Borehole Stability: Stresses and How Analysis is Done

Maurice Dusseault
Defining Limits in Our Well Plan

- Predicted MW for severe sloughing onset
- $\sigma_{h\text{min}}$, LC danger
- Onset of "ballooning" in shales
- $p_o$, onset of blowout if in a sand zone

Pressure or stress vs. depth

Gradient vs. depth
How are the MW Limits Defined?

- **Lower MW limit**
  - Pressure control
  - Rock Mechanics stability, experience, use of correlations to predict stability line, etc.
  - How much sloughing can we live with?
  - Underbalanced Drilling is a good example of RM

- **Upper MW limit**
  - Avoiding massive lost circulation
  - Fracture gradient, earth stresses analysis
  - The new concept of overbalanced drilling with LC-muds is an example of RM extending this envelope
Are All Limits Absolute?

- No, and here are examples:
  - Drilling underbalanced? OK as long as it is shales or lower permeability sands, and if the shales are strong (little sloughing)
  - Drilling overbalanced? OK for up to ~1000 psi with properly designed LCM in mud!
  - Drilling below sloughing line? OK if good hole cleaning, use increased MW for trips…
  - Pushing the envelope is typical in offshore drilling, HPHT wells… (e.g. mud cooling…)
  - Vigilance and RM understanding needed…
The Basic Symbols, 2-D Borehole

- Far-field stresses: natural earth stresses, pressures, generated by gravity, tectonics…
- Borehole stresses: formed by creating an opening in a natural stress field
- Far-field stresses: scale: 100’s of metres
- Borehole stresses scale: 20-30 × r_i (i.e. local- to small-scale)
“Predicting” Onset of Instability

- We now have methods of estimating *in situ* stresses (i.e.: estimate of fracture pressure)
- We also have methods of measuring or estimating rock strength and deformation…
- We can calculate \( \sigma_r, \sigma_\theta \) around a circular opening, subject to several assumptions…
- Putting these together allows prediction of shearing initiation on the borehole wall, giving
- …An estimate of “breakouts initiation” or the onset of severe sloughing
Compressional and Tensile Yield

- Compressional breakdowns
- Tensile axial fractures

3-D Borehole Stability

UBI Well A

FMI Well B

Well A

Breakouts

Courtesy Mark Zoback
The calculation model I will show next is only one of many approaches to calculating borehole stresses. These types of calculations are systematically done by a Petroleum Geomechanics expert before, during and after drilling operations. Among the many models, which is best? Some models are better for some applications, others for others. The most important points are:

1. Understand physics involved (rocks, stresses, T, p…)
2. Understand your assumptions (are they robust?)
3. Understand uncertainty (these are estimates only)
4. Expect the unexpected (monitor, measure, observe…)

and manage the risks appropriately
Discussion of Parameters in Equation

- $p_w - p_i$ is support pressure

- Usually, we ignore effects of “$\alpha$”, except in low porosity, stiff shales ($E > 30-40$ GPa)

- Poisson’s ratio for shales, 0.25 to 0.40 (ductile)

- $\sigma_1, \sigma_3$ are computed using equations converting 3-D stress to stresses in the plane of the borehole ($90^\circ$ to hole axis)
3-Dimensional Borehole Stresses

Borehole radial, axial & tangential stresses, $\sigma_r$, $\sigma_a$, $\sigma_\theta$

- $\Phi$, $\Psi$ are dip and dip direction (wrt x) of the borehole axis
- $x$, $y$, $z$ are coordinates oriented $\parallel$ to $\sigma_1$, $\sigma_2$, $\sigma_3$
- $\sigma_1$, $\sigma_2$, $\sigma_3$ are the principal total stress magnitudes
- $p_o$ is the pore pressure

Almost always, principle stresses can be taken as $\perp$ and $\parallel$ to the earth’s surface

Effective stresses:

- $\sigma'_1 = \sigma_1 - p_o$
- $\sigma'_2 = \sigma_2 - p_o$
- $\sigma'_3 = \sigma_3 - p_o$
We usually do borehole stability analyses in 2-D approximation, using the ppl. stresses resolved onto the X-sectional plane.
Plotting Stresses Around a Borehole

- Usually, we plot $\sigma_\theta$, $\sigma_r$ values in 2D along one or the other of the principal stress directions.

Far-field stresses

$\sigma'_\text{max}$

$\sigma'_\text{min}$

stress or pressure $\sigma$, $p$

$\sigma'_\theta$

$\sigma'_r$

$p_w = 0$

radius

Vertical borehole

$\sigma'_\text{max}$

$\sigma'_\text{min}$
Stresses Around a Borehole

- 1D stress case...
- A borehole induces a stress concentration
  - 2D & 3D cases are more complicated

- Stress “lost” must be redistributed to the borehole flanks (i.e.: $\sigma$ concentration)

\[
F/A = \text{stress}
\]

$F = \text{force}$,
$A = \text{Area}$,
$F/A = \text{stress}$

High $\sigma_\theta$ near the borehole, but low $\sigma_r$!
Stress Redistribution

- Around the borehole, a “stress arch” is generated to redistribute earth stresses.

- Elastic rocks have rigidity (stiffness).
- Everyone carries an equal load (theoretical socialism).
- In reality, some carry more load than others (higher $\sigma'_\theta$ near the borehole wall).
- Far away (~5D): ~no effect.
- "Lost" stress is redistributed by "elastic" rocks.
- These guys may "yield" if they are overstressed.
The pore pressure in the hole lower than the total stresses

Thus, the excess stress must be carried by rock near the hole

If the stresses now exceed strength, the borehole wall can yield

However, “yield” is not “collapse”! A borehole with yielded rock can still be stable…
Arching of Stresses

3-D Borehole Stability

Arches
Lintels
Load
Stress arching
- Shear stress - $\tau$ - is the cause of shear failure
- $\tau_{\text{max}}$ at a point is half ppl. stress diff. $(\sigma_1 - \sigma_3)$
- $\tau_{\text{max}} = (\sigma'_1 - \sigma'_3)/2$, or $(\sigma'_\theta - \sigma'_r)/2$ in the figure

Worst shear condition, with little confining stress, is on the borehole wall, $90^\circ$ from $\sigma_{\text{MAX}}$ direction
Assumptions:

- The simplest stress calculation approach is the **Linear Elastic** rock behavior model.
- This behavior model is very instructive.
- It leads to (relatively) simple equations.

\[
\sigma'_r = \frac{(\sigma'_{\text{max}} + \sigma'_{\text{min}})}{2}(1 - \frac{r_i^2}{r^2}) + \frac{(\sigma'_{\text{max}} - \sigma'_{\text{min}})}{2}(1 - \frac{4r_i^2}{r^2} + \frac{3r_i^4}{r^4})\cos \theta
\]

\[
\sigma'_\theta = \frac{(\sigma'_{\text{max}} + \sigma'_{\text{min}})}{2}(1 + \frac{r_i^2}{r^2}) - \frac{(\sigma'_{\text{max}} - \sigma'_{\text{min}})}{2}(1 + \frac{3r_i^4}{r^4})\cos \theta
\]

\[
\tau_{r\theta} = -\frac{(\sigma_{\text{max}} - \sigma_{\text{min}})}{2}(1 + \frac{2r_i^2}{r^2} - \frac{3r_i^4}{r^4})\sin 2\theta
\]

In all cases, \( r \geq r_i \), \( \theta \) is taken CCW from reference.

*Known as the “Kirsch” Equations*
The Linear Elastic Borehole

- The simplest rock behavior model we use...
  - Strains are reversible, no yield (failure) occurs
  - Linear relationship between stress & strain
  - Rock properties are the same in all directions

\[
\sigma' = \sigma'_1 = \sigma'_3
\]

\[
\sigma'_a = \epsilon_a
\]

Stress-strain plot

\[
E = \Delta \sigma / \Delta \epsilon = \text{Young's modulus}
\]
High $\sigma_{\text{HMAX}} - \sigma_{\text{hmin}}$ Cases (Tectonic)

When $\sigma_{\text{hmin}} - \sigma_{\text{HMAX}}$ is large, the borehole wall in the $\sigma_{\text{HMAX}}$ direction is in tension! Induced fractures can be generated during $p_w$ surges.

*Note: here, borehole pressure, $p_w$, is assumed = $p_o$
Plot of the Tangential Stresses

- $\sigma_\theta$ on the wall ($r_i$) plotted as a function of $\theta$

- Note the symmetry
- $\sigma_\theta$ is destabilizing
- $\sigma_r$ is stabilizing
Mud Weight Effect (equal $\sigma$ case)

Assume $\sigma_{HMAX} = \sigma_{hmin} = \sigma$

Here, we assume for simplicity that we have “perfect” mud cake, and that the pore pressure in the rock is zero.
Horizontal vs. Vertical Wellbore?

- $\sigma_v = 0.9 \text{ psi/ft}, \ \sigma_h = 0.6 \text{ psi/ft}, \ p = 0.4 \text{ psi/ft}$

In non-tectonic systems ($\sigma_{hmin} \sim \sigma_{HMAX}$) vertical holes are subjected to lower shear stresses; they are generally more stable than horizontal holes.
Tectonic Stress Conditions

This orientation is the best one for this case, showing the importance of the \textit{in situ} stresses.

- **Vertical well**
  - \(\sigma'_v = 0.5 \text{ psi/ft}\)
  - \(\sigma'_{h\text{min}} = 0.3 \text{ psi/ft}\)
  - \(\sigma'_{H\text{MAX}} = 1.0 \text{ psi/ft}\)

- **Horizontal well aligned with minimum stress, \(\sigma'_{h\text{min}}\)**
  - \(\sigma'_{h\text{min}} = 0.3 \text{ psi/ft}\)

- **Horizontal well aligned with maximum stress, \(\sigma'_{H\text{MAX}}\)**
  - \(\sigma'_{H\text{MAX}} = 1.0 \text{ psi/ft}\)

**3-D Borehole Stability**

- Vertical effective stress = 0.5 psi/ft
- Min. horizontal effective stress = 0.3 psi/ft
- Max. horizontal effective stress = 1.0 psi/ft
Stress at borehole wall \( (\sigma'_\theta) \) in a tectonically active area
(Compressive stresses are +ve; Tensile stresses are -ve)
Depth of investigation is 5,000 ft

<table>
<thead>
<tr>
<th>No.</th>
<th>Hole Configuration</th>
<th>Maximum Stress ( (\sigma'<em>\theta)</em>{\text{MAX}} )</th>
<th>Minimum Stress ( (\sigma'<em>\theta)</em>{\text{MIN}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Gradient (psi/ft)</td>
<td>Magnitude (psi)</td>
</tr>
<tr>
<td>1</td>
<td>Vertical</td>
<td>2.7</td>
<td>13,500</td>
</tr>
<tr>
<td>2</td>
<td>Parallel to minimum horizontal stress</td>
<td>2.5</td>
<td>12,500</td>
</tr>
<tr>
<td>3</td>
<td>Parallel to maximum horizontal stress</td>
<td>1.2</td>
<td>6,000</td>
</tr>
</tbody>
</table>
“Showing” the Best Trajectory

- This is a polar plot of “ease of drilling”
- Related to magnitude of shear stress on wall
- This is based in situ stress knowledge
- In this example, a horizontal well, W to E, seems to be “easiest”
- A horizontal well N to S is the worst (all other factors being equal)
Typical Troublesome Hole (GoM)

4960’ Stuck Pipe: no rotation, no circulation

Hole tight with pumps off

Increase MW to get out of hole

Losing 300 bbl.hr (ballooning?)

Pack-off

©MBDCI

©MBDCI
Control Parameters in Drilling

- Mud weight, rheological properties, filtrate geochemistry, cake quality, mud type (WBM, OBM, foam, etc.), temperature...
- LCM content in the mud, type and gradation
- Tripping and connection practices:
  - Surging (run-in), swabbing (pull-out) pressures
- Drilling parameters:
  - ROP, bit type...
- Hydraulics and hole cleaning
- ECD (BHA characteristics, mud properties)
- Well trajectory, and maybe a few others
Effect of Mud Weight Increase

3-D Borehole Stability

Increasing MW (with good cake) reduces the stresses on the wall

\[ \tau_{\text{max}} = c' + \sigma'_n \tan \phi' \]
Effect of Loss of Good Filter Cake

With loss of mudcake effect, radial support disappears, shear stress increases.
Swabbing Effects on Pressure

Each blip is pulling up a stand of pipe

Bem et al., 2004, SPE #89737
Tripping Into the Hole

Each blip is running in a stand of pipe

Bem et al., 2004, SPE #89737
Uncontrollable Parameters

- Constrained trajectory (when we have no choice as to the wellbore path)
- Sequence of rock types (stratigraphy)
- Rock strength and other natural properties
  - Fractured shales
  - Clay type in shales (swelling, coaly, fissile)
  - Salt, etc.
- Formation temperatures and pressures, plus other properties such as geochemistry
- Natural earth stresses and orientations
Mud Cooling to Increase Borehole Stability in Shales
Heating occurs uphole, cooling downhole. The heating effect can be large, exceptionally 30-35°C in long open-hole sections in areas with high T gradients.

Heating is most serious at the last shoe. The shale expands, and this increases $\sigma'_\theta$, often promoting failure and sloughing.

At the bit, cooling, shrinkage, both of which enhance stability.

Commercial software exists to draw these curves.
**ΔT Effects in the Borehole**

- Mud goes down the drillpipe fast: ~5 to 10 × faster than it returns up the annulus
- It picks up heat from rising mud in annulus
- At the bit, still 10°-40°C cooler than rock in HT wells with long open-hole sections
- Rising uphole, the mud picks up heat from formation, and heats rapidly till the cross-over point (T diff. Is as large as 30°-40°C)
- Then, it cools all the way to the surface
- It gets to the tanks hot, and loses some heat, but usually goes back in quite warm
A Simple Quantitative Example...

- Change in $\sigma'_\theta$ at the wall is given by:
  \[ \Delta \sigma'_\theta ]_\text{ri} \sim (\Delta T \cdot \beta \cdot E)/(1-\nu) \]
- $E =$ Young’s modulus $= 1$ to $5 \times 10^6$ psi
- $\beta =$ Thermal exp. coef. $= 10-15 \times 10^{-6}$/°C
- $\nu =$ Poisson’s ratio $= 0.30 - 0.35$
- $\Delta T =$ Temperature change
- Reasonable values are: $E = 3 \times 10^6$ psi, $\beta = 12 \times 10^{-6}$/°C, $\nu = 0.35$, $\Delta T = +25$°C
- $\sigma'_\theta \uparrow$ at the wall by $\sim 1400$ psi (10 MPa)
- Not good for shale stability!
Heat Also Reduces Strength a Bit

About 10% strength loss for this $\Delta T$, so this is a secondary effect.
More Temperature Effects

- $+T$ reduces strength, increases stress
- $+T$ also makes adsorbed water more mobile
- Absorbed water layer thickness is reduced
- Either water is expelled, or stresses must change because the pore pressure changes
- In either case, additional $\Delta V$ takes place, in addition to thermoelastic effects
- Furthermore, reaction rates change with $\Delta T$
- Boy! Does this make modeling difficult!
The mud is cooled at surface through heat exchangers and sea water. As much as -30°C to -40°C is feasible in some cases.

Now, the amount of heating at the shoe is very small, only a few degrees.

Also, the shale remains stronger by virtue of the cooling.

There are other benefits as well…
Benefits of Mud Cooling

- Increases shale stability throughout hole!
- Low temperature reduces the rate of negative geochemical reactions between the mud filtrate and the shale
- Generally, mud properties are far easier to maintain with cooler mud, lower cost
- Tanks are less hot (in some areas, mud can exit the hole almost boiling!)
- BHA is “protected” from high T
- Use it when appropriate!
Lessons Learned

- We can analyze the behavior of the borehole during drilling, despite uncertainties.
- Analysis helps us understand the onset of sloughing and breakouts.
- Also, our mathematical models can help us analyze borehole effects when we heat the wall, cool the mud, shrink the shale, and so on.
- A good prognosis, robust models, and understanding the physics helps us to make decisions during drilling: risk management.
Example: Drilling Underbalanced

- It is a Rock Mechanics issue, a pore pressure issue, and a fluids type issue
  - If the shale is strong enough to be self supporting in a bore hole with a negative $\sigma_r$
  - If the pore pressure is not so high that it “blows” sand and shale into the borehole
  - If the fluids that enter the hole are “safe”, i.e., not oil and gas in large quantities

- Excellent for drilling through depleted zones, fast drilling through good shale, entering water sensitive gas-bearing strata, reservoirs that are easy to damage
Some tensile stress exists near the hole wall in underbalanced drilling because $p_o > p_w$. 

High shear stress at the borehole wall.

$p_w < p_o$
High gel strength can cause mud losses on connections, trips

- Increases surge and swab effects when BHA is in a small dia. Hole
- Also affects ECD
- Mud rheology & density can be changed for trips to sustain hole integrity
- Hydraulics is a vital part of borehole stability!
To increase hole stability, the best orientation is that which minimizes the principal stress difference normal to the axis.

\[ \sigma_v >> \sigma_{HMAX} > \sigma_{hmin} \]

Favored hole orientation

60-80° cone

Drill within a 60° cone (±30°) from the most favored direction

\[ \sigma_{HMAX} \sim \sigma_v \]

\[ \sigma_{HMAX} >> \sigma_{hmin} \]
Can You Live with Breakouts?

- Yes, in most cases breakouts are because of high stress differences, and are controllable.
- In exceptional cases, the breakouts are so bad that massive enlargement takes place.
- If hole advance is necessary, there are special things that can be done:
  - Some new products, silicates, polymers that set in the hole and can even be set and then drilled.
  - Increase MW, even to the point of overbalance.
  - Gilsonite and graded LCM can help somewhat.
  - In desperation, set casing!
Some Diagnostic Hole Geometries

- a. General sloughing and washout
- b. Keyseating
- c. Fissility sloughing
- d. Swelling, squeeze
- e. Induced by high stress differences
- f. Breakouts

Only breakouts are symmetric in one direction with an enlarged major axis.
Drilling and Shale Fissility

- If a hole is within 20° of strong fissility…
  - Sloughing is more likely
- Shale breaks like small brittle beams
- Breakouts can develop deep into strata

In this GoM case, in the “tangent” section, the hole angle was 61°
Vertical offset hole, **no problems**

Courtesy Stephen Willson, BP
Coping with Fissile Shale Sloughing

- If possible, stay at least 30° away from the fissility dip direction (see sketch)
- Otherwise, keep your mud properties excellent, keep circulation rate & ECD low, gilsonite and fn-gr LCM in mud may help…

Keep the drillhole within this cone to avoid severe fissility sloughing problems

Normal to bedding planes

100-120° cone
From: Bruce Matsutsuyu

Note that the majority of the shale sloughing appears to be from the top of the borehole.
Drilling Through Faults

- The fault plane region is often:
  - Broken, sheared, weak shales and rocks
  - It may have a high permeability
  - It can be charged with somewhat higher $p_o$

- First, expect the faults from your data:
  - Seismic data analysis
  - Near salt diapirs, especially shoulders

- Accurate mud $\Delta V(t)$ measurements can be of great value to good drilling

- Cavings monitoring

- MWD (ECD, resistivity, bit torque….)
Borehole Shear Displacement

- High angle faults, fractures can slip and cause pipe pinching
  - Near-slip earth stresses condition
  - High MW causes $p_w$ charging
  - Reduction in $\sigma'_n$ leads to slip
  - BHA gets stuck on trip out

- Can be identified from borehole wall sonic scanner logs (profile logs)

- Raising MW makes it worse! Lower MW!

- Also, LCM materials to plug the fault or joint plane are effective
Slip of a High-AngleFault Plane

\[ \sigma_v = \sigma_1 \]
\[ \sigma_h = \sigma_3 \]

borehole

slip of joint surface

high pressure transmission

slip of joint

casing bending and pinching in completed holes

pipe stuck on trips

(after Maury, 1994)
Slip Affected by Hole Orientation!

OFFSET ALONG PRE-EXISTING DISCONTINUITIES

Effective normal stress (bar)

Azimuth:
- 0
- 10
- 20
- 30
- 40
- 50
- 60
- 70
- 80
- 90
- 100

Inclination (δ) (deg)

TYPICAL MUD OVER-PRESSURE

Courtesy Geomec a.s.
Diagnostics for Fault Slip Problems

- In tectonic areas, near salt diapirs…
- On trips, BHA gets stuck at one point
- Easy to drop pipe, hard to raise it
- Borehole scanner shows strange shapes: not the same as keyseating or breakouts

Start of keyseat | Serious keyseat | Evidence of fault plane slip
Curing Fault Plane Slip Problems

- Usually occurs up-hole in normal faulting regimes that are highly faulted, jointed, as MW is increased to control $p_o$ downhole
- Suddenly near the bit – a fault is encountered
- Back-ream through the tight zone
- High $p_w$ contributes to the slip of the plane, thus reduce your MW if possible
- Condition the mud to block or retard the flow of mud pressure into the slip plane:
  - Gilsonite, designed LCM in the mud
- Use an avoidance trajectory for the well
Mud Volume Measurements

- Extremely useful, but, accurate $\Delta V/\Delta t$ needed
- Case A: fracture/fault encountered, quickly blocked, now analyze data for $k$ and aperture!
- Case B: fractured rock not healed by LCM
- Other cases have their own typical response curves (ballooning, slow kick…)
- Diagnostics!
A Precise Mud Volume Installation

Outlet mud line
Precision flow meter

(taken from SPE 38177 - Agip well)
Actual Field Example of Analysis

This information proved extremely valuable for reservoir engineers in this case, as a gas reservoir was found.

Courtesy Geomec a.s
Losses Identify Fractured Zones

Likely, each event involved filling a single fracture
Problems in Coal Drilling

- OBM are worse than WBM in Coal
  ➞ Filtrate penetrates easily (oil wettability)
- Coal fractures open easily if $p_w > p_o$
  ➞ Coal is extremely compressible
- Difficult to build a filter cake on the wall
  ➞ Fissure apertures open with surges
- Sloughing on trips, connections, large washouts, …
- Packing off of cuttings and sloughed Coal around the pipe, even during trips
Drilling in Coal

3-D Borehole Stability

stresses around wellbore

σ_r

σ_θ

Mud rings and pack-off caused by slugs of cavings and cuttings

Deep pore pressure penetration because of coal fractures

Massive sloughing

fracture-dominated coal
Drilling Fractured Coal Safely

- Keep jetting velocities low while drilling through the coal (avoid washouts)
- Keep MW modest to avoid fractures opening and coal pressuring, low ECDs while the BHA is opposite the coal seams
- Drill with graded LCM in the mud to plug the fractures and build a cake zone
- Avoid swabbing and surging on trips
- Best to drill with WBM in coal and fissile carbonaceous shales
A Case History of Salt Diapir Drilling in the North Sea
North Sea Case, Shallow Depth

Well A

1a

2000 m

Shallow Gas

Gas Pull Down

Courtesy Geomec a.s.
Normal faulting above the diapir, likely to be zones of substantial mud losses (low $\sigma_{\text{hmin}}$)

Beds are distorted, likely shearing has occurred along the bedding planes (weaker)

Seismic data show strong “gas pull-down effect”, lower seismic velocities because of free gas in the overlying shales and high $p_0$

Free gas zones are noted in the strata, and these will increase gas cuts

(Gas “pull-down” refers to the effect of free gas on seismic stratigraphy)
Deeper, Around the Diapir

Well A

1b

Gas Pull Down

Mid-Miocene regional pressure boundary

2000 m

3000 m

This region avoided

Top Balder
Top Chalk
Intra Hod/Salt

3-D Borehole Stability

Courtesy Geomec a.s.
What Was Done to Improve Drlg?

- A trajectory was chosen to avoid the worst of the crestal faulting and gas pressures
  - Shales also intersected at ~ 90° to fissility
- Mud losses were carefully monitored with depth in the critical zones, then analyzed
- Designed LCM in the mud allowed a bit of overbalance in a critical region
- Of course, gas cuts, shale chip geometry, total cutting volumes, etc., and many other things were monitored in “real-time”
These wells were drilled with overbalance: a MW above the lowest estimated $\sigma_{h\text{min}}$ in the zone.

Courtesy Geomec a.s.
Interim Conclusions

- Fracturing pressure can be increased by several 100 psi by graded LCM, analysis
- Young’s mod. (E) is the control parameter
- Induced fractures or even natural fractures encountered open up almost immediately to their final width:
  - This aperture controls LCM design
- Plugging happens rapidly with right LCM
- The effect is enhanced with high viscosity mud and slower ROP
- Design tools are available for this
A Well Plan, North Sea

- classical MW window is too narrow; cannot avoid instability
- low mud weight → breakouts
- high mud weight → destabilized fractured zones & losses
- breakout problems are controllable by good hole cleaning; fracture zones are uncontrollable

Strategy:
- keep mud weight low
- manage breakouts with good hole cleaning before increasing mud weight during trips
- monitor cavings, mud losses for warning of fractured zones

Courtesy Stephen Willson, BP
Executing this Difficult Well...

- Background gas controlled by ROP, not MW
- Monitoring greatly reduced “wiper trips”
- Continuous ECD and mud volume monitoring to avoid destabilization (+”charged” faults)
- Chip analysis to identify fractured shales
- Strength profile modified “on-the-fly” using ISONIC MWD + behavior + prognosis
- Ballooning analysis refined $\sigma_{h\text{min}}$ data
- Hole condition from CRD scan on trips
- Weighted pills placed for trips
- Mud properties well maintained (ECD…)
Trajectory Variations Example

- Erskine HPHT field
- Deviated holes need MWD, better control, the dashed line path was abandoned
- Reach was established above HTHP zone, then the well turned vertical
- No MWD used, hole cleaning was better, lower ECD, etc…
- Also, low flow rates, low surge-swab, etc…
Real-Time Wellbore Stability

- For deep, difficult, costly holes only
- Quality prognosis is needed – $p_o(z)$, $\sigma_{h\text{min}}(z)$
- Diagnostic tools used:
  - Real-time pressures (ECD management)
  - Caliper and resistivity data, D-exponent data
  - Borehole imagery (on trips)
  - Accurate mud loss gauges & ballooning analysis
  - Cuttings volumes and visual classification
- Prevention and and remediation options:
  - Mud properties and special chemicals
  - Hydraulics, drilling parameters, reamers…
  - Special cures… (pills, LCM,„„)
### Things to Do at the Shaker

- Classify as to whether cuttings or cavings
  - Based on size
  - Based on shape and morphological features
  - Based on color, mineralogy…
- Relate cavings morphology to the type of shale problem: Fractured shale? High $\sigma_\theta$?
- What is volume of material at the shaker?
  - Only the cuttings? 10% more? 200% more?
  - Surges of cavings…
- Take samples and preserve them (in oil?)
- Measurements on chips is also possible
Examination of Shale Chips

- Mode of failure: shear, spalling, sloughing
- Adequate cleaning? $p_o > p_w$? Remedies?

Sheared surfaces

Borehole wall

Bedding planes

Preexisting cleavages planes in natural fracture/joint sets

Top view

Side view
Shale Chip Morphology

- Sheared surfaces are usually visible on drill bit fragments, learn to identify them
- Large curved splinters usually indicate borehole instability sourced chips
- Flat planar features usually indicate sloughing of naturally fractured shales
- Geochemical alterations on planar surfaces indicate naturally fractured shales
- Highly dispersed chunks indicate poor inhibition in a WBM
- Etc.
Shale Fragments From 12400’

Note the abundance of linear breaks (yellow) which appear to be oblique to shale bedding surfaces, indicating the probability of pre-existing fractures.
Typical Blocky Cavings
Small and Mixed Cavings

- Smaller blocky cavings
- Gravel-like cavings
Look at the Shaker!

- The nature morphology of the cavings gives clues as to what the problem is!
- Blocky cavings = fractured shale
- Splintery cavings = stresses are high and failure is being induced
- Mushy cavings = swelling is a problem
- Coal = fractured coal problems
- Where are cavings coming from in hole?
- Develop your own experience in your area!
- Don’t lose experience; find a way to exploit it.
Tests on the Rig Floor on Chips

- Performed on “intact” cuttings
- Brinnell hardness is related to strength
- The dielectric properties can be related to the shale geochemical sensitivity
- Sonic travel time can be related to strength and stiffness empirically
- You can use dispersion tests in water of different salinities to assess swelling
- Even some others can be used
- These can be taken regularly and plotted as a log versus depth (very useful)