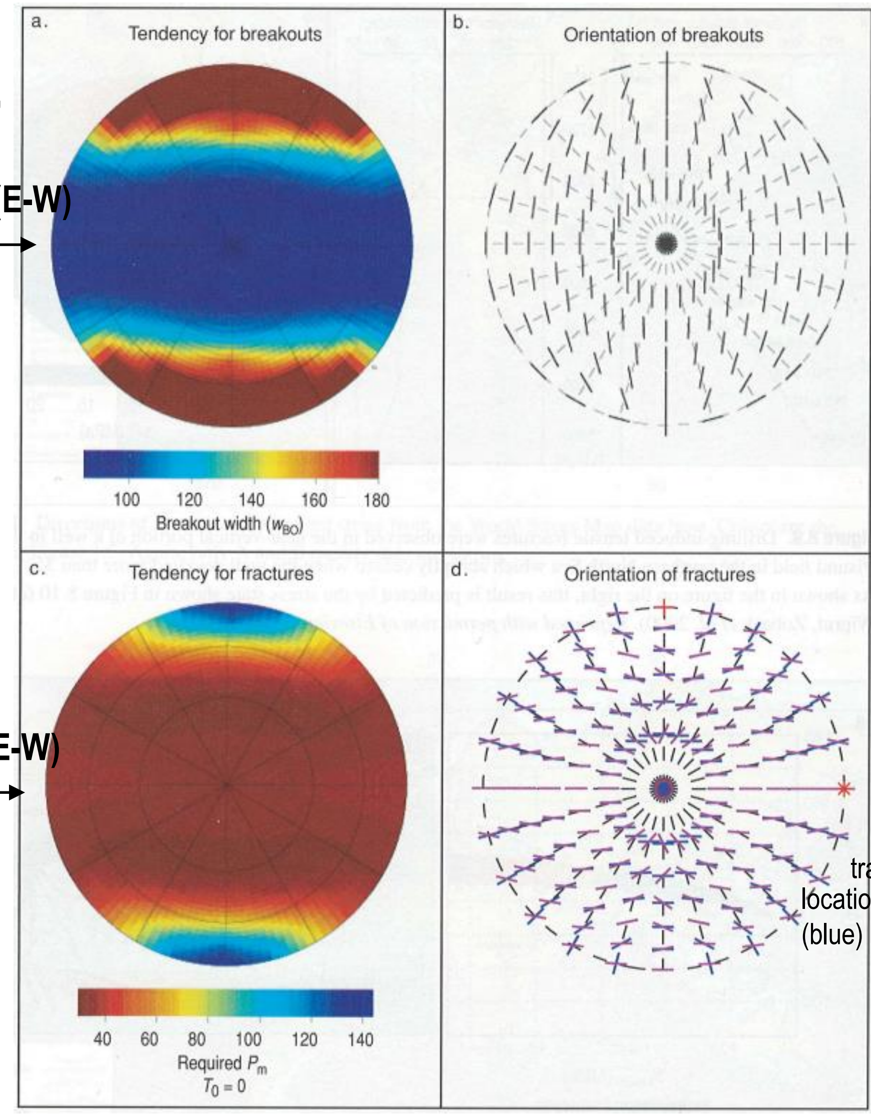
- Borehole breakout and DITF
  - Strike slip fault, UCS=45MPa, μ = 1.0, SH=90 MPa, Sv=88.2 Mpa, Sh=51.5MPa, Pp=31.5 MPa
  - Breakout width
    - Vertical: ~90°
    - Horizontal in N-S: ~180° (very unstable→ wash out)
  - DITF
  - Are likely a wide range of orientations
  - Fractures are significantly inclined wrt wellbore axis – *en echelon*

S_{Hmax} (E-W)

S_{Hmax} (E-W)



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Q. Figure 8.5a, how do we understand it?

This is expressed for vertical well, but we can adjust to horizontal well

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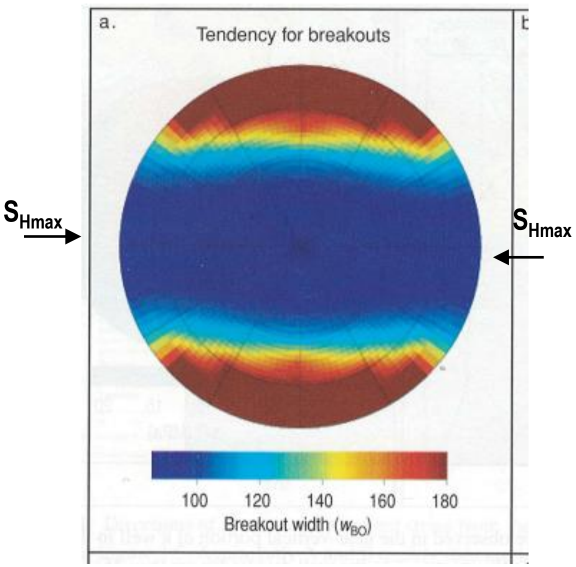
- Is this correct?



In situ stress & pore pressure

- $S_{\mathrm{Hmax}} = 90$ MPa
- S_{Hmax} orientation is N90°E (east–west)
- $S_{\mathrm{v}} = 88.2$ MPa (depth 3213m)
- $S_{\mathrm{hmin}} = 51.5$ MPa
- $P_{\mathrm{p}} = P_{\mathrm{mud}} = 31.5$ MPa

Stress distribution around the borehole

$$\sigma_{rr} = \frac{1}{2}(S_{\mathrm{Hmax}} + S_{\mathrm{hmin}} - 2P_0)\left(1 - \frac{R^2}{r^2}\right) + \frac{1}{2}(S_{\mathrm{Hmax}} - S_{\mathrm{hmin}}) \times \left(1 - \frac{4R^2}{r^2} + \frac{3R^4}{r^4}\right)\cos 2\theta + \frac{\Delta P R^2}{r^2}$$

$$\sigma_{\theta\theta} = \frac{1}{2}(S_{H\max} + S_{h\min} - 2P_0)\left(1 + \frac{R^2}{r^2}\right) - \frac{1}{2}(S_{H\max} - S_{h\min}) \times \left(1 + \frac{3R^4}{r^4}\right)\cos 2\theta - \frac{\Delta P R^2}{r^2} - \sigma^{\Delta T}$$

$$\sigma_{\theta\theta} = S_{\mathrm{hmin}} + S_{\mathrm{Hmax}} - 2(S_{\mathrm{Hmax}} - S_{\mathrm{hmin}})\cos 2\theta - 2P_0 - \Delta P - \sigma^{\Delta T} \quad (6.4)$$

$$\sigma_{rr} = \Delta P \quad (6.5)$$

※ Calculation of maximum tangential stress (hoop stress)

① vertical well

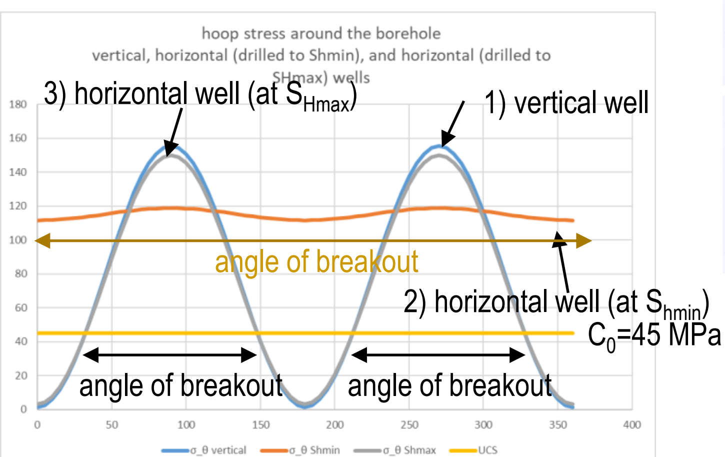
$\sigma_{\theta\theta}^{max} = 3 S_{Hmax} - S_{hmin} - 2P_o$
$= 3 \times 90.0 - 51.5 - 2 \times 31.5 = 155.5$ MPa

② Horizontal well (drilled at the direction of S_{hmin}) N-S

$\sigma_{\theta\theta}^{max} = 3 S_{Hmax} - S_v - 2P_o$
$= 3 \times 90.0 - 88.2 - 2 \times 31.5 = 118.8$ MPa

③ Horizontal well (drilled at the direction of S_{Hmax}) E-W

$\sigma_{\theta\theta}^{max} = 3 S_v - S_{hmin} - 2P_o$
$= 3 \times 88.2 - 51.5 - 2 \times 31.5 = 150.1$ MPa.



"Max hoop stress" & "Widest breakout angles" has to be evaluated differently!!

Q. What will be the angles of borehole breakout when we increased P_{mud} from 31.5 MPa to 33.5 MPa?

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Failure of arbitrarily deviated wells
Tensile fractures (traces)

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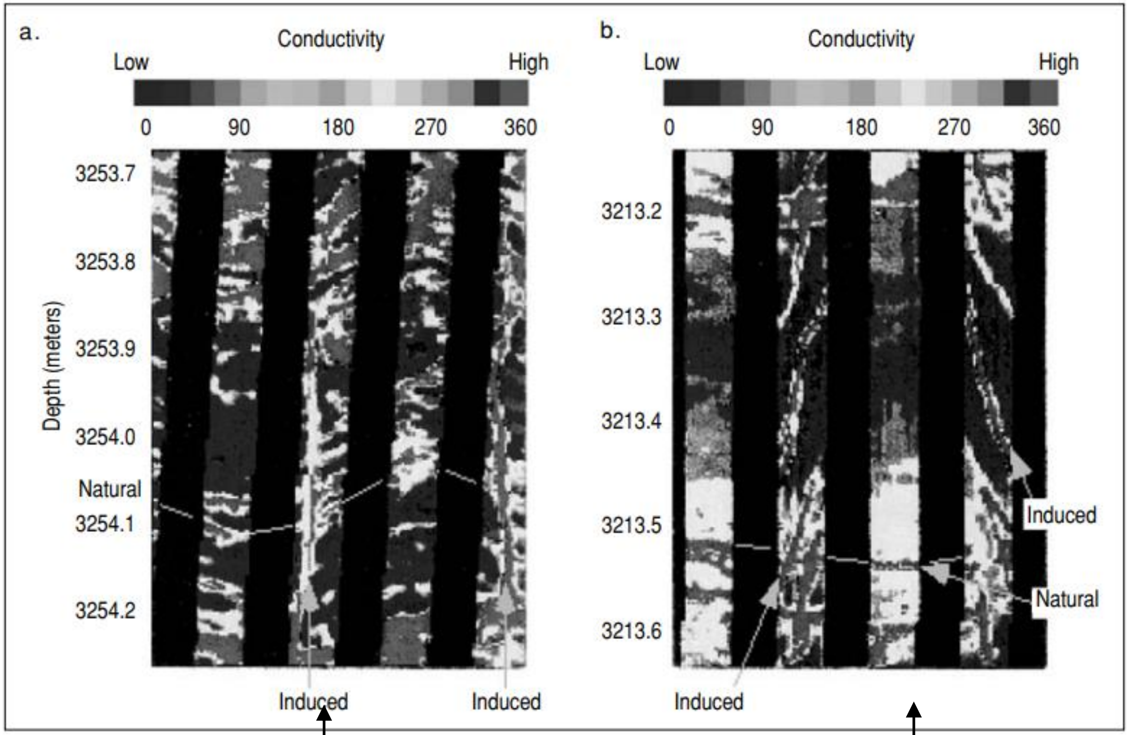
- Example at KTB borehole (Germany)
  - Even in vertical borehole, inclined tensile fractures are found when stress field is locally perturbed by slip on active faults



Axial tensile fractures

inclined tensile fractures when stress field were perturbed

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Failure of arbitrarily deviated wells
Tensile fractures (traces)

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- Minimum principal stress and orientation of tensile fracture
  - *En echelon* type tensile fracture is formed when minimum principal stress is tensile
  - Effect of mud pressure – wider angular span (θt) with bigger mud pressure

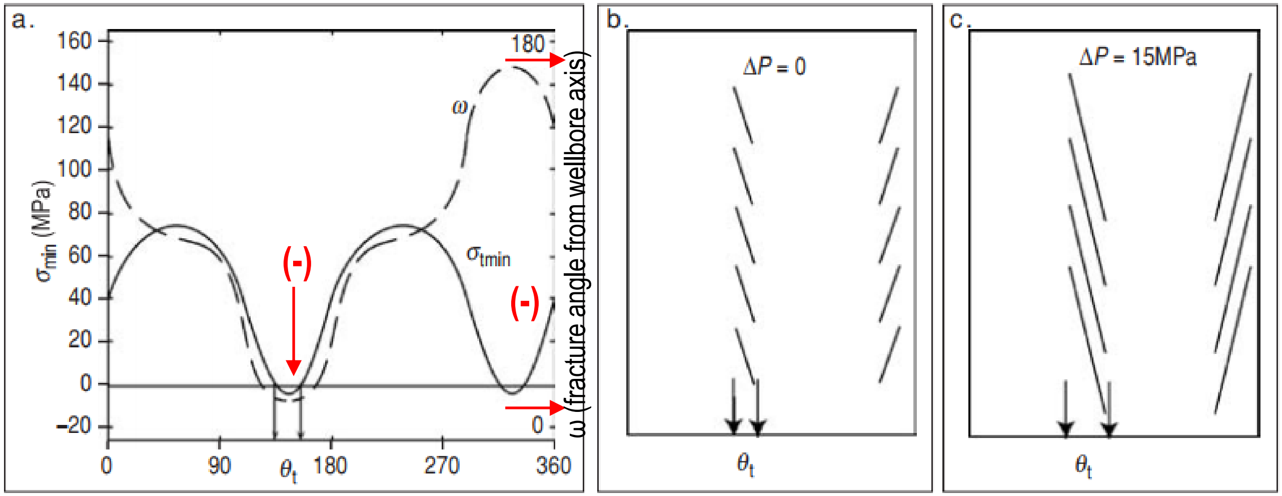

Figure 8.7. Theoretical illustration of the manner of formation of *en echelon* drilling-induced tensile fractures in a deviated well. (a) The fracture forms when σ_{tmin} is tensile. The angle the fracture makes with the axis of the wellbore is defined by ω, which, like σ_{tmin} varies around the wellbore. (b) The *en echelon* fractures form over the angular span θ_t, where the wellbore wall is in tension. (c) Raising the mud weight causes the fractures to propagate over a wider range of angles because σ_{tmin} is reduced around the wellbore's circumference.

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Confirming S_{Hmax} and S_{hmin} are prinicipal axis

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- Understanding on deviated well enhances the understanding on the determined in situ stress in vertical well
  - Near vertical drilling induced tensile fractures (KTB, Germany; ~7km, Siljan, Sweden) confirms that "S_{Hmax} and S_{hmin} are principal stresses)
  - Assumption that "principal stresses in situ are vertical and horizontal is generally valid"

Estimating S_{Hmax} from breakouts and tensile fractures in deviated wells

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- S_{Hmax} and S_{hmin} determination from observation in deviated boreholes
  - Presence of tensile fractures
  - Position of the fractures, θ
  - Their deviation wrt borehole axis, ω
  - LOT/mini frac results?

Examples in geothermal well in Japan

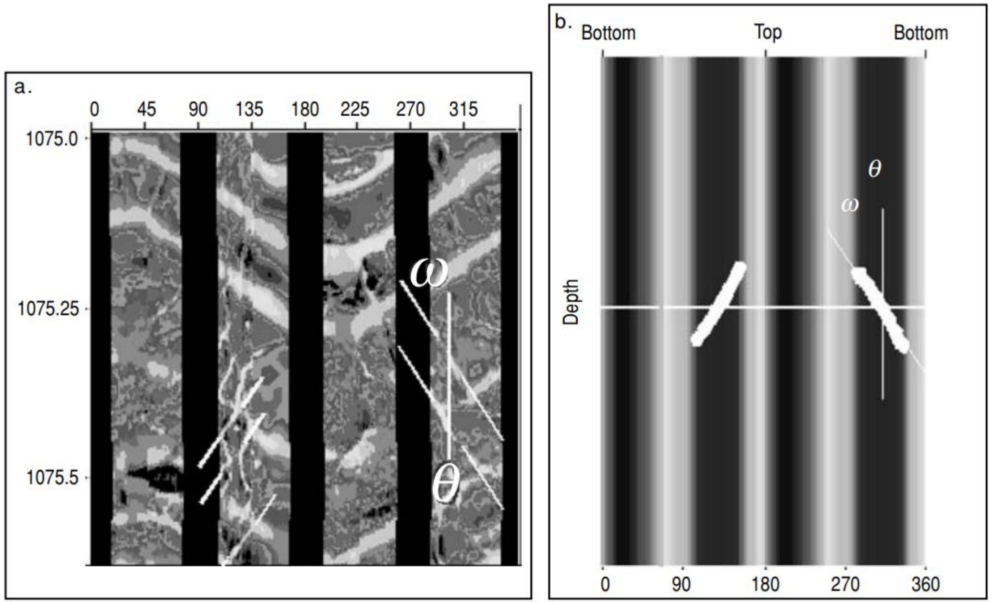

Figure 8.8. (a) Drilling-induced tensile fractures in a geothermal well in Japan make an angle ω with the axis of the wellbore and are located at position indicated by the angle θ from the bottom of the wellbore. (b) Theoretical model of the observed fractures in (a) replicate both ω and θ for the appropriate value of the magnitude and orientation of S_{Hmax}.

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Estimating S_{Hmax} from breakouts and tensile fractures in deviated wells

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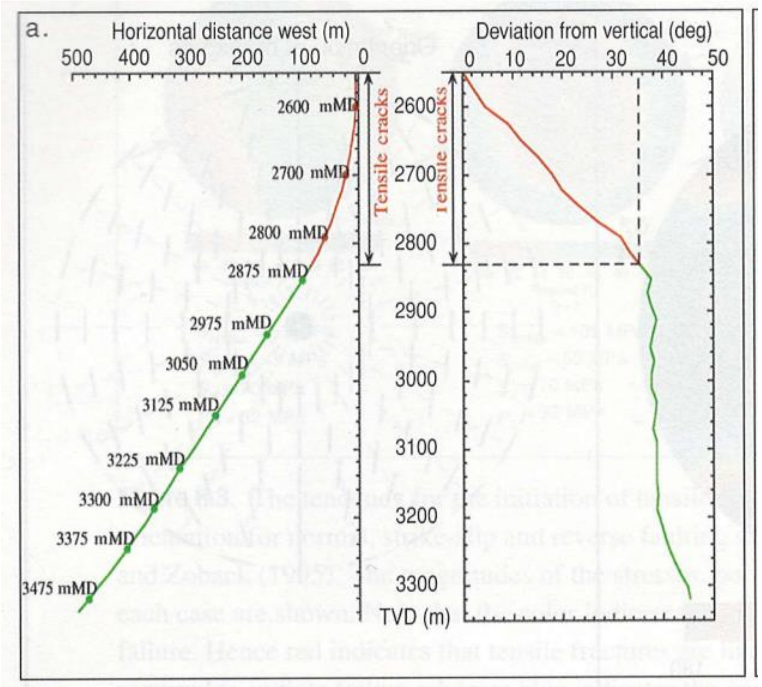
- Example in Visund field (northern North Sea)
  - Numerous drilling induced tensile fractures at near vertical section but it abruptly stopped at a measured depth of ~2,860m when deviation of the well reached ~35°.
  - Quality of electrical image data was good, drilling conditions were the same.
  - ECD was ~ 6 MPa during drilling.



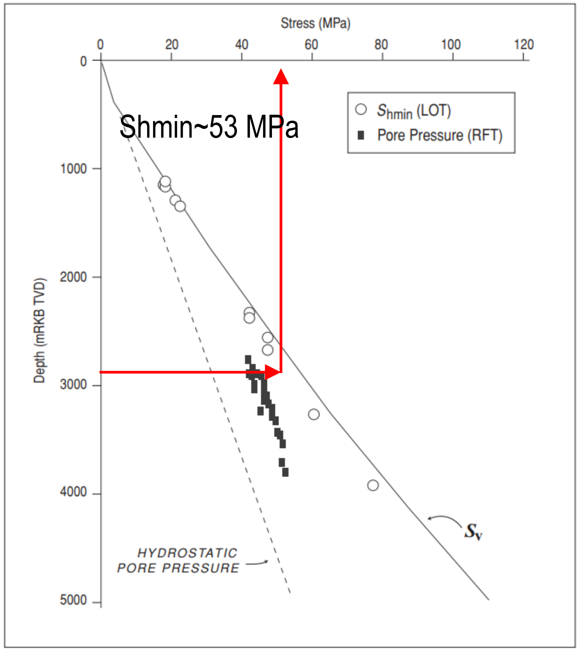


Figure 7.4. Least principal stress as a function of depth determined from extended leak off tests in the Visund field (after Wiprut, Zoback *et al.* 2000). The least principal stress is slightly below the overburden stress (determined from integration of density logs). The pore pressure is somewhat above hydrostatic (shown by the dashed line for reference). *Reprinted with permission of Elsevier*.

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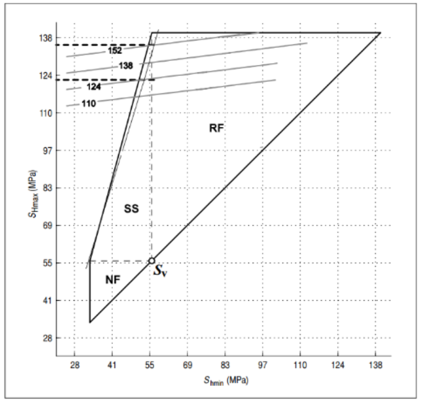
Estimating S_{Hmax} from breakouts and tensile fractures in deviated wells

- Example in Visund field (northern North Sea)
  - S_{Hmax} vs. S_{hmin} relationships for tensile and breakout can be used.
  - At around 35° deviation, Δp~9MPa: more or les explains the stop of tensile fractures



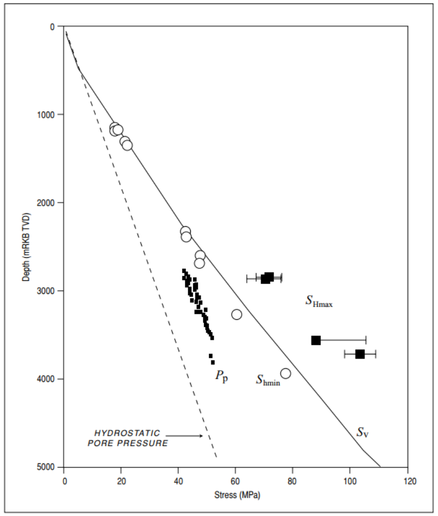
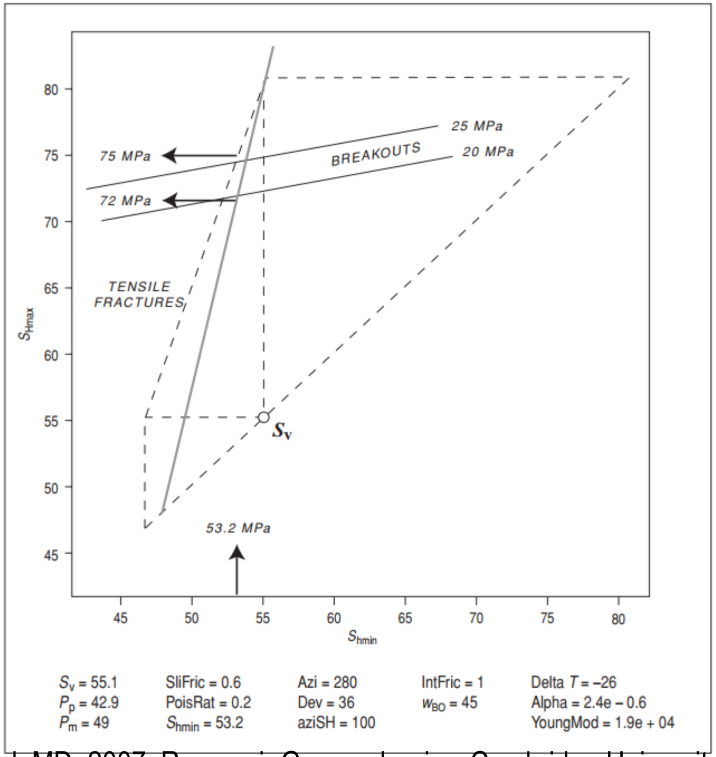
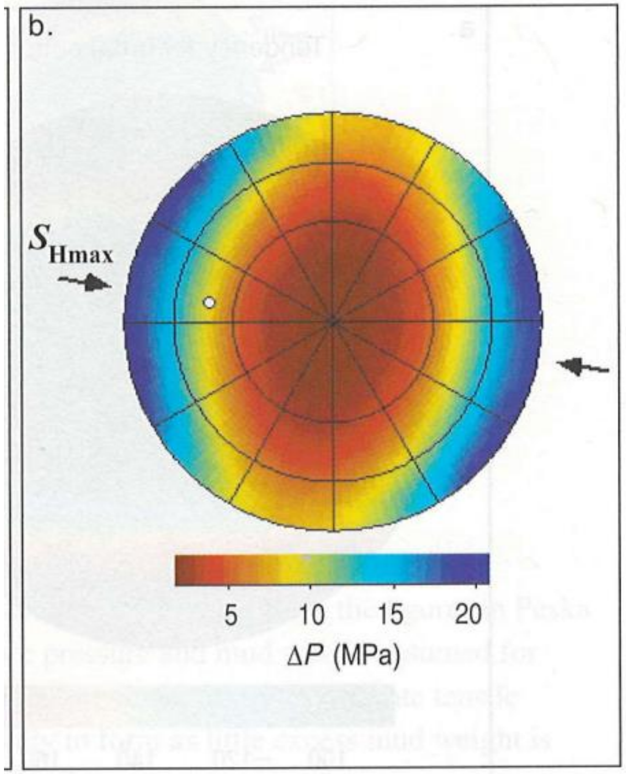


Figure 7.13. Similar to Figure with estimates of S_{Hmax} (dots with error bars) determined from analysis of drilling-induced tensile fractures in the Visund field of the northern North Sea (after Wiprut, Zoback *et al.* 2000). *Reprinted with permission of Elsevier.*





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Estimating S_{Hmax} from breakouts and tensile fractures in deviated wells

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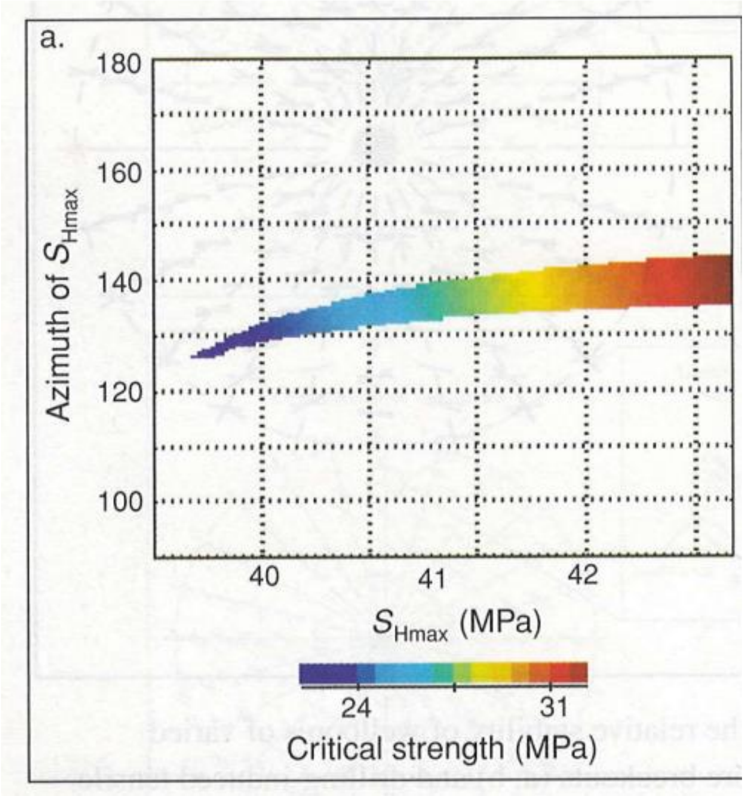
- Example (Gulf of Mexico)
  - Iteration of SHmax
  - Issue about caliper log in deviated well: key seat problem



Zoback MD, 2007, Reservoir Geomechanics, Cambridge University Press

Distinguishing drilling–induced tensile fractures from natural fractures

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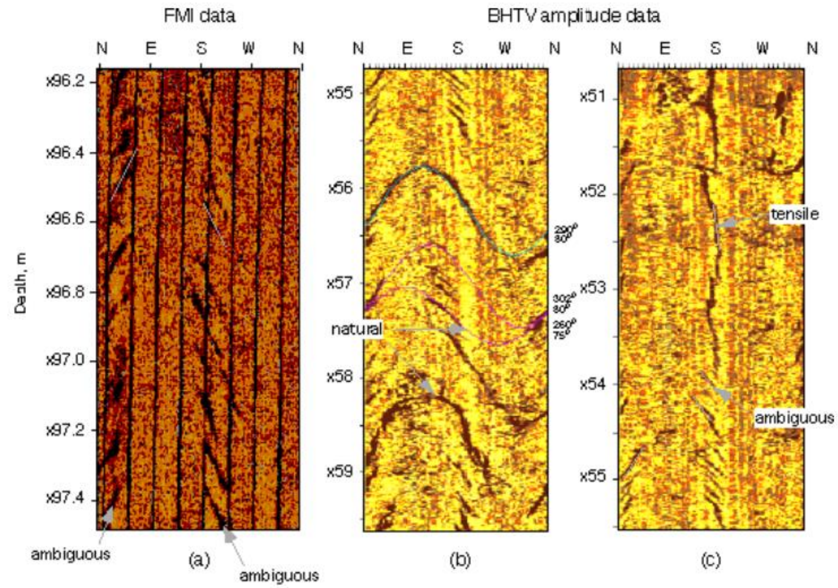
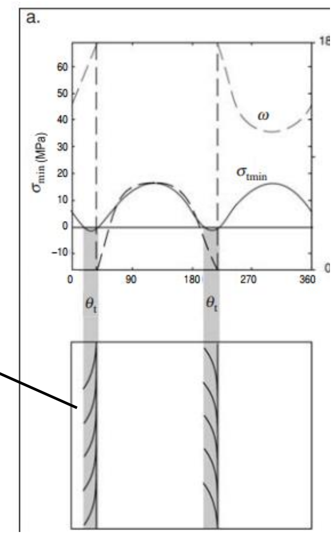
- Natural fractures vs. drilling induced tensile fractures (example at Geothermal well, Soultz, France)
  - Poor quality data, small aperture, …
- Natural fractures
  - Sinusoidal trace
  - Can be partially seen
  - Partial sinusoid tends to occur at the same azimuth
    of tensile fractures. Drilling enhanced fractures
- Drilling induced tensile fractures
  - Curvature changes but not sinusoidal (fish-hook or J-fractures)



Geotherma well at Soultz, France

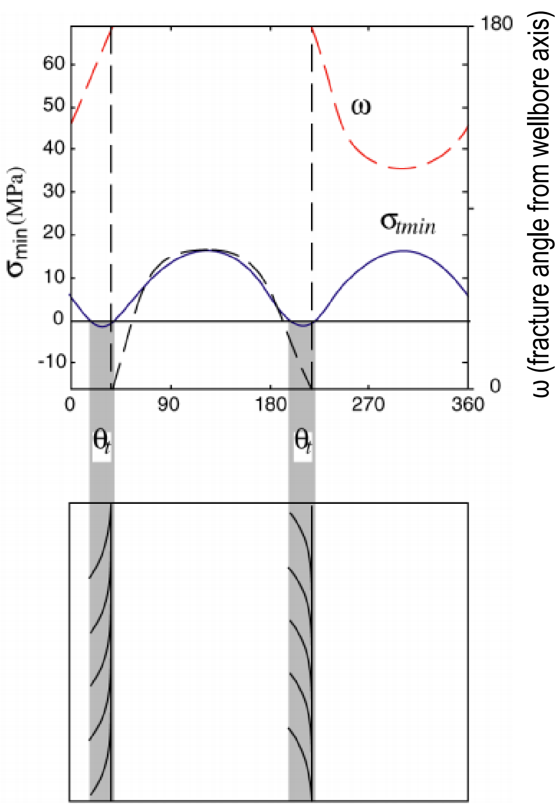


DITF

Zoback MD, 2007, Reservoir Geomechanics, Cambridge University Press

Distinguishing drilling–induced tensile fractures from natural fractures

- Examples (Argentina & Soultz)



Theoretical illustration of curved drilling induced tensile fracture

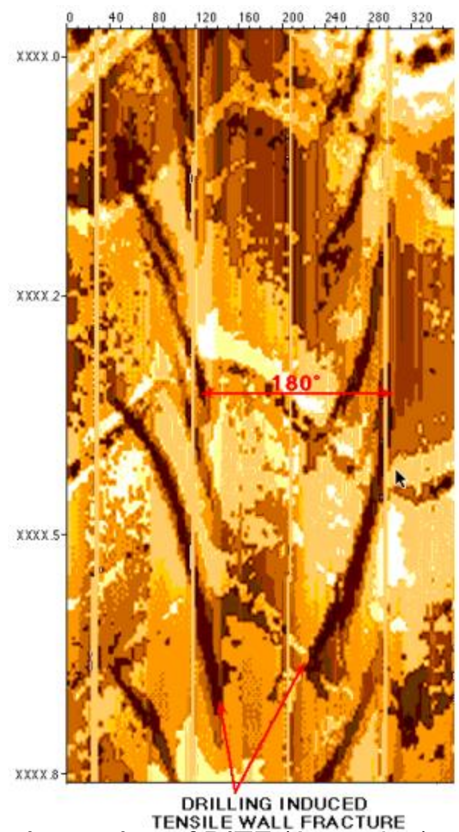


Image log of DITF (Argentina)

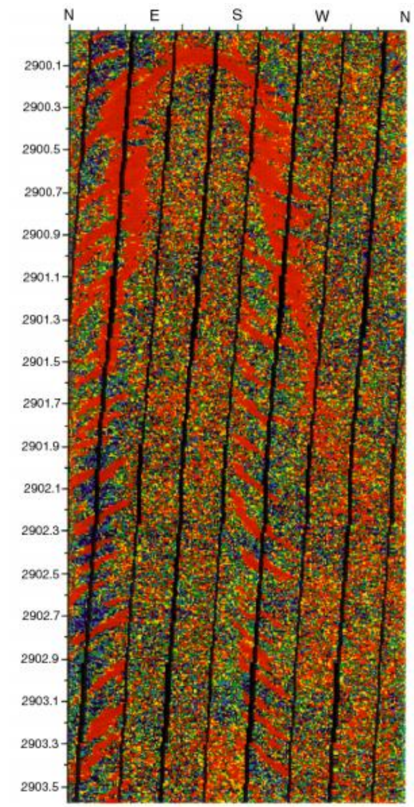


Image log of DITF (Geothermal, Soultz)

Zoback MD, 2007, Reservoir Geomechanics, Cambridge University Press

Determination of S_{Hmax} orientation from shear velocity anisotropy in deviated wells

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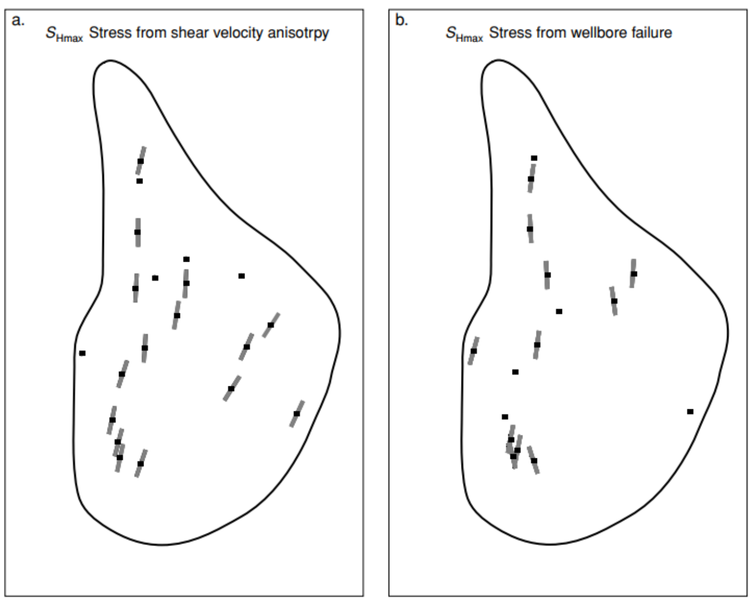
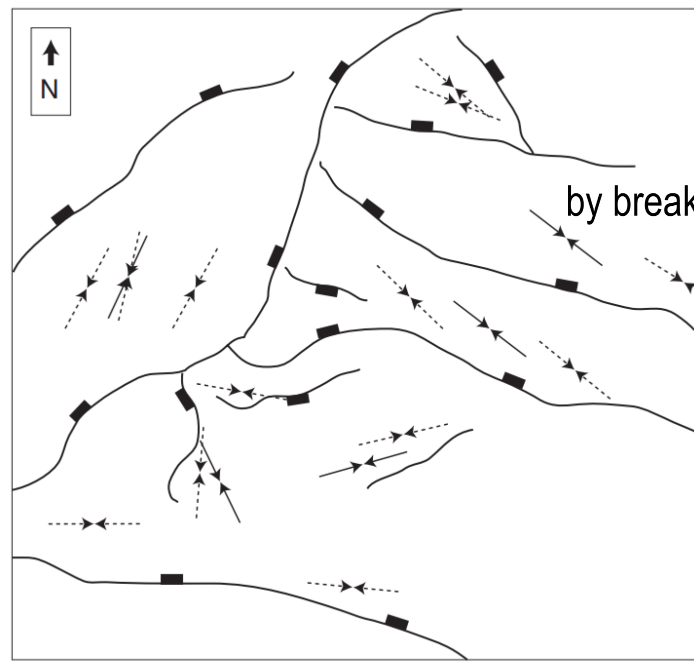
- Dipole sonic logs in vertical wells
  - Fast shear polarization direction → S_{Hmax}
  - This can be used for determining orientation of S_{hmax}
  - Additional factor for deviated borehole



An oilfield in SE Asia



North Sea

Zoback MD, 2007, Reservoir Geomechanics, Cambridge University Press