The Geometry of Borehole Shear Failures

Shear failure will occur when 2 perpendicular stresses of ***different magnitudes*** are acting on each other in a plane.

Assuming the rocks that we drill are linear elastic, the largest stress differences will occur at the borehole wall. Therefore, we would expect rock failure to initiate at the borehole wall.

At the borehole wall, there are 3 wellbore stresses (σ_r, σ_t, σ_a).

Their stress magnitudes can be ordered in 6 different ways:

a) $\sigma_a > \sigma_t > \sigma_r$

b) $\sigma_t > \sigma_a > \sigma_r$

c) $\sigma_a > \sigma_r > \sigma_t$

d) $\sigma_r > \sigma_a > \sigma_t$

e) $\sigma_r > \sigma_t > \sigma_a$

f) $\sigma_t > \sigma_r > \sigma_a$

All 3 wellbore stresses are orthogonal.

In each of these 6 different scenarios we have a maximum and minimum wellbore stress.

For example, in a) the maximum stress is σ_a and the minimum stress is σ_r.

The ***difference*** between these 2 stresses will govern the magnitude of the shear stress.

Pure shear failure does not depend on the intermediate stress σ_t.

If this shear stress is large enough to satisfy the failure condition, then rock failure will occur in the wall of the borehole.

The most common scenarios are conditions a) b) and c).

It should be noted that **post failure behavior is very difficult to model.**

a) Shear Failure Shallow Knockout (ssko):

$\sigma_a > \sigma_t > \sigma_r$

This mode of failure occurs when the axial stress (σ_a) is maximum and the radial stress (σ_r) is minimum.

Geometry and Orientation of ssko Failure:

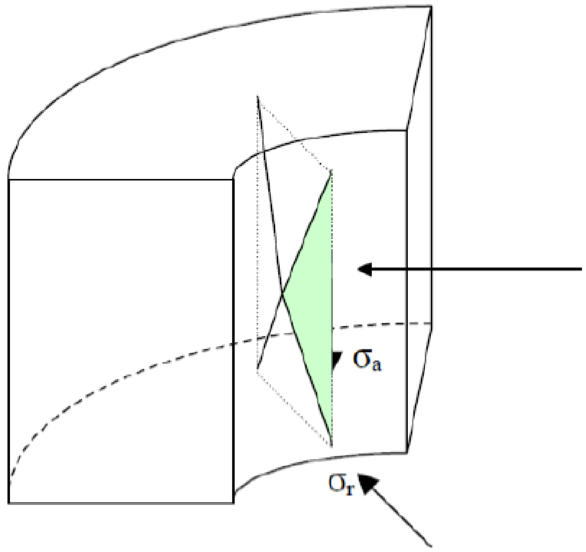
The failure will occur in the radial / axial plane because the maximum (σ_a) and minimum (σ_r) stresses are oriented in this plane (a vertical plane).

The thickness of the failure (ie the circumferential coverage) will be small as this plane (the plane tangent to the circumference of the borehole) contains the tangential stress σ_t which does not affect the ssko failure mechanism.

The *orientation* of ssko failures will always be in the **direction of minimum horizontal stress**. This is because the failure will occur preferentially in the direction where the axial stress is greatest and the radial stress is smallest. This condition gives a maximum shear stress.

The radial stress is constant (= p_w) for all azimuthal orientations ($\sigma_r = p_w$), Reference to equation ($\sigma_a = \sigma_v - 2(\sigma_H - \sigma_h)\,\mathrm{v}\cos 2\theta$) shows that σ_a is maximum when $\theta = 90°$ ($\rightarrow \cos 2\theta = -1$), θ is defined as the direction from the maximum horizontal stress. Hence when $\theta = 90°$ this is in the direction of minimum horizontal stress.

The image in Figure 1 shows an example of **ssko**. The failure is highlighted and is shown to cover a small circumferential area. Also we can see that the direction of minimum horizontal stress is NE-SW.
The ssko failure can be confused with a vertical fracture due to the small circumferential area.



Shear failure shallow knockout occurring in the plane of σ_a / σ_r (i.e. in a plane perpendicular to the borehole wall).

The failure region is given by the light blue color.

b) Shear Failure Wide Breakout (swbo):

This mode of failure occurs when the tangential stress (σ_t) is maximum and the radial stress (σ_r) is minimum. $\sigma_t > \sigma_a > \sigma_r$

Geometry and Orientation of swbo Failure:
The failure will occur in the radial / tangential plane because the maximum (σ_t) and minimum (σ_r) stresses are oriented in this plane (the horizontal plane).

This failure is called a breakout. It is generally wide because the failure covers a large arc, from 30° to 90°.

The *orientation* of swbo failures will always be in the **direction of minimum horizontal stress**. This is because the failure will occur preferentially in the direction where the tangential stress is greatest and the radial stress is smallest. This condition gives a maximum shear stress.

The radial stress is constant (= pw) for all azimuthal orientations ($\sigma_r = p_w$),

Reference to equation ($\sigma_t = (\sigma_H + \sigma_h) - 2(\sigma_H - \sigma_h)\cos 2\theta - p_w$) shows that σ_t is maximum when $\theta = 90°$ ($\rightarrow \cos 2\theta = -1$)

When $\theta = 90°$ this is in the direction of minimum horizontal stress

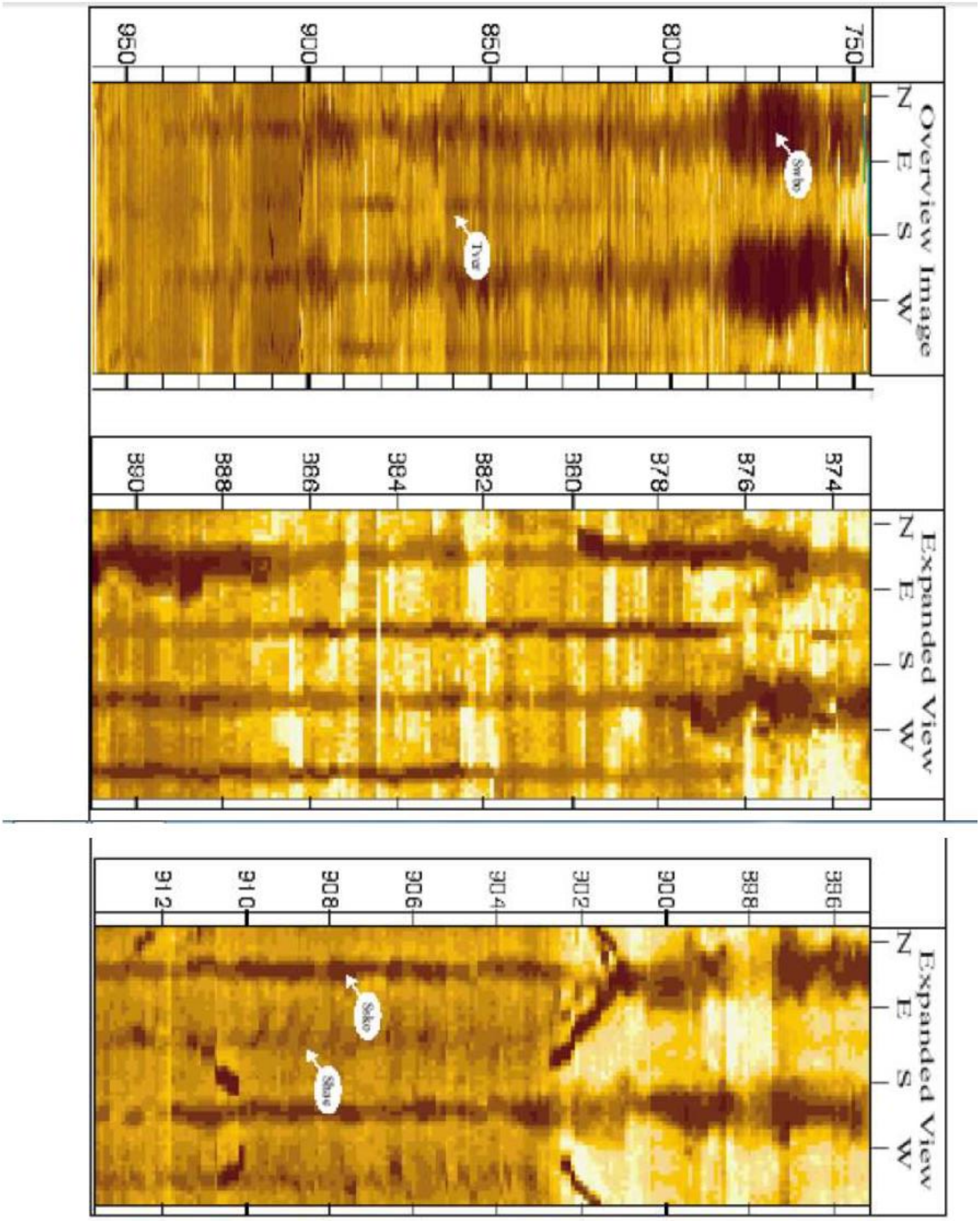


Figure 1: Wellbore Failure in RAB images

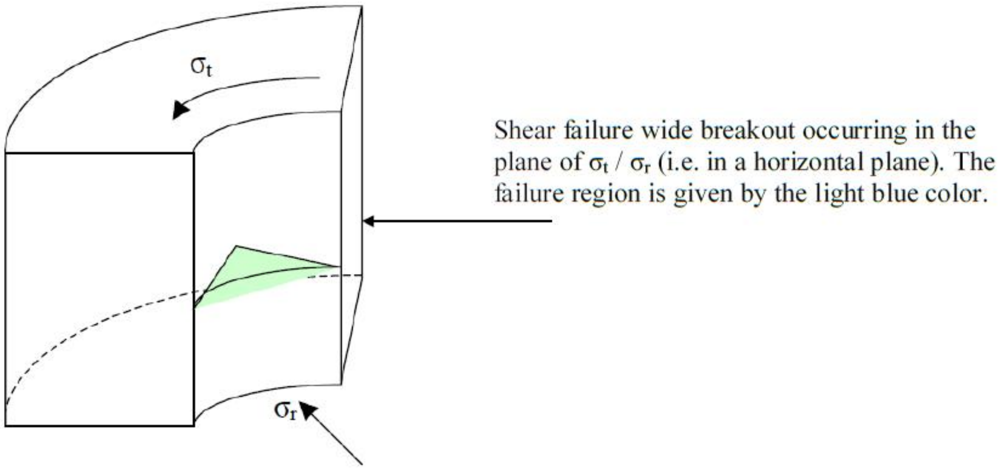


Figure 2 shows an example of **swbo**. The failure is highlighted and is shown to cover a large circumferential area (30° to 90°). The direction of minimum horizontal stress can be determined from the location of the breakout on the image.

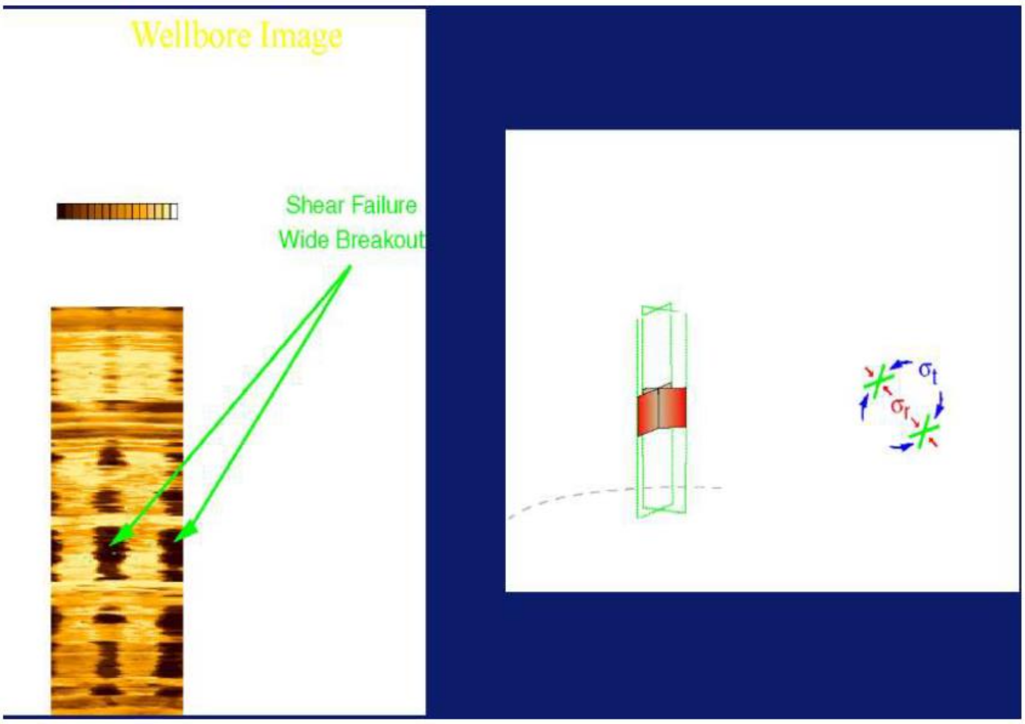


Figure 2: Appearance and geometry of Shear Failure Wide Breakout on RAB images

c) Shear Failure High-Angle Echelon (shae):

$\sigma_a > \sigma_r > \sigma_t$

This mode of failure occurs when the axial stress (σ_a) is maximum and the tangential stress (σ_t) is minimum.

Geometry and Orientation of shae Failure:

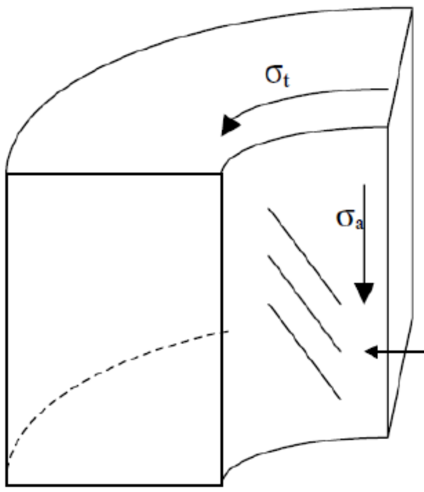
The failure will occur in the axial / tangential arc because the maximum (σ_a) and minimum (σ_t) stresses are oriented in this arc (the arc of the borehole wall).

This failure forms high-angle fractures that cover up to a quarter of the borehole circumference.

In determining the *orientation* of shae failures, σ_a is maximum when $\theta = 90°$ ($\sigma_a = \sigma_v - 2(\sigma_H - \sigma_h)\,\mathrm{v}\cos 2\theta$) and σ_t is minimum when $\theta = 45°$ ($\sigma_t = (\sigma_H + \sigma_h) - 2(\sigma_H - \sigma_h)\cos 2\theta - p_w$).

Figure 3 shows an example of **shae**. The failure originates in the orientation of **maximum horizontal stress** and extends away at high angle (60°).

It is very difficult to predict the post failure behavior the shae failures.



Shear failure high angle echelon occurring in the arc of σ_a / σ_t (i.e. in the arc of the borehole wall). The failure originates at the azimuth of the maximum horizontal stress and extends away at high angle (60°).

d) Shear Failure Narrow Breakout (snbo):

$\sigma_r > \sigma_a > \sigma_t$

This mode of failure occurs when the radial stress (σ_r) is maximum and the tangential stress (σ_t) is minimum.

Geometry and Orientation of snbo Failure:

The failure will occur in the radial / tangential plane because the maximum (σ_r) and minimum (σ_t) stresses are oriented in this plane (the horizontal plane).

This failure is called a breakout. It is generally narrow because the failure covers an arc< 30°.

The *orientation* of snbo failures will always be in the **direction of maximum horizontal stress**.

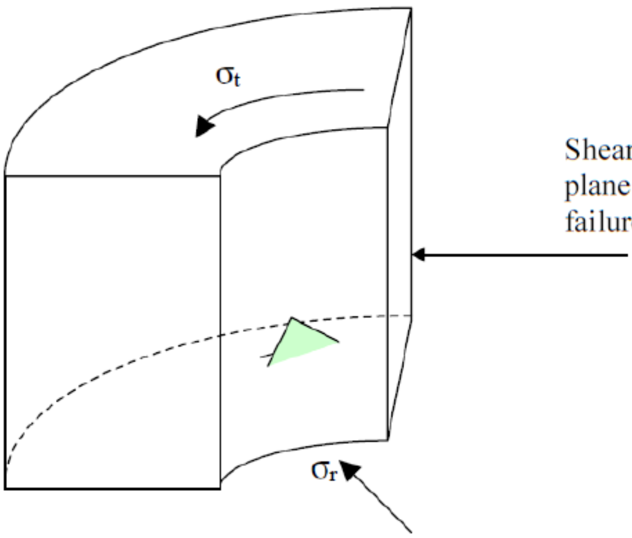
This is because the failure will occur preferentially in the direction where the radial stress is greatest and the tangential stress is smallest. This condition gives a maximum shear stress.

The radial stress is constant (= pw) for all azimuthal orientations ($\sigma_r = p_w$),

Reference to equation ($\sigma_t = (\sigma_H + \sigma_h) - 2(\sigma_H - \sigma_h)\cos 2\theta - p_w$) shows that σ_t is minimum when θ = 0° (→ cos0 = 1)

When θ = 0° this is in the direction of maximum horizontal stress.

Figure 7 shows an example of **snbo**. The failure is highlighted and is shown to cover a small circumferential area (20°). The direction of maximum horizontal stress can be determined from the location of the breakout on the image.



e) Shear Failure Deep Knockout (sdko):

$\sigma_r > \sigma_t > \sigma_a$

This mode of failure occurs when the radial stress (σ_r) is maximum and the axial stress (σ_a) is minimum.

Geometry and Orientation of sdko Failure:

The failure will occur in the radial / axial plane because the maximum (σ_r) and minimum (σ_a) stresses are oriented in this plane (a vertical plane).

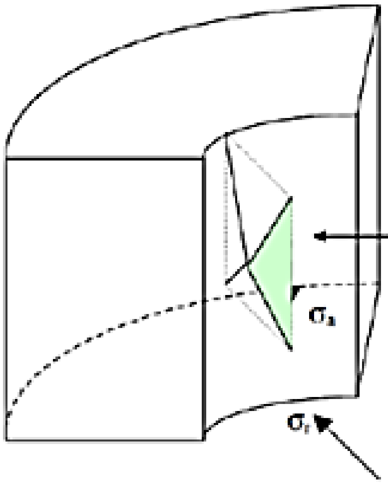
The thickness of the failure (i.e. the circumferential coverage) will be small as this plane (the plane tangent to the circumference of the borehole) contains the tangential stress σ_t which does not affect the sdko failure mechanism.

The *orientation* of sdko failures will always be in the **direction of maximum horizontal stress**. This is because the failure will occur preferentially in the direction where the radial stress is greatest and the axial stress is smallest. This condition gives a maximum shear stress.

The radial stress is constant (=pw) for all azimuthal orientations ($\sigma_r = p_w$),

Reference to equation ($\sigma_a = \sigma_v - 2(\sigma_H - \sigma_h)\text{v}\cos 2\theta$) shows that σ_a is minimum when θ = 0° (→ cos0 = 1) θ is defined as the direction from the maximum horizontal stress. Hence when **θ = 0°** this is in the direction of maximum horizontal stress.

The sdko failure can be confused with a vertical fracture due to the small circumferential area.



Shear failure deep knockout occurring in the plane of σ_a / σ_r (i.e. in a plane perpendicular to the borehole wall).
The failure region is given by the light blue color.

f) Shear Failure Low-Angle Echelon (slae):

$\sigma_t > \sigma_r > \sigma_a$

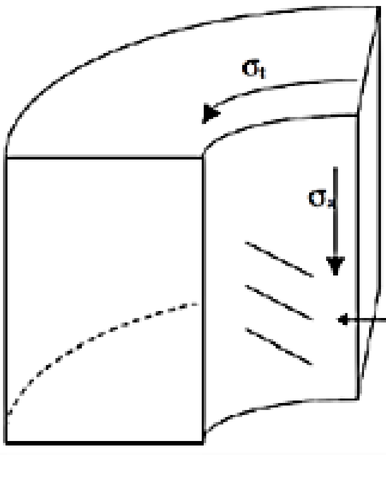
This mode of failure occurs when the tangential stress (σ_t) is maximum and the axial stress (σ_a) is minimum.

Geometry and Orientation of slae Failure:

The failure will occur in the axial / tangential arc because the maximum (σ_t) and minimum (σ_a) stresses are oriented in this arc (the arc of the borehole wall). This failure forms low-angle fractures.

In determining the *orientation* of slae failures, σ_t is maximum when θ = 90° ($\sigma_t = (\sigma_H + \sigma_h) - 2(\sigma_H - \sigma_h)\cos 2\theta - p_w$) and σ_a is minimum when θ = 0° ($\sigma_a = \sigma_v - 2(\sigma_H - \sigma_h)\,v\cos 2\theta$). This could be the reason why the low angle echelon failures are spread over a larger circumferential area than knockouts or breakouts.

The slae failure originates in the orientation of **minimum horizontal stress** and extends away at low angle.



Shear failure low angle echelon occurring in the arc of σ_a / σ_t (i.e. in a the arc of the borehole wall).
The failure originates at the azimuth of the minimum horizontal stress and extends away at low angle.

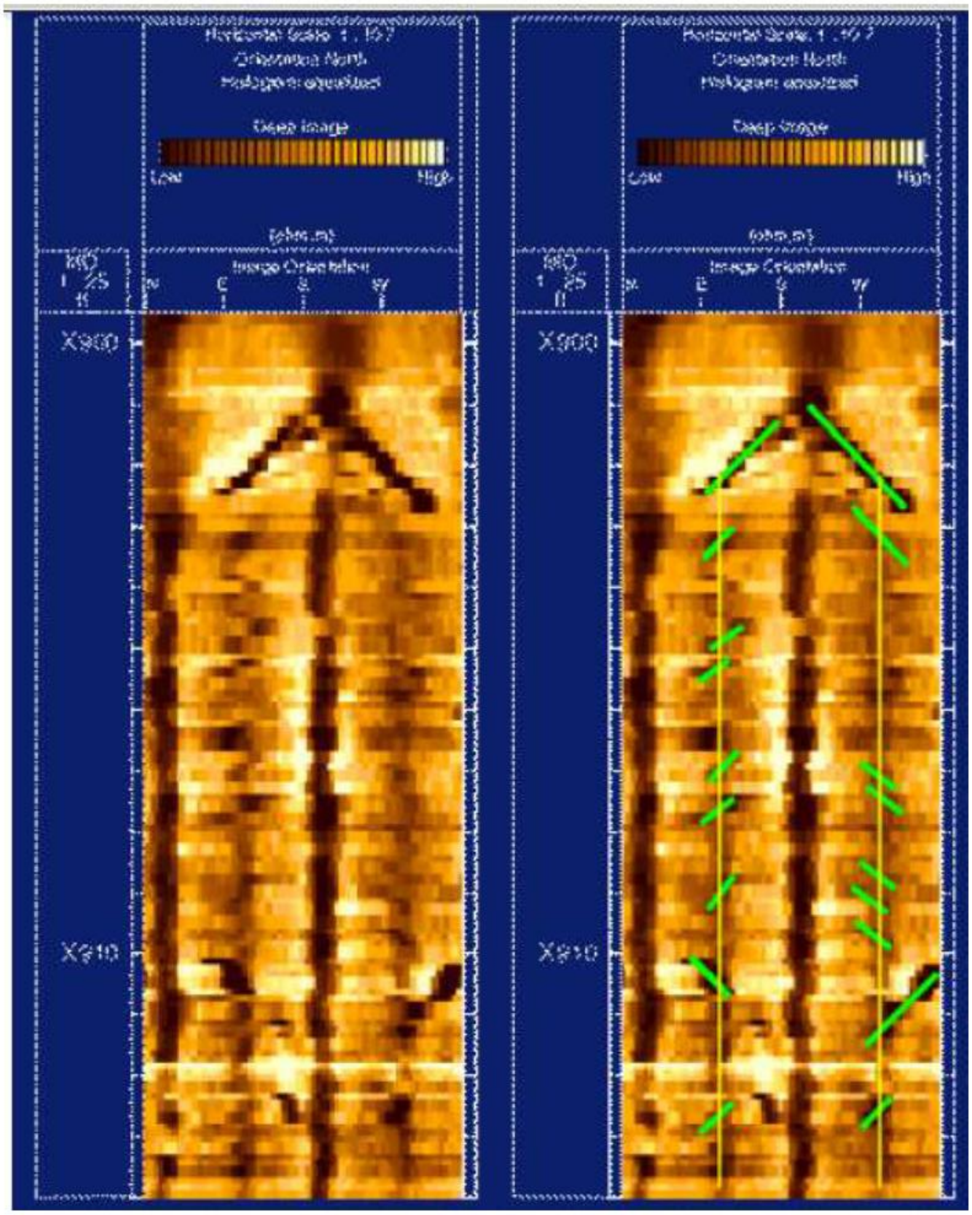


Figure 3: Shear Failure High Angle Echelon failures on RAB images

The Geometry of Borehole Tensile Failures

When a formation is subject to a tensile stress, the constituent grains are pulled apart in the direction of the tensile stress.

A crack ***perpendicular*** to the tensile stress is created and the formation fails in tension.

There are 3 different tensile stresses that can exceed the tensile strength of the formation:

a) Radial stress σ_r

b) Axial stress σ_a

c) Tangential stress σ_t

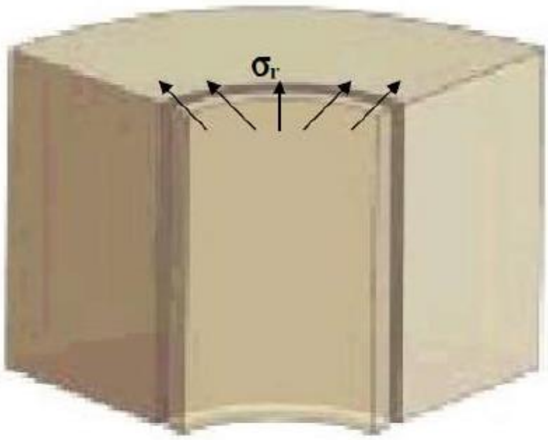
The tensile strength T_o of the formation is usually rather low – generally < 10 % of the unconfined compressive strength C_o.

a) Tensile Failure Cylindrical (tcyl):

$\sigma_r \leq -T_o$

This mode of failure occurs when the radial stress (σ_r) is lower than the negative of the tensile strength of the formation (T_o)

Geometry and Orientation of tcyl Failure:
This failure is concentric with the borehole wall and cannot be seen on images.
A low mud weight would favor the tcyl failure due to the magnitude of σ_r being lower.



Tensile Failure Cylindrical (Tcyl)

b) Tensile Failure Horizontal (thor):

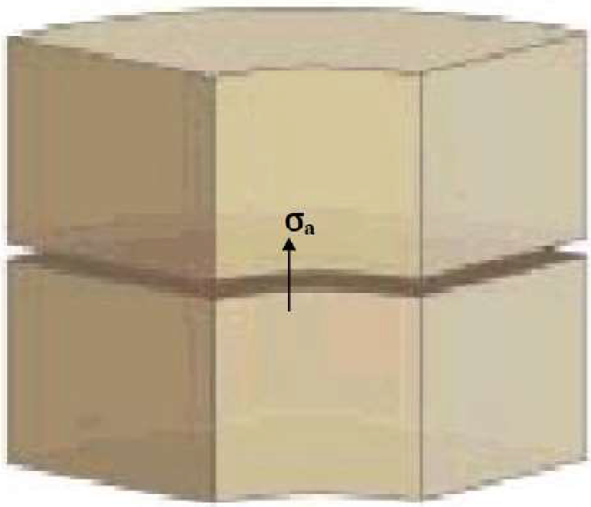
$\sigma_a \leq -T_o$

This mode of failure occurs when the axial stress (σ_a) is lower than the negative of the tensile strength of the formation (T_o)

Geometry and Orientation of thor Failure:

This failure creates horizontal fractures.

On an image the horizontal fracture would appear as a thin black horizontal line throughout all azimuthal orientations.



Tensile Failure Horizontal (Thor)

c) Tensile Failure Vertical (tver):

$\sigma_t \leq -T_o$

This mode of failure occurs when the tangential stress (σ_t) is lower than the negative of the tensile strength of the formation (T_o).

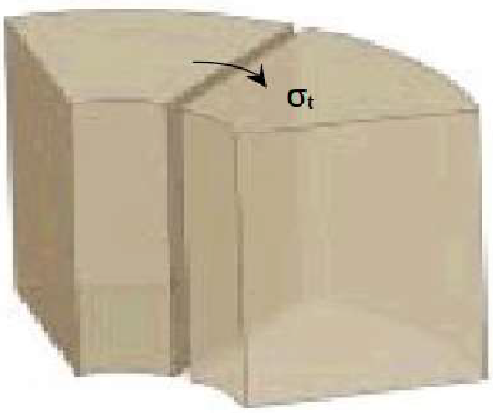
Geometry and Orientation of tver Failure:

This failure creates a vertical fracture parallel with the maximum horizontal stress direction.

This is because in this orientation the tangential stress has to overcome the smallest formation tensile strength (that consisting of a minimum horizontal stress, σ_h).

Figure 4 shows an example of **tver**. The thin vertical line represents the vertical fracture. The fracture is oriented parallel to the direction of maximum horizontal stress (in figure 1 SW-NE).

If the mud weight increases, then σ_t decreases (becomes more negative) ($\sigma_3' \leq -T0$) until the condition for the tver failure described above. This is the opposite scenario for the tensile failure cylindrical where a low mud weight decreases the magnitude of σ_r.



Tensile Failure Vertical (Tver)

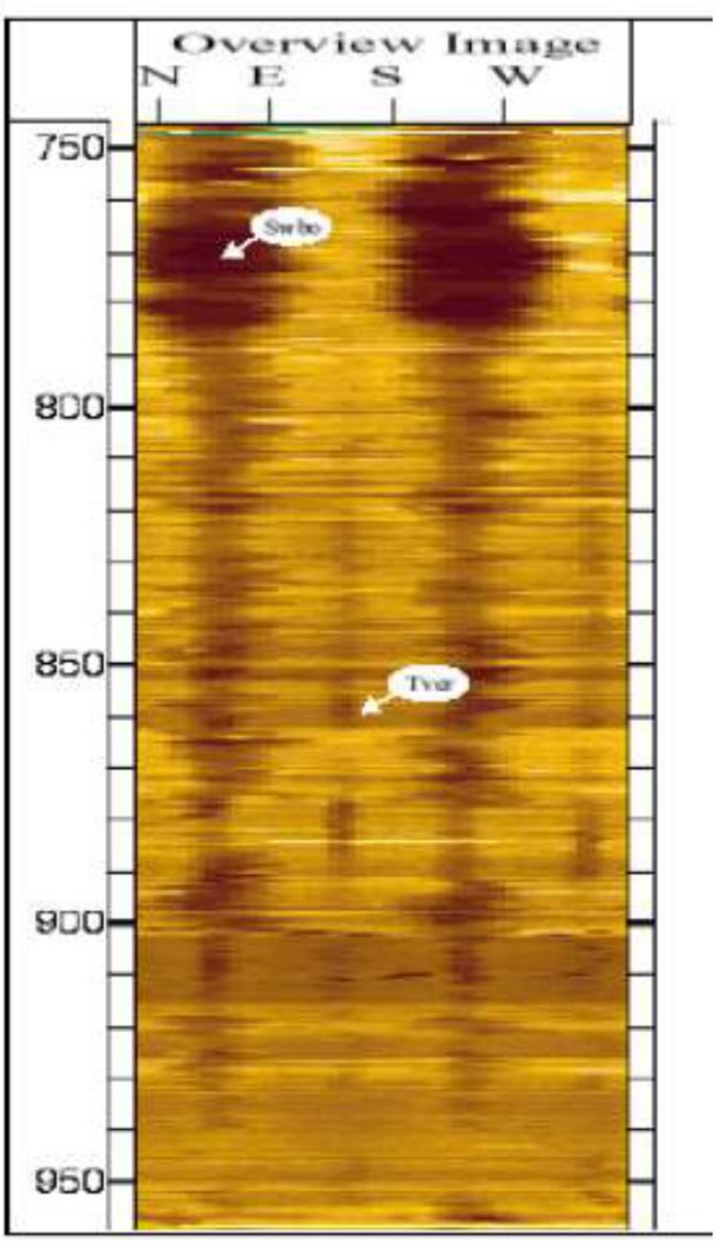


Figure 4: Tensile Failure Vertical in RAB image as labelled above

We can summarize the various failure mechanisms by using a truth table:

Failure Type	Failure name	Stress Involved	Appearance on Image	Orientation
Shear Failure	Shallow Knockout(ssko)	Max = σ_a Min = σ_r	Dark vertical feature with narrow width (around 20°)	In axis of σh
	Deep Knockout(sdko)	Max = σ_r Min = σ_a	Dark vertical feature with narrow width (around 20°)	In axis of σ_H
	Wide Breakout(swbo)	Max = σ_t Min = σ_r	Dark vertical feature with wide width (30°-90°)	In axis of σ_h
	Narrow Breakout (snbo)	Max = σ_r Min = σ_t	Dark vertical feature with narrow width (around 20°)	In axis of σ_H
	High Angle Echelon (shae)	Max = σ_a Min = σ_t	Dark feature inclined at high angle (>50°)	Originates at σ_H, extending away at angle
	Low Angle Echelon (slae)	Max = σ_t Min = σ_a	Dark feature inclined at low angle (<40°)	Originates at σ_h, extending away at angle
Tensile Failure	Cylindrical (tcyl)	σ_r	Not observed on images	N/A
	Horizontal (thor)	σ_a	Dark narrow horizontal feature covering all azimuths	All azimuthal orientations –a horizontal line
	Vertical (tver)	σ_t	Dark vertical feature with very width (< 20°)	In axis of σ_H

Table 1: Table summarizing the various borehole failure mechanisms

If we already know the orientation of the minimum horizontal stress σ_h then a feature occurring in the direction of σ_h could either be a shear failure shallow knockout or a shear failure wide breakout. These two possibilities can be distinguished by the relative width of the feature. The wide breakout would have wider borehole coverage than the shallow knockout.

If the feature occurs in the direction of σ_H then it could be one of 3 failure modes: shear failure deep knockout, shear failure narrow breakout and vertical tensile failure.

All 3 failures occur because σ_r is too large. Hence the mud weight is too high.