SPE GCS Geomechanics Congress
“Recent Advancement in Petroleum Geomechanics”

Pore pressure prediction and wellbore stability analysis to reduce drilling risks

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18th April 2018
Woodlands, Texas

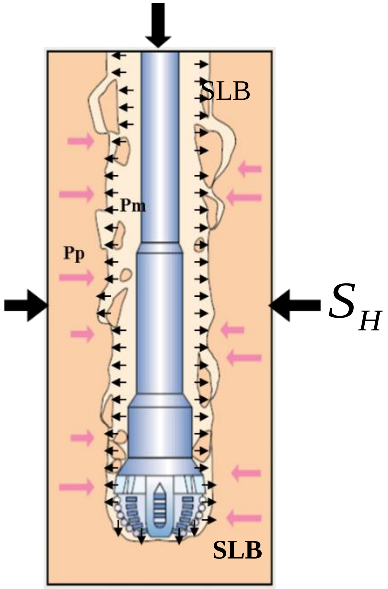
Outline

- Pore pressure prediction.
- Fracture gradient prediction.
- Wellbore strengthening.
- Borehole stability.

Pore pressure prediction

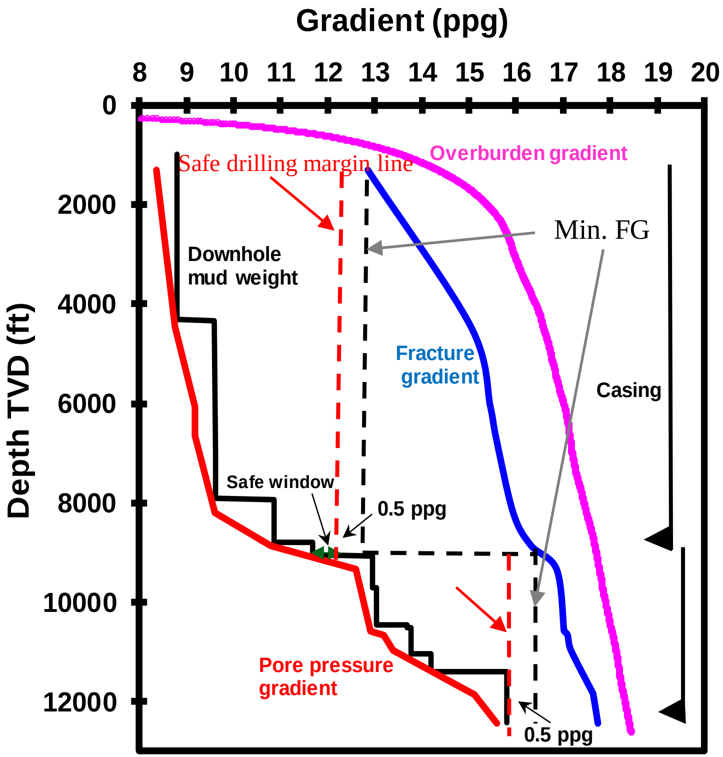
Statistics show: PPFG incidents (including wellbore instability events) account for over 41% of total NPT for subsalt wells in GOM (OTC-20220), including influx, kick, blowout, mud losses, lost circulation. wellbore collapse, and pack-off etc.

Pore pressure prediction is a key to avoid influx, kick, well blowout



BSEE new regulation:

Downhole MW> Pp
and ≤ min. FG - 0.5ppg.



Pre-drill PPFG prediction in an offshore well.

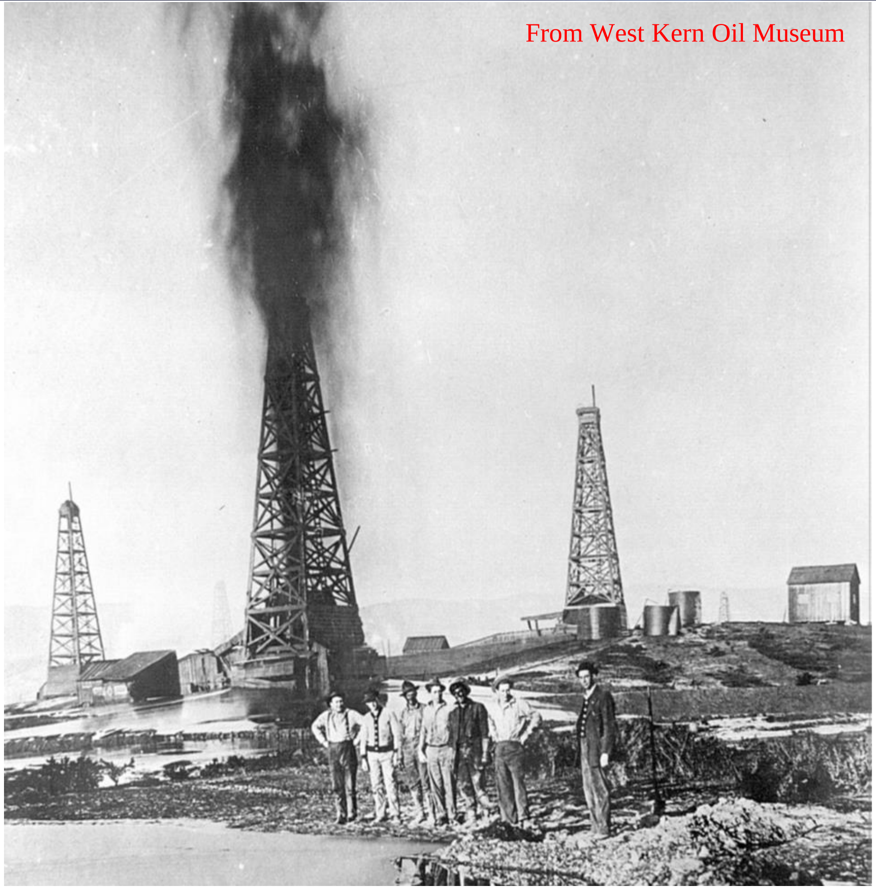
BSEE = Bureau of Safety and Environmental Enforcement

Pore pressure-related blowouts

- Exploration wells have big **uncertainties in** pore pressure **prediction.**

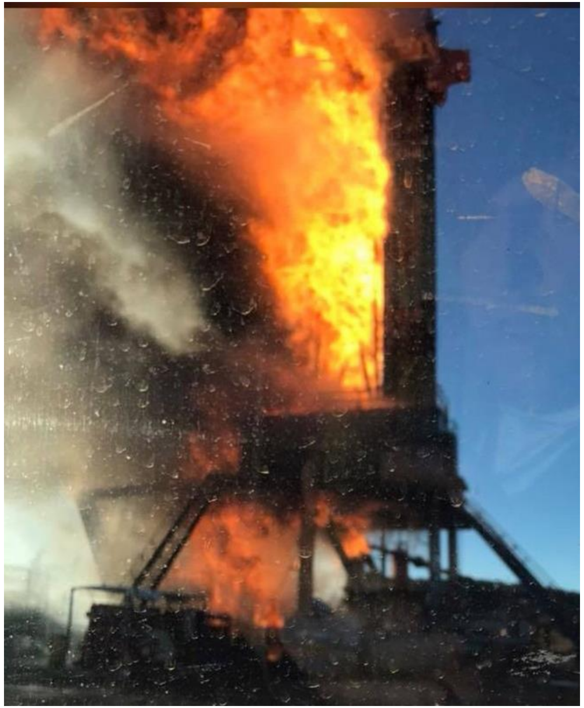
- **PPP may be underestimated 1-2 ppgs, causing kicks, even blowouts.**

The Lakeview gusher of 1910 spewed 9 million barrels of oil. The largest oil-well blowout, took 18 months to get under control.

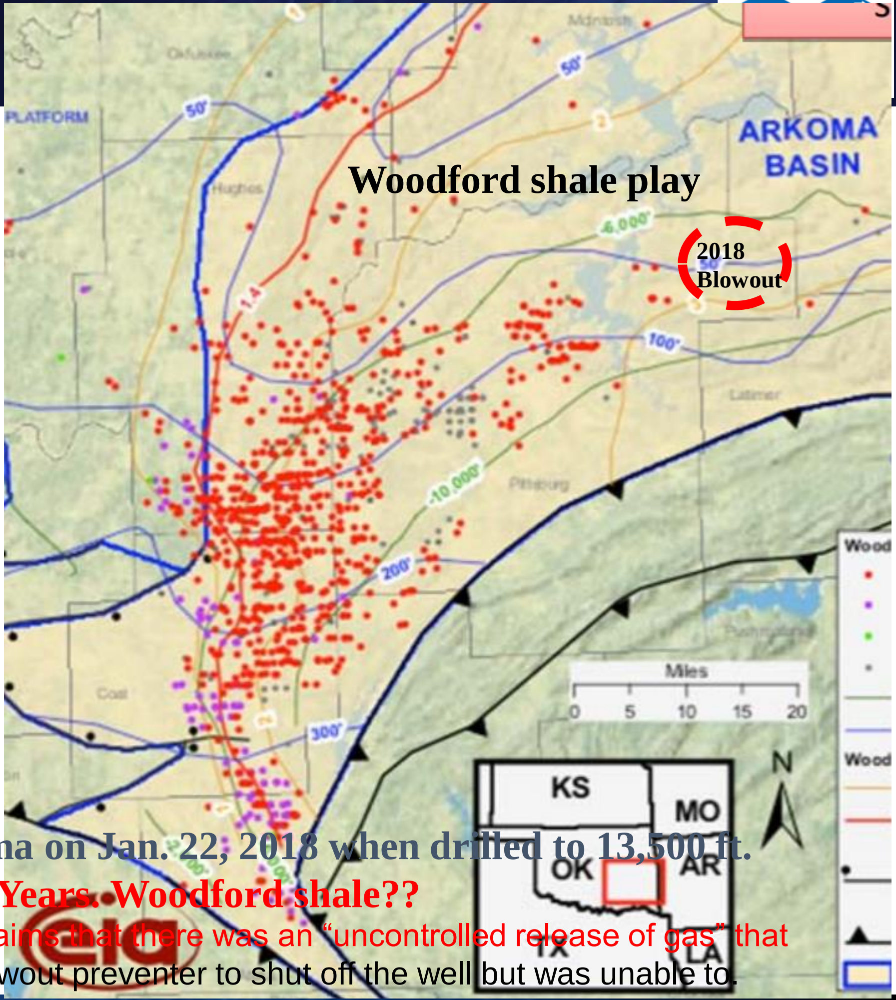


From West Kern Oil Museum

Recent pore pressure-related blowout and explosion



Oil rig explosion in Quinton Jan 22, 2018. (Photo Courtesy Zayne Erickson)



Blowout and explosion in Arkoma basin in Oklahoma on Jan. 22, 2018 when drilled to 13,500 ft. Killed 5 people: Deadliest U.S. Drilling Accident In Years. Woodford shale??

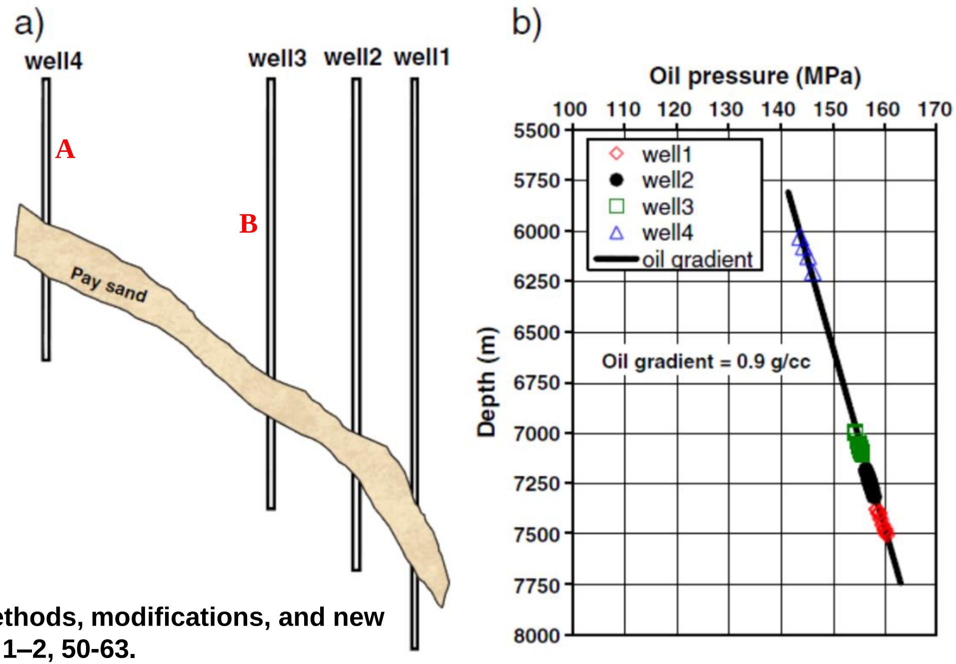
An initial report released by the Oklahoma Corporation Commission claims that there was an "uncontrolled release of gas" that caught fire. A rig worker attempted to activate a device known as a blowout preventer to shut off the well but was unable to.

Pore pressure predictions in shales and sands are different

Pore pressure prediction in sandstones - “permeable” rocks or reservoirs:

If measured Pp is available, then fluid connection model can be used.

$$p_A = p_B - \rho_o g(Z_B - Z_A)$$



Zhang, 2011. Pore pressure prediction from well logs: Methods, modifications, and new approaches. Earth-Science Reviews. Volume 108, Issues 1–2, 50-63.

Pore pressure prediction in shales

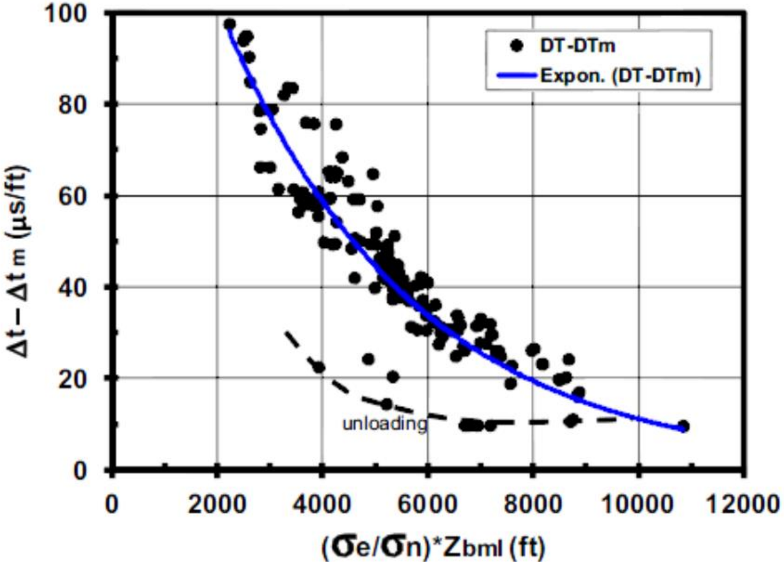
Based on Karl von Terzaghi's effective stress law,

$$p_p = \sigma_V - \sigma_e$$

Effective stress, σ_e, can be correlated to well logging data, e.g.,

sonic DT, Vp, porosity, Resistivity….

$$\sigma_e = f(\phi, res, Vp, DT, orDx)$$

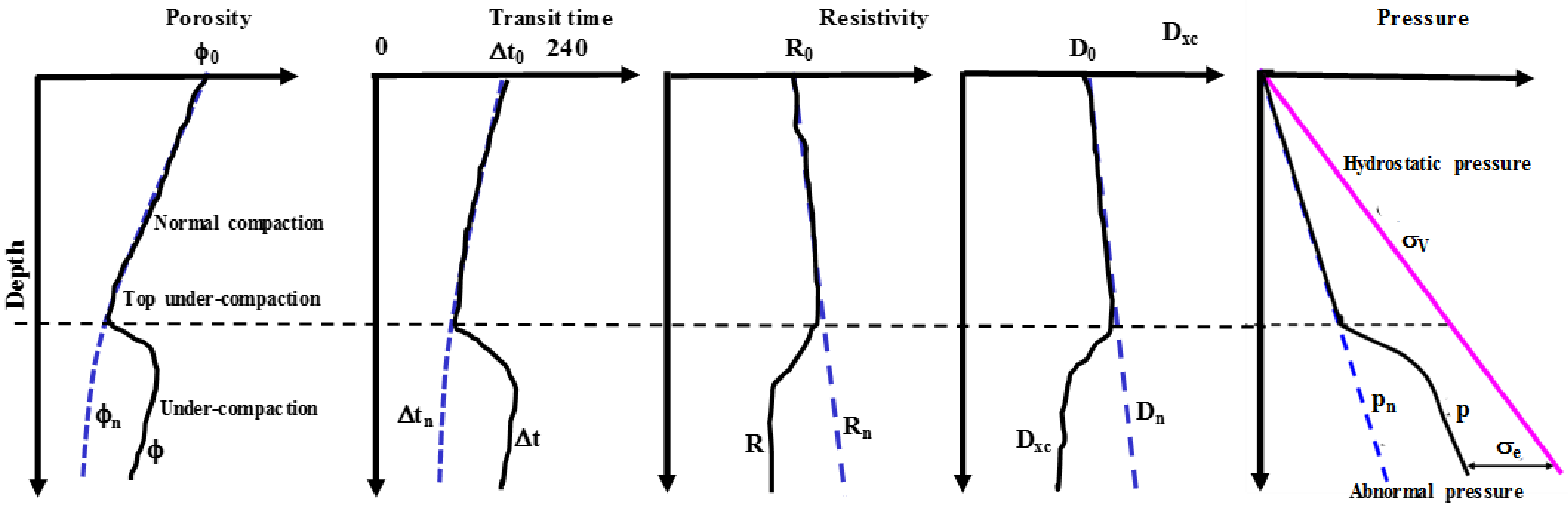


$$\Delta t = \Delta t_m + 175.49 e^{-0.00026 \mathbb{Z}(\sigma_e/\sigma_n)}$$

Zhang, 2013. Effective stress, porosity, velocity and abnormal pore pressure prediction accounting for compaction disequilibrium and unloading. Marine and Petroleum Geology 45, 2-11.

NCT and abnormal pore pressure in shales

Overpressure caused by undercompaction.



Generalized normal compaction trends (NCTs) and abnormal pressures caused by under-compaction. From left to right: porosity, transit time, resistivity, D-exponent, and pore pressure plots.

Zhang and Yin, 2017. Real-Time Pore Pressure Detection: Indicators and Improved Methods. Geofluids.

Pore pressure prediction from velocity or DT

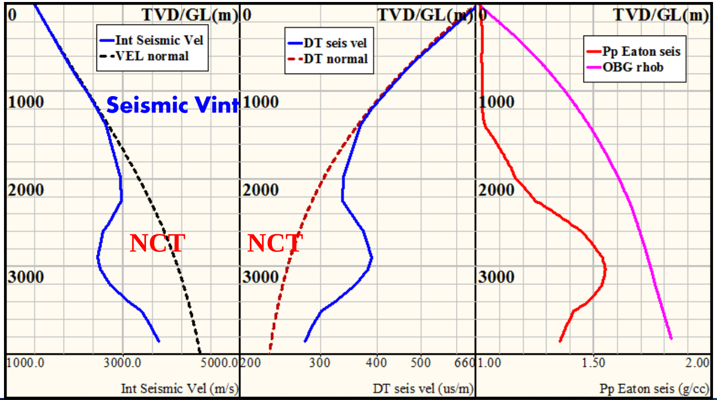
Pp from DT (e.g., Eaton method):

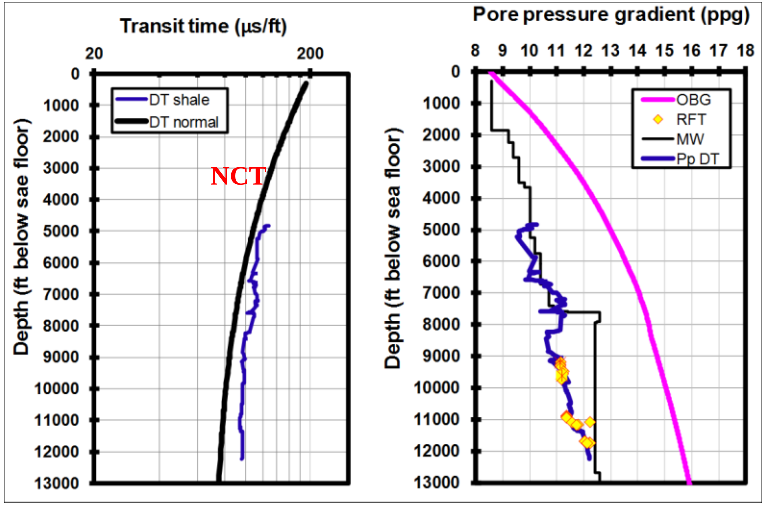
$$P_{pg} = OBG - (OBG - P_{ng})(\Delta t_n / \Delta t)^3$$

Need to obtain Δt_n, or normal compaction trendline NCT

New normal compaction trendline (Zhang, 2011)

$$\Delta t_n = \Delta t_m + (\Delta t_{ml} - \Delta t_m) e^{-cZ}$$





Bowers' equation:

$$p = \sigma_V - \left(\frac{v_p - v_{ml}}{A} \right)^{\frac{1}{B}}$$

DT = Δt = transit time or slowness

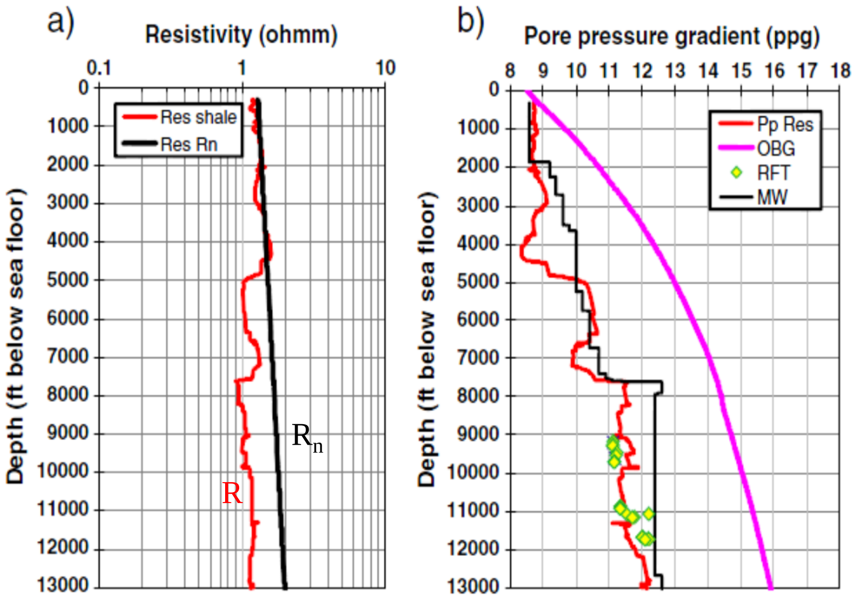
P_{ng} = Normal pressure gradient or Hydrostatic pressure gradient

Pore pressure from resistivity

Pp from Res, Eaton method:

$$P_{pg} = OBG - (OBG - P_{ng})\left(\frac{R}{R_n}\right)^n$$ (Eaton, 1975)

$$R_n = R_0 e^{bZ}$$ (Zhang, 2011)



GoM well

Zhang, 2011. Pore pressure prediction from well logs: Methods, modifications, and new approaches. Earth-Science Reviews. Volume 108, Issues 1–2, 50-63.

Fracture gradient prediction

Fracture gradient prediction

Fracture gradient is the pressure gradient required to fracture the formation and cause mud losses from the wellbore into the induced tensile fractures.
It is the upper bound of the MW.

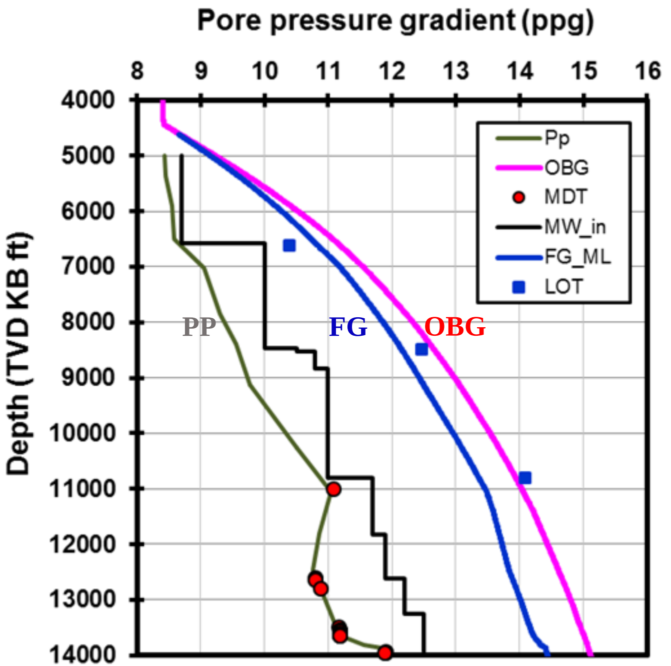
Eaton's method (min. stress)

$$FG = \frac{\nu}{1-\nu}(OBG - P_p) + P_p$$

Matthews and Kelly method

$$FG = k_f (OBG - P_p) + P_p$$

k_f is the effective stress coefficient.



Note that FGs in shale and sand are different.

Fracture gradient prediction and LOT

Matthews and Kelly method

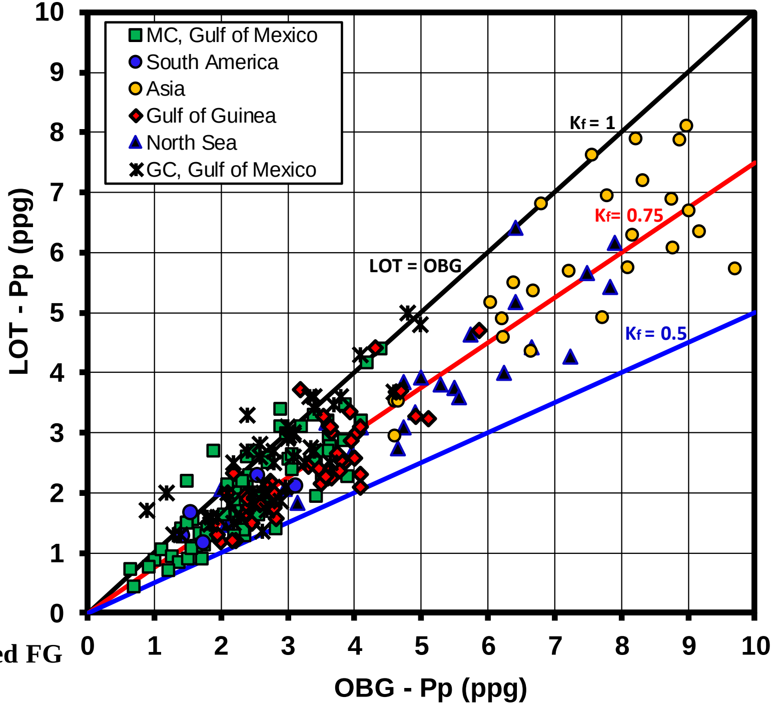
$$FG = k_f(OBG - P_p) + P_p$$

k_f = 0.5 to 1

ML case: k_f = 0.75 for shales

k_f is depth-dependent (Zhang and Yin, 2017)

$$k_f = k + a / e^{Z/b}$$



LOT = Leak-Off Test or measured FG

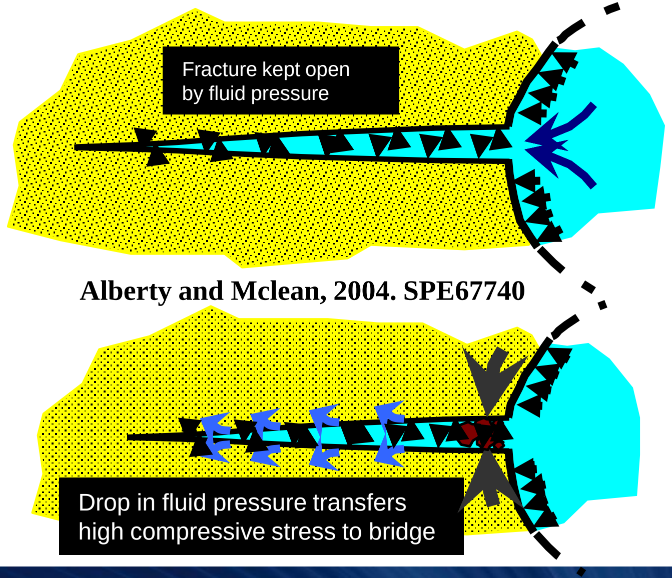
LOT pressure gradients in shales versus the effective overburden gradients (OBG) in 229 offshore wells in several worldwide petroleum basins

Zhang and Yin, 2017. Fracture gradient prediction: an overview and an improved method. Petroleum Science.14 (4), 720–730.

Wellbore strengthening

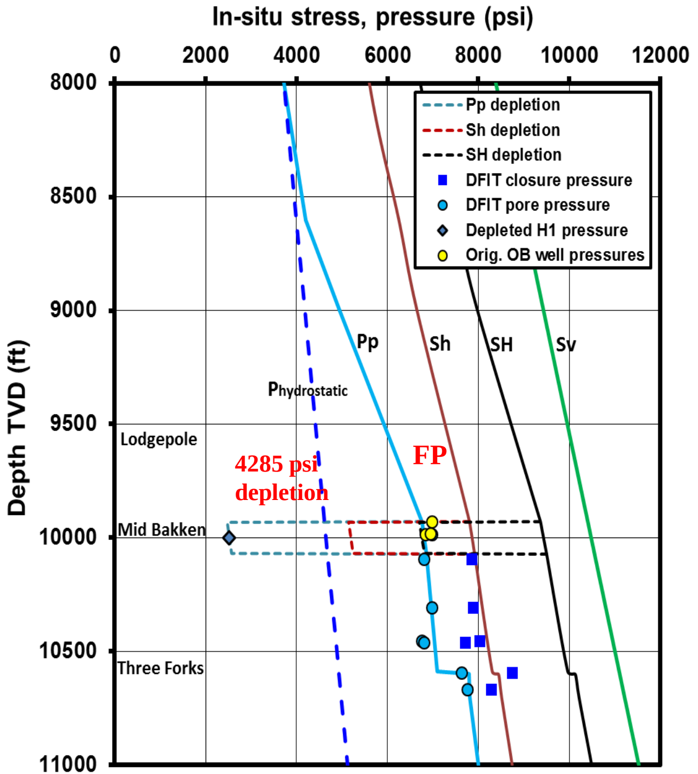
Wellbore strengthening to increase FG

- Wellbore strengthening technology, e.g. Stress Cage, can be used.
- High drilling ECD (target FG) is used to intentionally fracture the rock.
- Particles are added into the mud to plug the fractures, thereby increasing the hoop stress around the wellbore.



Alberty and Mclean, 2004. SPE67740

Pressure depletion reduces fracture gradient



Dohmen, Zhang et al., 2013. SPE166274

Fracture width for WBS

To apply wellbore strengthening, it needs to calculate fracture width for selecting the particle size.

2-D vertical well solution, Alberty and Mclean, 2004:

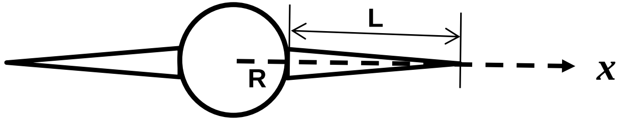
$$w(x) = \frac{4(1-\nu^2)}{E}(p_w - S_h)\sqrt{(L+R)^2 - x^2}$$

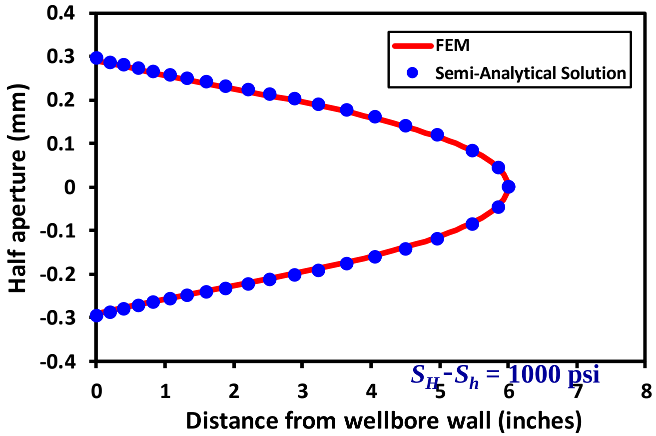
Old eq. is only suitable for $S_h = S_H$.

Semi-analytical solution using superposition principle (Zhang et al., 2016):

$$w(x) = \frac{4(1-\nu^2)}{E}[p_w - S_{\min} + c(S_{\max} - S_{\min})]\sqrt{(L+R)^2 - x^2}$$

$$c = \frac{0.368R^{1/2}}{(L+3x_w)^{1/1.3}}$$

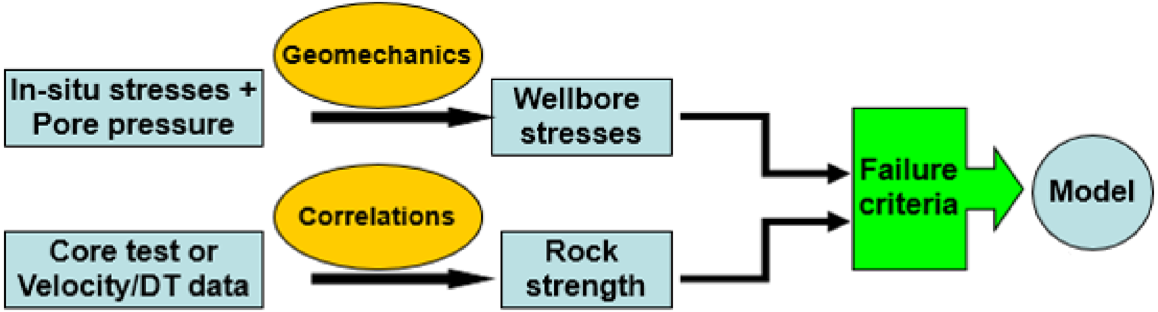


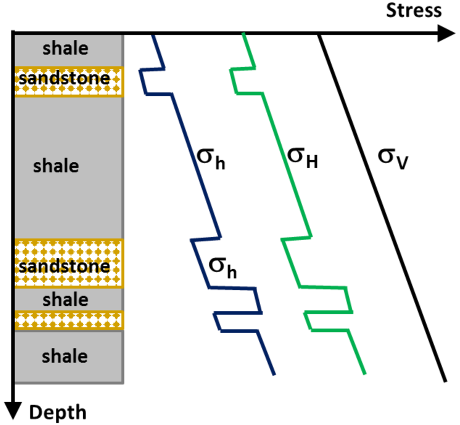


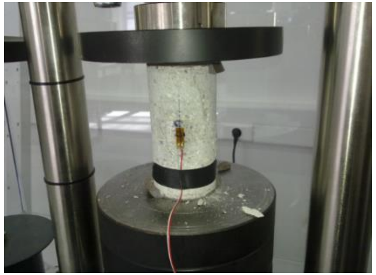
Zhang et al., 2016. A semi-analytical solution for estimating the fracture width in wellbore strengthening applications. SPE-180296.

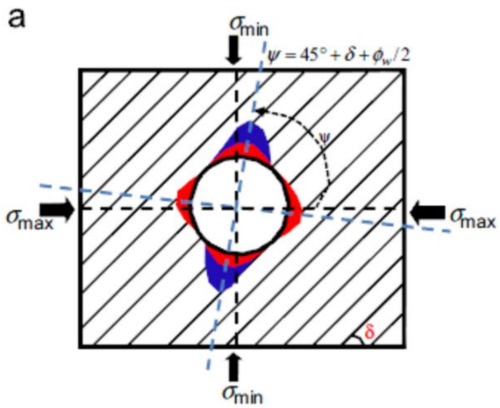
Borehole stability

Borehole stability analysis – workflow





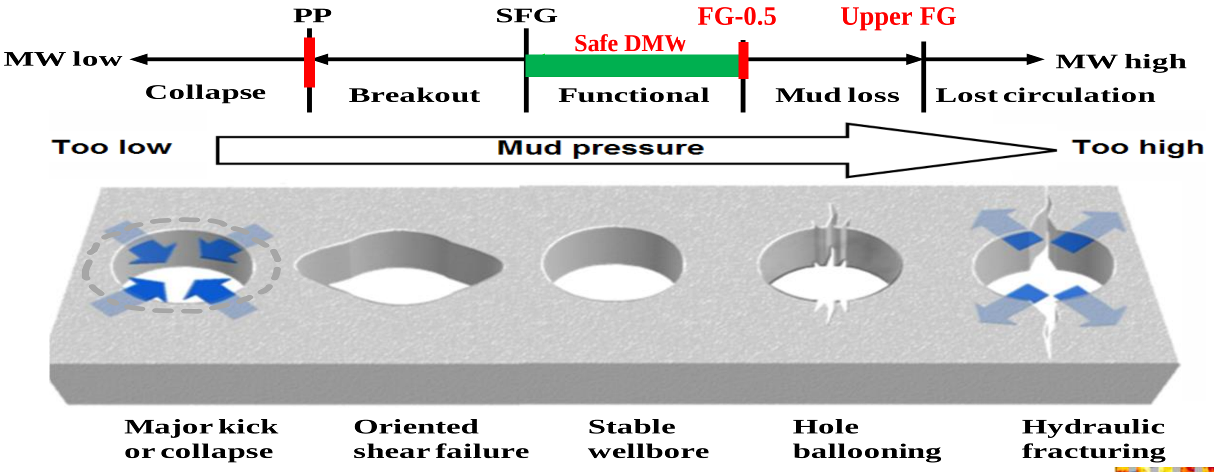




Zhang, Y. Zhang, J., 2017. Lithology-dependent minimum horizontal stress and in-situ stress estimate. Tectonophysics. 703-704, 1-8

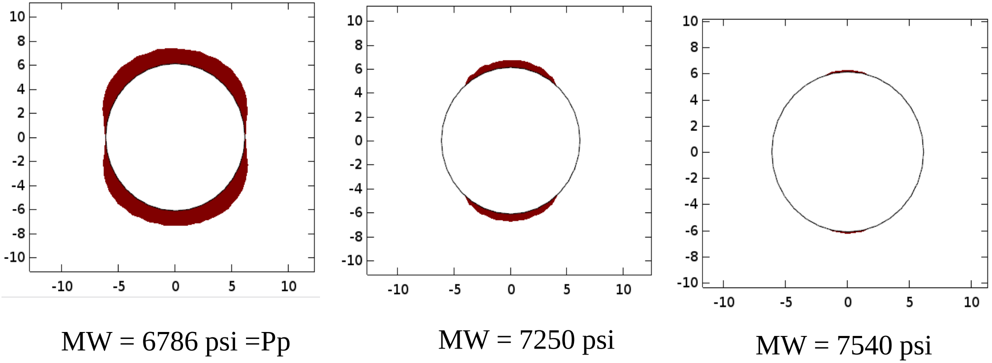
Zhang, 2013. Borehole stability analysis accounting for anisotropies in drilling to weak bedding planes. Int. J. Rock Mech. and Min. Sci. 60, 160-170.

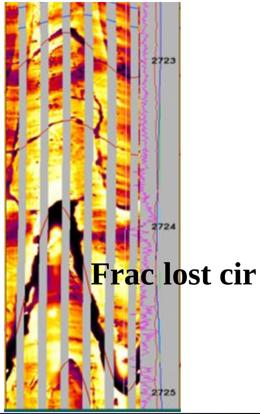
Borehole stability analysis for safe MW window



Zhang, 2013

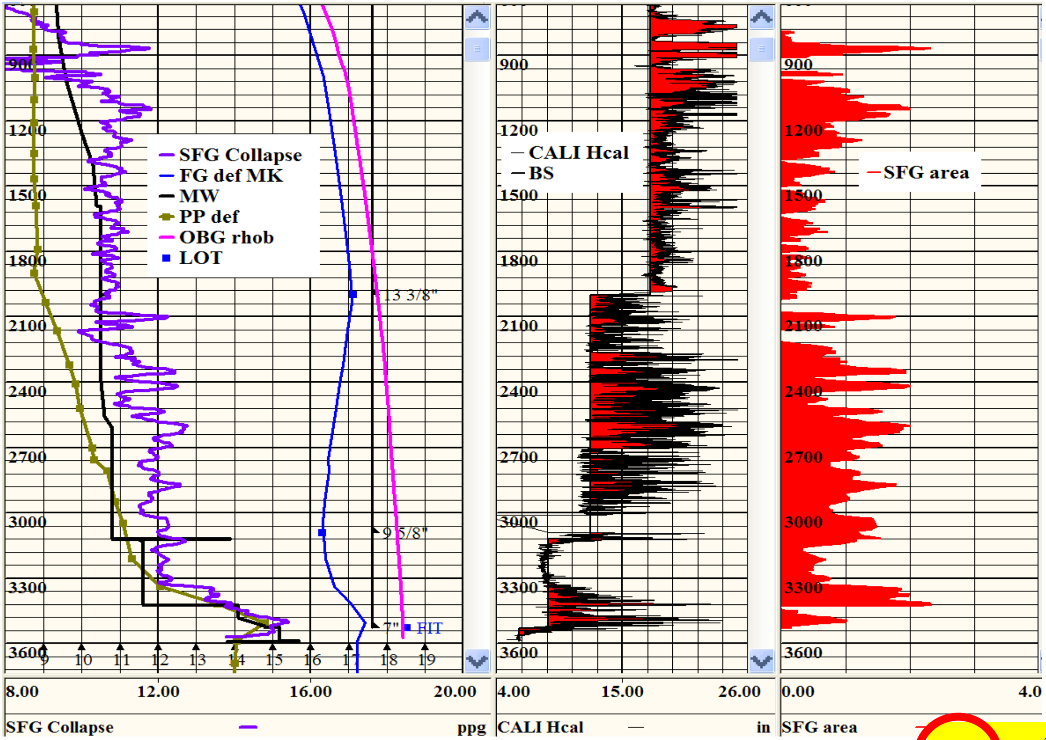
FEM modeling, UCS =1000 psi





SFG = Shear Failure Gradient, or Collapse pressure gradient

Borehole stability: collapse pressure gradient



Post-well analysis

Simplified equation for illustration

$$p_m \geq \frac{1}{2}(3\sigma_H - \sigma_h)(1-\sin\phi) - c\cos\phi + p_p \sin\phi$$

Conclusions

- **Accurate PPFG prediction and wellbore stability analysis can reduce drilling risks and cost.**
- **Wellbore strengthening technology can increase FG and make undrillable wells drillable.**
- **Geomechanics analysis can reduce drilling NPT.**

Thank you and questions

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