Introduction to Earth Stresses

Richard A. Plumb PhD

Presenter

Richard A. Plumb PhD
Principle,
Plumb Geomechanics, LLC

Poll Question

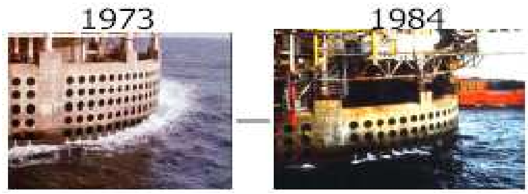
What is your job function?

Objective

Explore the critical role that earth stresses have on subsurface rock deformation and their impact oil field operations.

Costly mistakes remind us of the **risks**

Webinars



Compaction and Subsidence.

SPE International

5

Outline

Webinars

1. Basic concepts and terminology
   - Stress, pressure, effective stress, strain, elasticity
2. Mohr’s circle and the Coulomb failure criterion
   - Stable and unstable states of stress
3. Earth stress
   - Reference states, pore pressure, overpressure, stress measurement, observations
4. Impact that changes of stress and pressure have oilfield operations

SPE International

Pressure, stress, effective stress, strain, linear elasticity

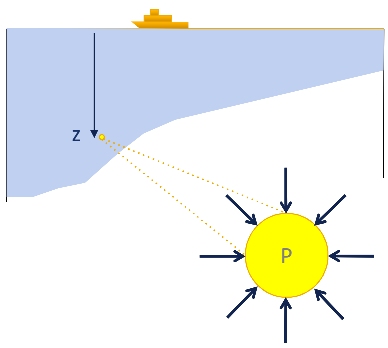
BASIC CONCEPTS

Pressure

Pressure describes forces acting in liquids and gases

Pressure also has units F/A

- is a scalar quantity-independent on direction
- acts normal to surfaces.
- units of F/A



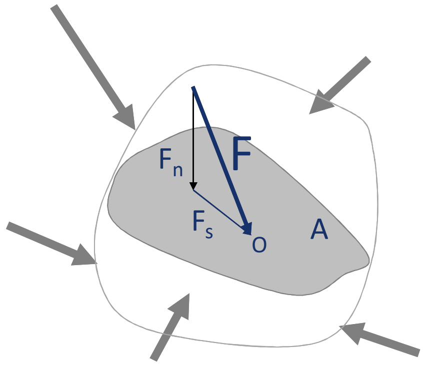
$$P = \rho_w g z$$

Familiar pressures that affect rock deformation include: reservoir pressure, pore pressure, wellbore pressure....

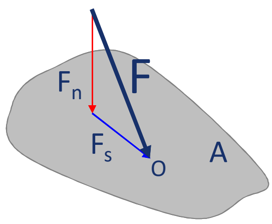
Concept of stress

- Stress is defined as force intensity (F/A) in solid bodies.
- The stress at a point, O , on a plane with area A, is the limiting value F/A as the A approaches 0

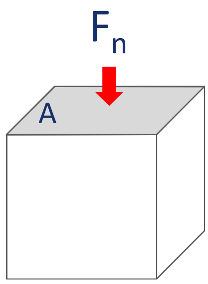
$$\sigma = \lim_{\delta A \to 0} \frac{\delta F}{\delta A}$$



Two types of stress



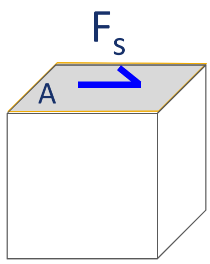
Normal stress σ



$$\sigma = \frac{F_n}{A}$$

governs volume changes

Shear stress τ

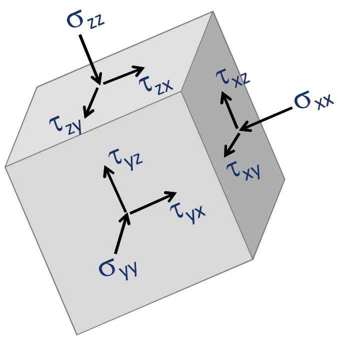


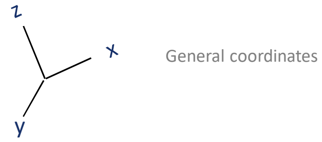
$$\tau = \frac{F_s}{A}$$

governs shape changes

Stress tensor: general coordinates

Webinars





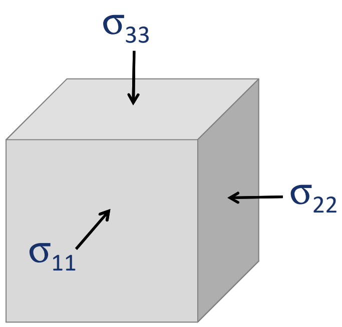
$$\sigma_{ij} = \begin{bmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{xy} & \sigma_{yy} & \tau_{yz} \\ \tau_{xz} & \tau_{yz} & \sigma_{zz} \end{bmatrix}$$

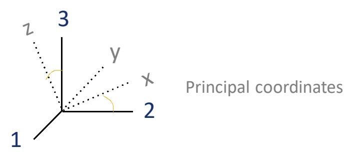
Six numbers are required to describe the state of stress at any "point" in a solid body in static equilibrium: 3 normal stress components and 3 shear stress components

SPE International

Stress tensor-principle coordinates

Webinars





$$\sigma_{ij} = \begin{bmatrix} \sigma_{11} & 0 & 0 \\ 0 & \sigma_{22} & 0 \\ 0 & 0 & \sigma_{33} \end{bmatrix}$$

In principle coordinates, there are no shear stresses acting on principle planes.

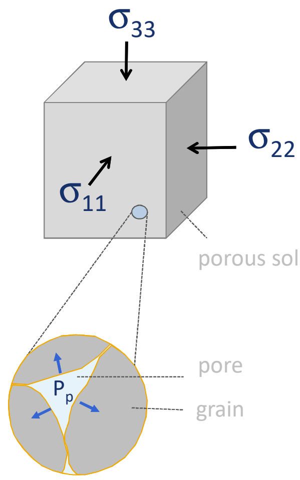
SPE International

Effective stresses

- Porous rock deforms in response to applied stress *and* fluid pressure.
- This behavior is approximated by using effective normal stress (σ) in *elasticity or failure* calculations.
- The effective *normal* stress is defined:

$$\sigma' = (\sigma - \gamma P_p)$$

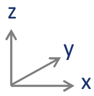
Where σ is total stress and γ is dependent on physical process



The concept of of strain

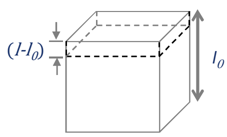
- Strain is a dimensionless measure of deformation
- Two types of strain: elongation or normal strain and shear strain
- Like stress, strain is a second rank tensor
- Elongations contribute to volume changes
- Shear strains measure distortion
- Strain tensor referred to principle axes:

$$\begin{bmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{bmatrix}$$



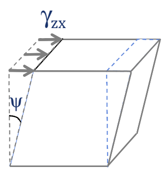
- Strain data come mainly from rock mechanics laboratories

Elongation ε



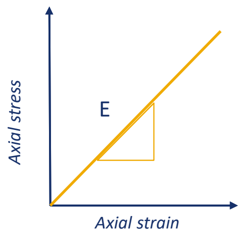
$$\varepsilon = \frac{(l - l_0)}{l_0}$$

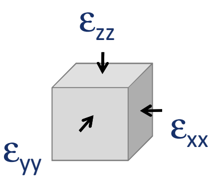
Shear strain γ



$$\gamma = tan\,\psi$$

Linear-elastic stress-strain response: isotropic material

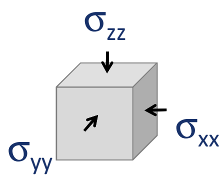




$$\varepsilon_{xx} = \frac{\sigma_{xx}}{E} - \frac{\nu}{E}\sigma_{yy} - \frac{\nu}{E}\sigma_{zz}$$

$$\varepsilon_{yy} = -\frac{\nu}{E}\sigma_{xx} + \frac{\sigma_{yy}}{E} - \frac{\nu}{E}\sigma_{zz}$$

$$\varepsilon_{zz} = -\frac{\nu}{E}\sigma_{xx} - \frac{\nu}{E}\sigma_{yy} + \frac{\sigma_{zz}}{E}$$

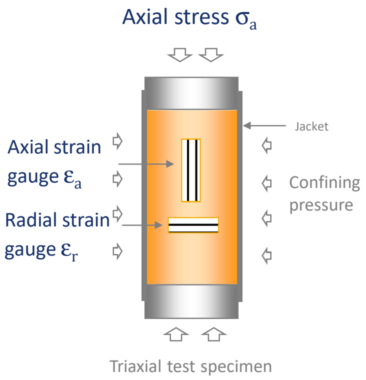


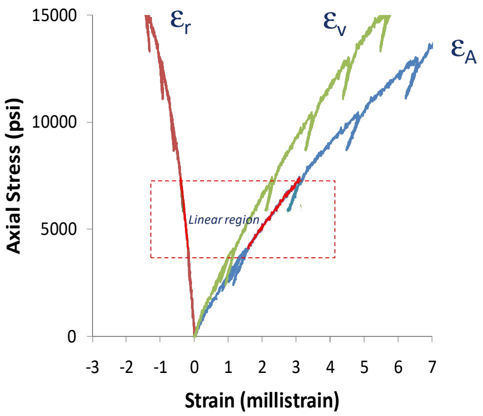
The linear-elastic approximation applies to many rocks where strains are ~ < 10^{-6}

The lower the prososity the better is this approximation

For example strains imposed by the passage of seismic waves is in the order of 10^{-8}

Elastic parameters* from laboratory tests





Young's modulus

$$E = \frac{d\sigma_a}{d\varepsilon_a}$$

Poisson's ratio

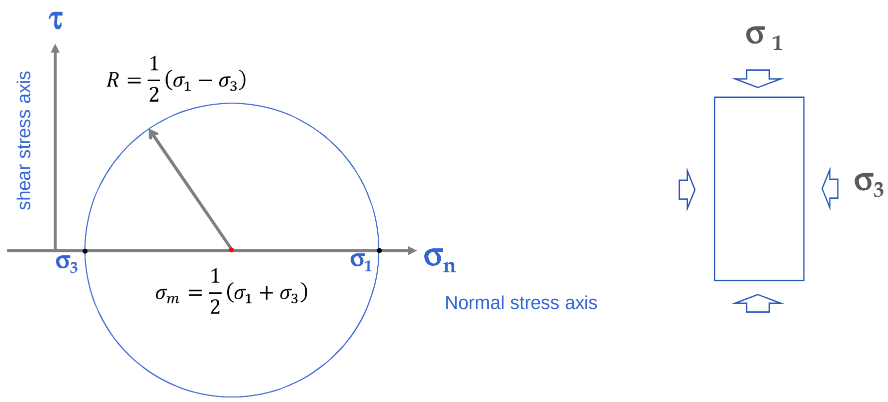
$$\upsilon = \frac{-d\varepsilon_r}{d\varepsilon_a}$$

* Assuming isotropic material

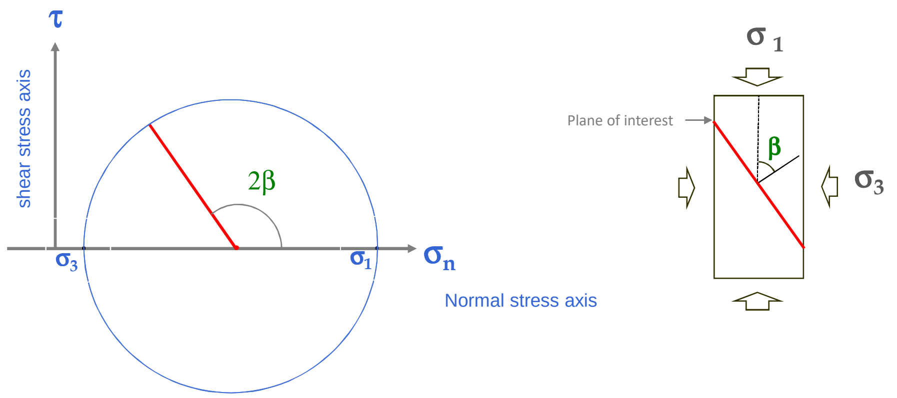
Construction and applications

MOHR'S CIRCLE

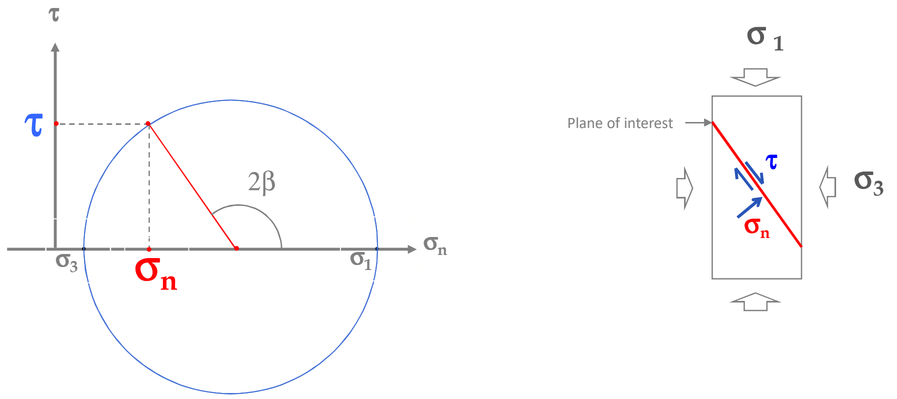
Constructing Mohr's circle



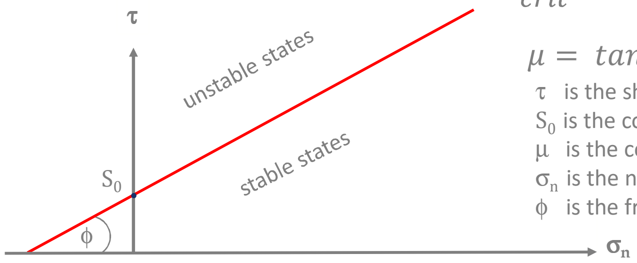
Stresses on an arbitrary plane



Stresses on an arbitrary plane



Coulomb failure criterion



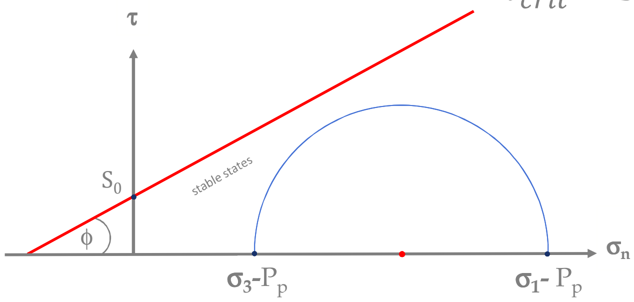
$$\tau_{crit} = S_0 + \mu\sigma_n$$

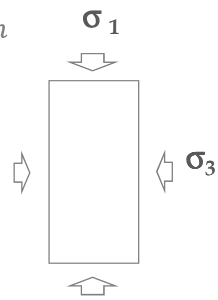
$$\mu = tan\phi$$

- τ is the shear strength
- S_0 is the cohesive strength
- μ is the coefficient of internal friction
- σ_n is the normal stress on the failure plane
- ϕ is the friction angle

A stable state of stress

$$\tau_{crit} = S_0 + \mu\sigma_n$$

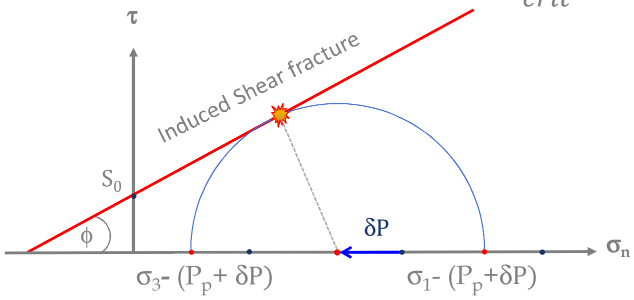


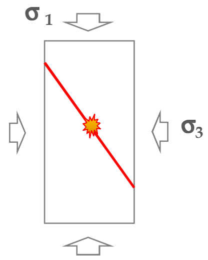


Use effective normal stresses when evaluating stability

Failure due to increased Pp

$$\tau_{crit} = S_0 + \mu\sigma_n$$

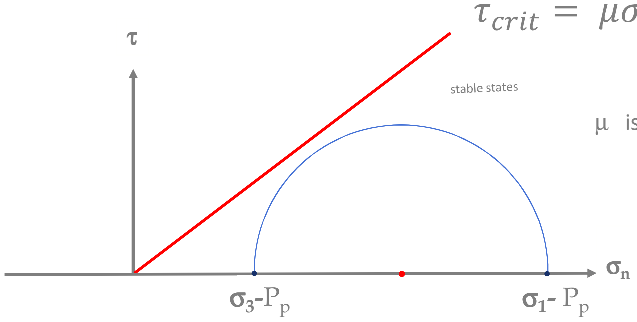




Center of the circle moves left by δP into a state of instability

Fault stability

$$\tau_{crit} = \mu\sigma_n$$



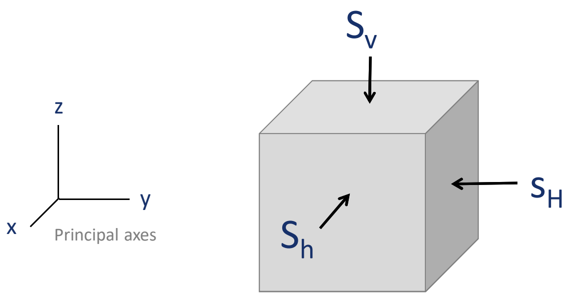
μ is the coefficient of sliding friction

For sedimentary rocks: $0.6 \leq \mu \leq 0.85$

Reference states, pore pressure, stress measurement, variations of S_h

EARTH STRESS

Earth stress as a principle stress

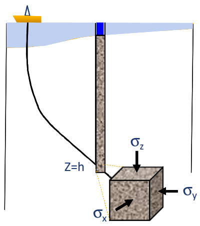


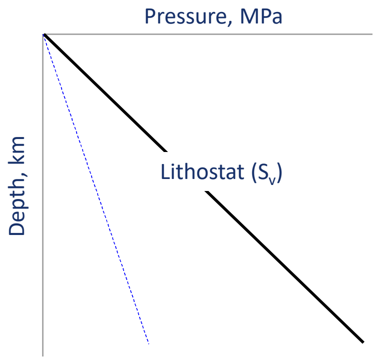
- At earth's surface, shear stresses vanish, so the vertical axis is a principle stress axis,
- by definition, the other two principle axes must be horizontal.
- This simplifying assumption fails: near active faults, areas of strong topographic relief and at salt margins.

In what follows, S_v is treated as a principle stress

Lithostatic or vertical stress S_v

Webinars





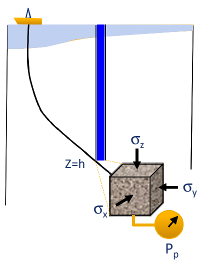
$$L = g\int_0^z \rho_b(z)dz$$

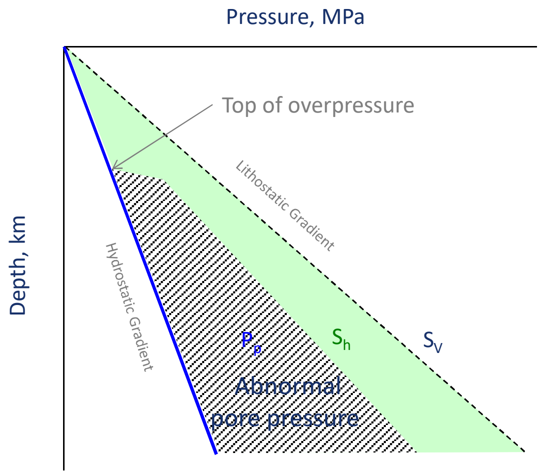
0.85 psi/ft < **L** < 1.2 psi/ft

A lithostatic gradient of 1 psi/ft (22.6 MPa/km) is a common initial hypothesis for S_v

Hydrostatic pressure and over pressure

Webinars

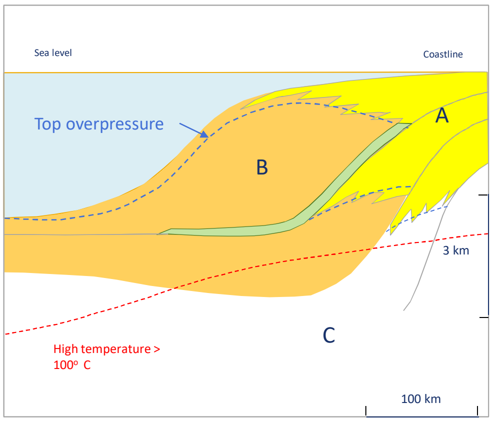




$$P = g\int_0^z \rho_f(z)dz$$

0.433 psi/ft < *P* < .465 psi/ft

Pore pressure regimes: ocean margins



After Swarbrick et al., 2011

Regime A: normally pressured sediments

Regime B: **Type 1** overpressure due to rapid accumulation of sediments.

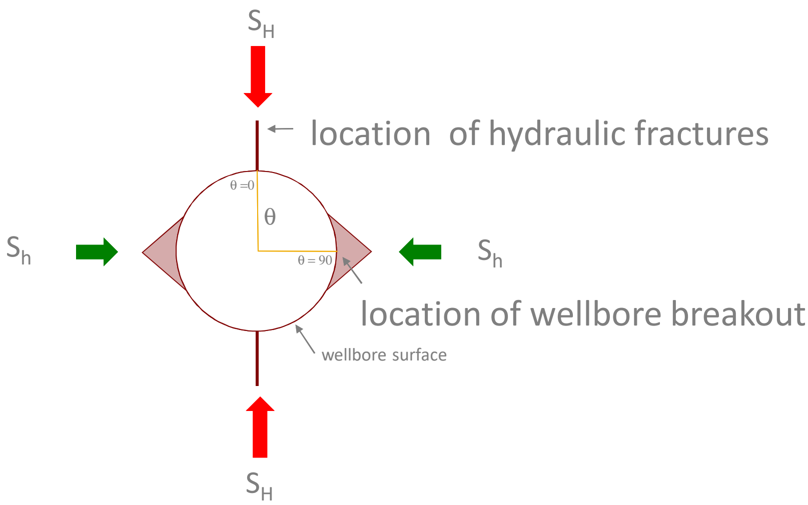
Regime C: **Type 2** overpressure due to fluid expansion and hydrocarbon maturation.

Constraining Earth stresses

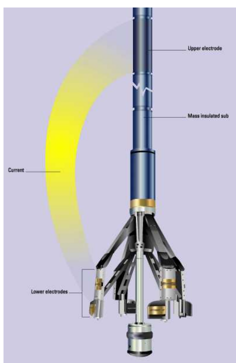
We require three principle stress magnitudes and horizontal stress directions

- S_v can be calculated from a vertical profile of bulk density.
- Stress direction can be measured using borehole images.
- S_h can be measured by hydraulic fracturing.
- S_H *cannot be directly measured* it can only be *estimated* from modeling.

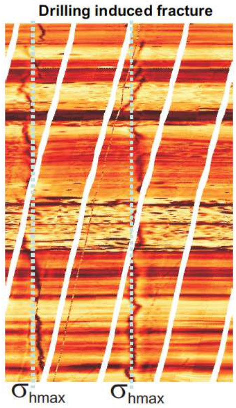
Stress direction from stress-induced wellbore damage



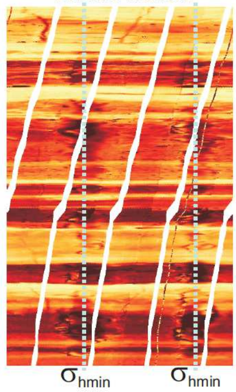
Stress direction from borehole images


Tool drawing courtesy Schlumberger

Drilling induced fracture

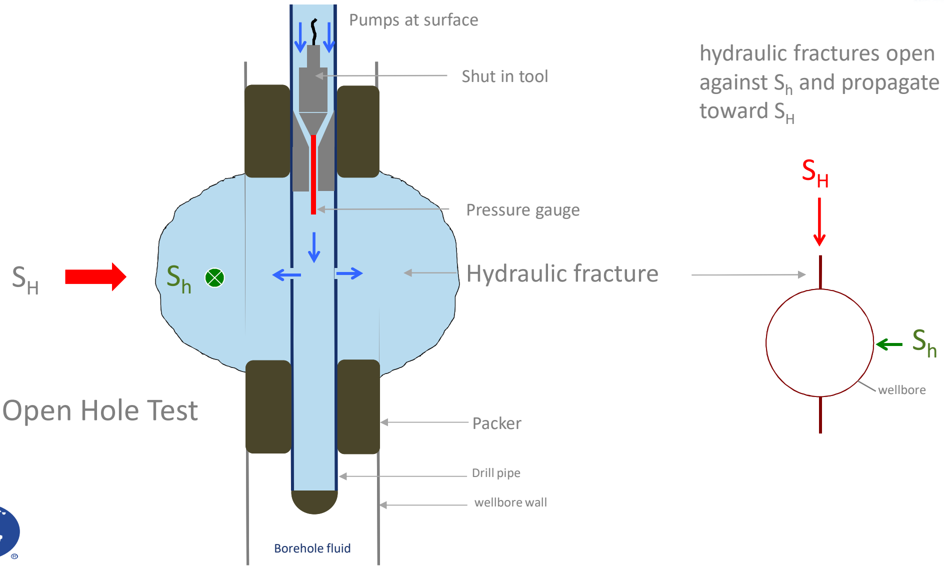


Borehole breakout

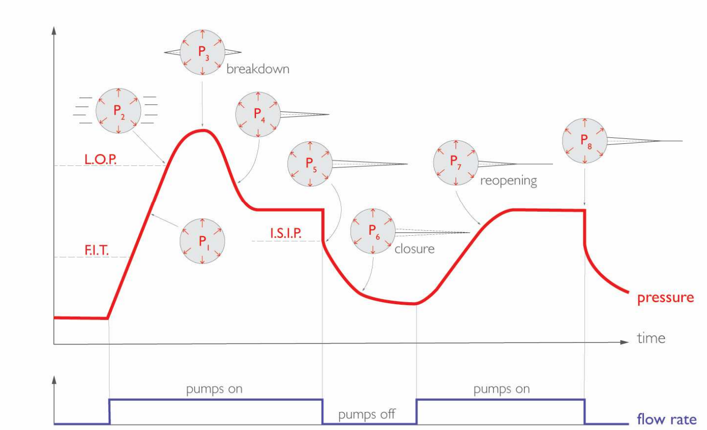


Images courtesy HEF Petrophysical Consulting

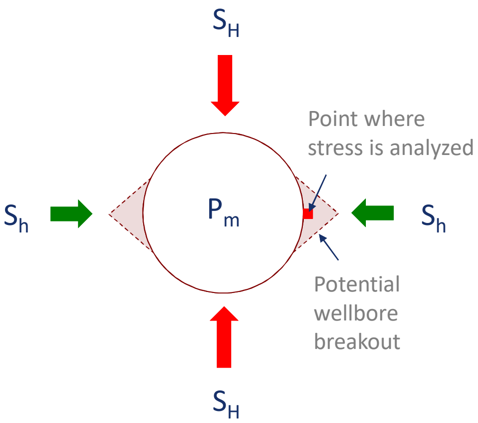
Hydraulic fracturing stress measurement

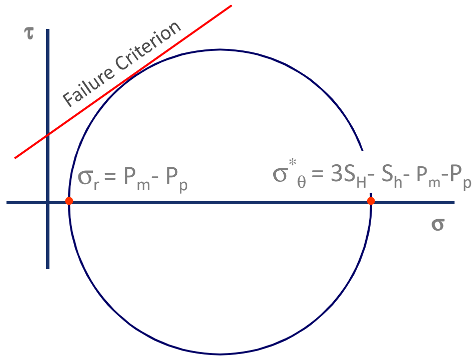


Hydraulic fracturing pressure-time record



Estimating S_H





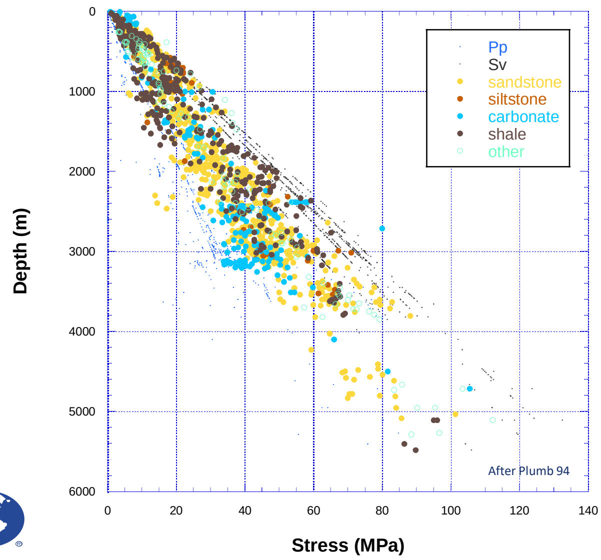
$S_H = 1/3(\sigma^*_\theta + S_h + P_m + P_p)$

σ^*_θ = effective tangential stress that satisfies the failure condition given S_h and σ^*_r

Dependence of S_h on Basin setting, pore pressure and lithology

OBSERVATIONS FROM MEASUREMENTS OF EARTH STRESSES IN SEDIMENTARY ROCK

Measurements of S_h in sedimentary rock



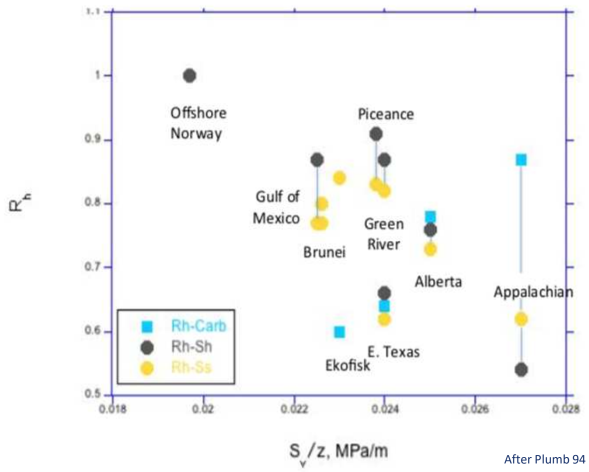
Features

- stress measured by hydraulic fracturing
- sampled 43+ basins, 20 countries

Observations

- Shales do not relax to lithostatic stress
- No obvious lithology dependence

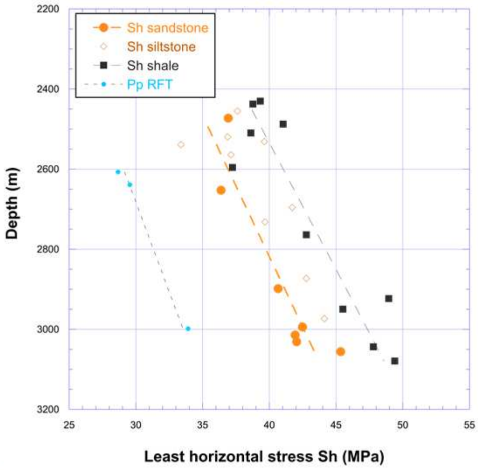
S_h dependence on basin setting



Data sorted by basin setting reveals a dependence of S_h on:

- degree of consolidation (Sv)
- lithology
- pore pressure

S_h dependence on lithology



- East Texas basin
- Measurements in a single well
- Sediments share a common diagenetic history
- Sediments are normaly pressured
- Sh shale > Sh sandstones (here)

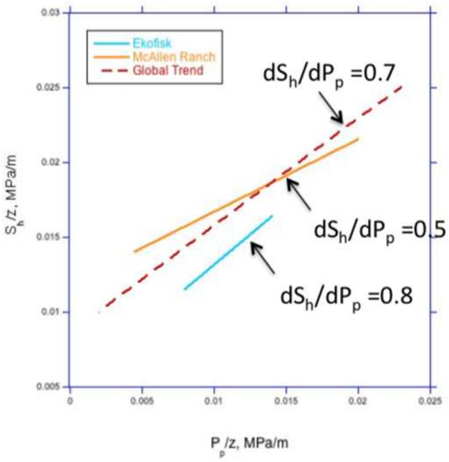
S_h dependence on P_p

Measurements of S_h are strongly correlated with P_p, as expected from poroelastic theory:

$$S_h = \left(\frac{\upsilon}{1-\upsilon}\right) S_V + \left(\frac{1-2\upsilon}{1-\upsilon}\right) \alpha P_p$$

$$\frac{dS_h}{dP_p} = \left(\frac{1-2\upsilon}{1-\upsilon}\right) \alpha$$

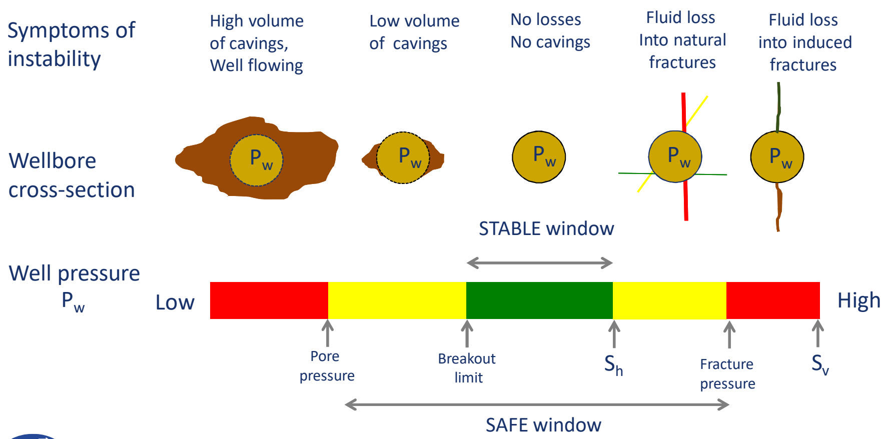
For $\alpha=1$, dS_h/dP_p ranges from 0.33 to 0.88 ($\upsilon = 0.4$ to 0.1.)



Wellbore stability, sanding, reservoir deformation, hydraulic fracture containment

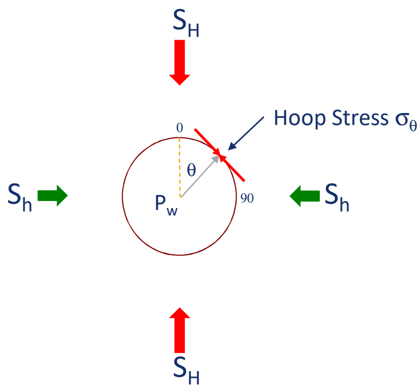
IMPACT OF STRESS ON OILFIELD APPLICATIONS

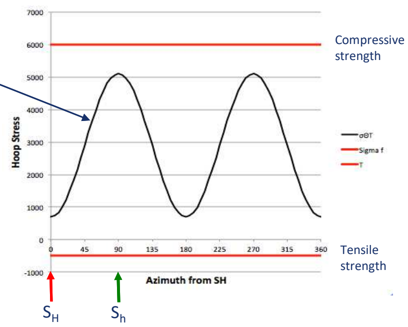
Well Pressure window P_w



Note: The window varies with depth and lithology

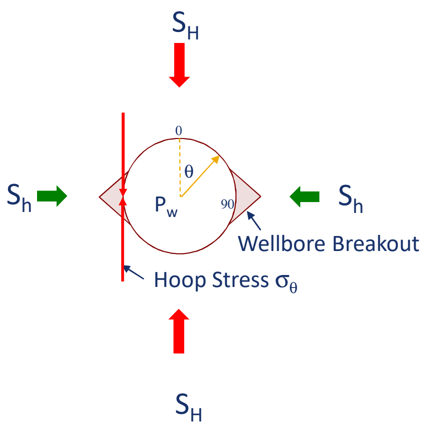
Well Pressure: just right

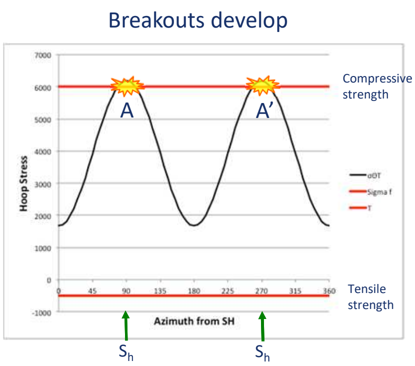




No mechanical failure at the wellbore surface

Well pressure too low

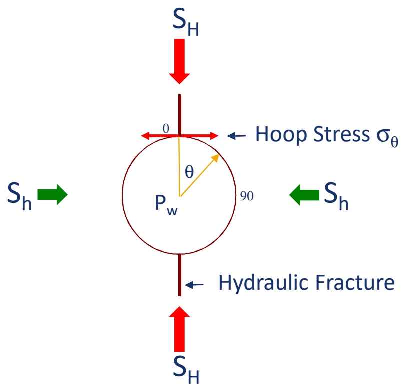


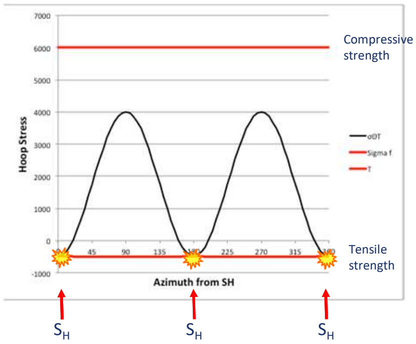


Shear failure at the azimuth of S_h

Well Pressure: too high

Webinars





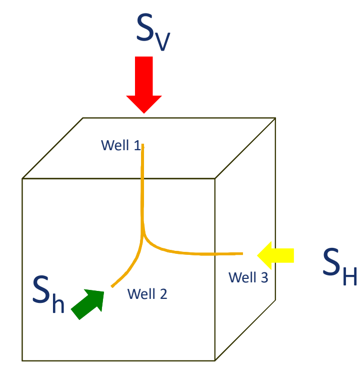
Hydraulic fractures develop

Shear failure at the azimuth of S_h

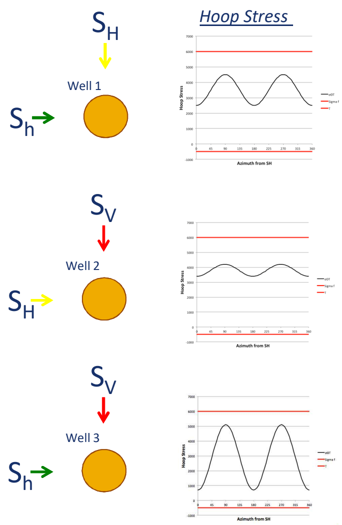
SPE International

Relative stability: deviated wells

Webinars



Example: normal faulting stress regime, $S_h < S_H \sim S_v$



Relative Stability

Intermediate

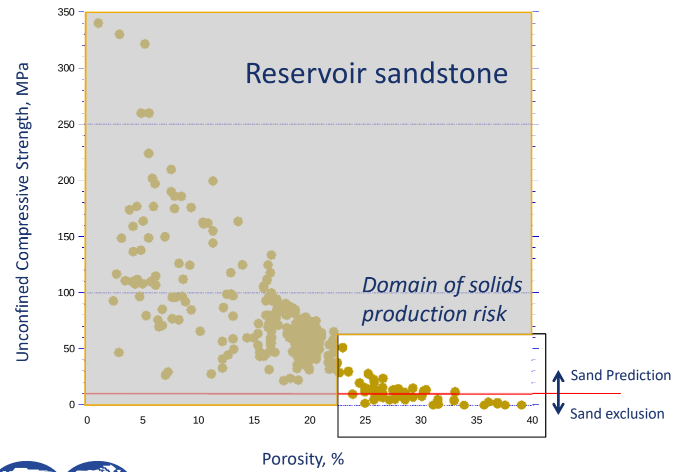
Most

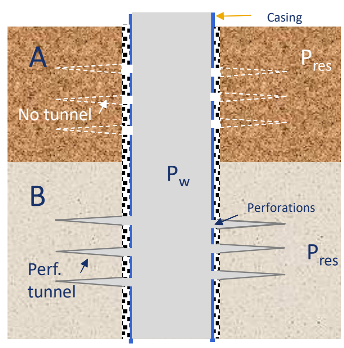
Least

Key to assessing relative stability is the difference between the far field stresses acting in the plane perpendicular to the well axis.

SPE International

Solids production risk

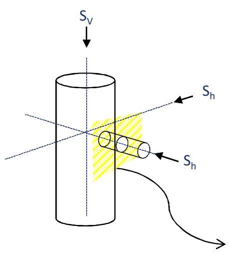




Bed A UCS < 10 MPa,
no perf. tunnel : solids exclusion

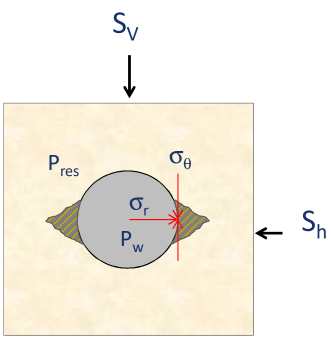
Bed B UCS > 10 MPa,
perf. tunnel exists: sand prediction

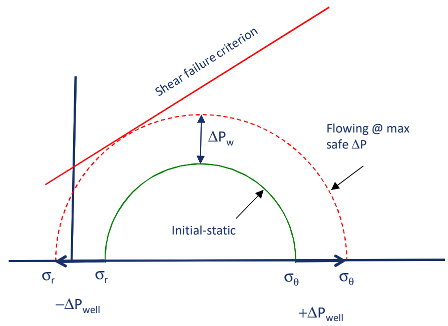
Drawdown-induced sand production



Example: normal faulting stress regime, $S_h < S_H \sim S_v$

Sand prediction example:
UCS >> 10 MPa



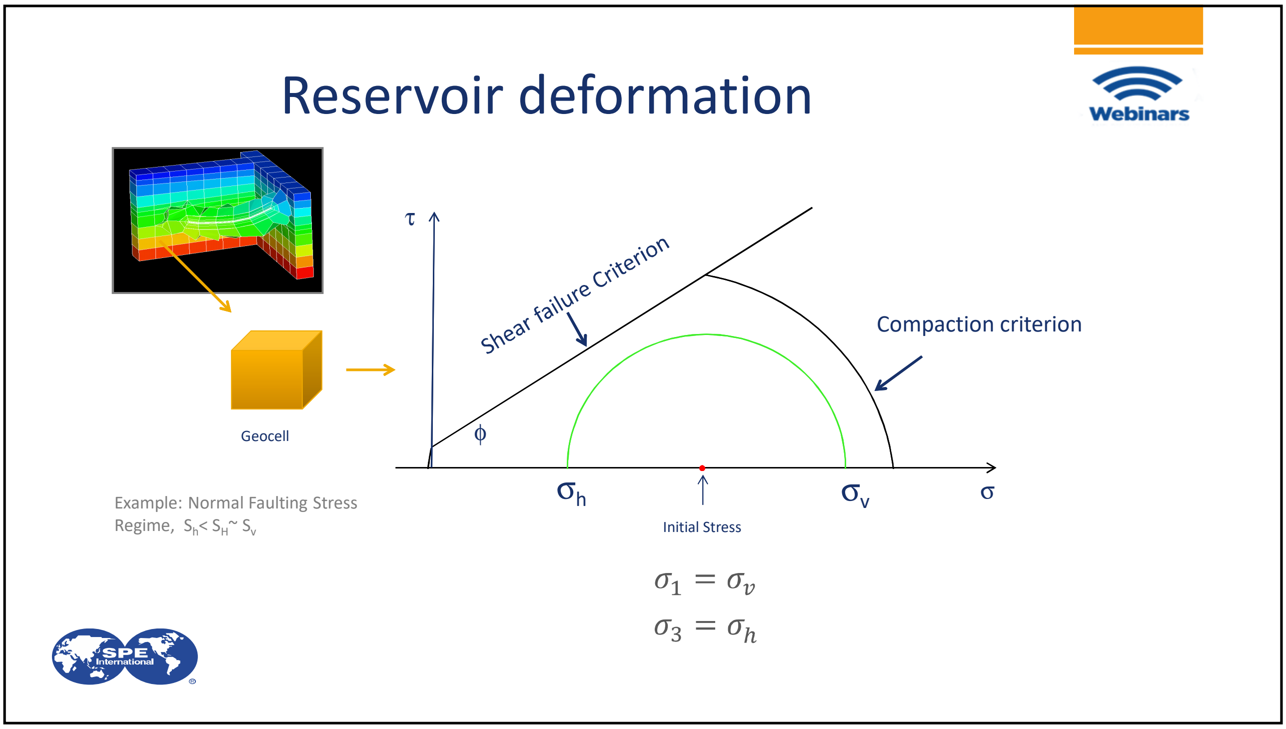


Stress analysis of the perforation tunnel

$$\sigma_1 = \sigma_\theta$$
$$\sigma_3 = \sigma_r$$

Failure is predicted on the sides of the tunnel when the critical drawdown pressure is reached.
No Failure, No Sand.

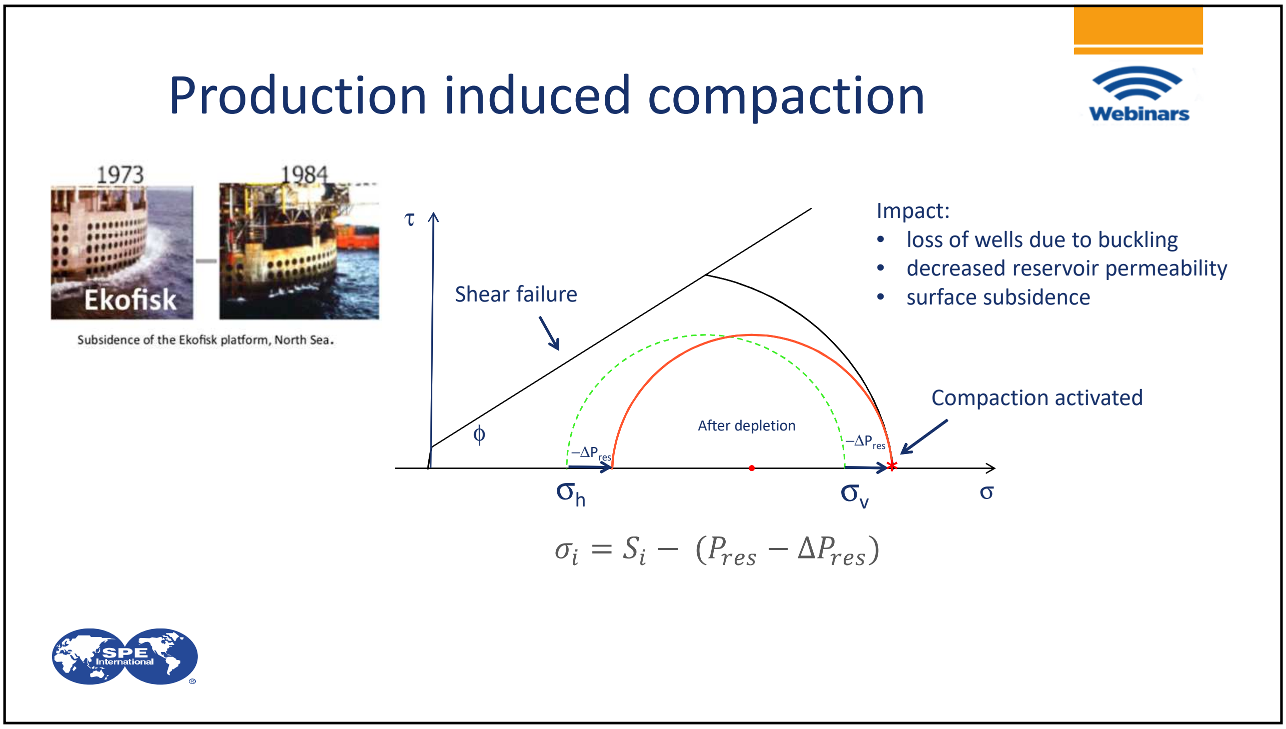
Reservoir deformation



Example: Normal Faulting Stress Regime, $S_h < S_H \sim S_v$

$$\sigma_1 = \sigma_v$$
$$\sigma_3 = \sigma_h$$

Production induced compaction



Impact:

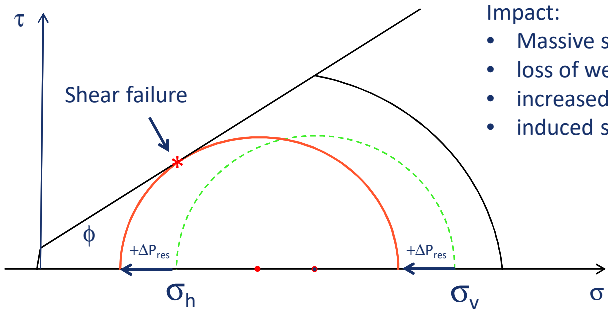
- loss of wells due to buckling
- decreased reservoir permeability
- surface subsidence

$$\sigma_i = S_i - (P_{res} - \Delta P_{res})$$

Injection-induced failure

Webinars

Massive solids production from a well



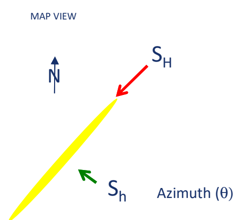
Impact:
- Massive solids product
- loss of wells due to shearing
- increased reservoir permeability
- induced seismicity

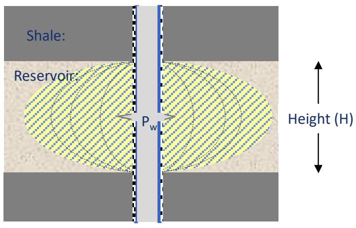
$$\sigma_i = S_i - (P_{res} + \Delta P_{res})$$

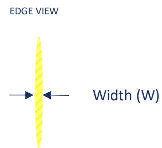
SPE International

Impact of earth stresses on hydraulic fracturing

Webinars





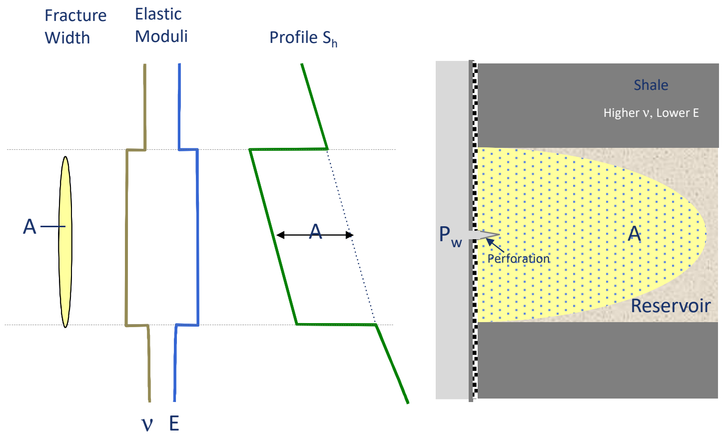


"Only" 4 Unknowns ...	Geomechanical Parameter
Fracture azimuth (θ)	S_H azimuth and magnitude of S_h and S_H
Fracture height (H)	Vertical profile of S_h (z)
Fracture width (W)	Static Young's modulus E
Fracture length (L)	L= F(H,W, volume pumped)

SPE International

When the principle stress difference is low, other factors such as natural fractures, reservoir geometry, or rock strength heterogeneity can affect propagation path.

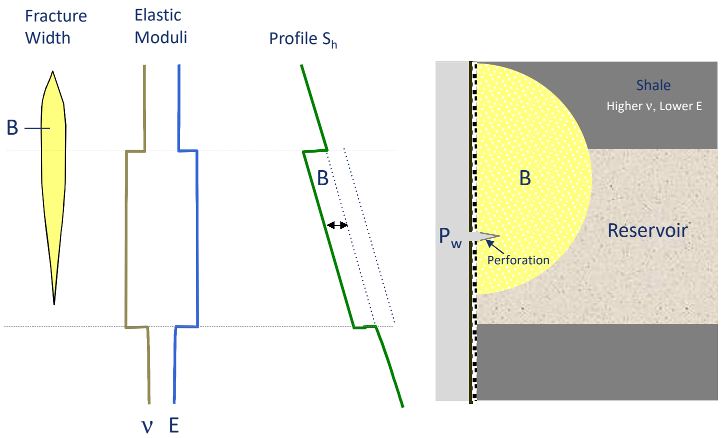
Hydraulic fracture containment



High bed-to-bed stress contrast limits hydraulic fracture height growth

Hydraulic fracture height growth

Steam injection that erupted at the surface.



Low to no, bed-to-bed stress contrast (B) does not prevent fracture height growth. Fractures can grow upward faster than they propagate into the reservoir.

Summary

Webinars

- Knowledge of contemporary stress is important for evaluating and managing the risk of subsurface rock deformation and failure.
- It is practical to *estimate* the full stress tensor using commercially available data.
- The magnitude of S_h varies systematically with S_v, P_p, lithology and basin setting.
- Changes of stress and pressure can, and do, adversely affect oilfield operations including: wellbore stability, compaction/subsidence, reservoir seismicity, fracture permeability, hydraulic fracture stimulation.
- The dependence of stress on pore pressure and lithology should be understood for each field.

SPE International

Webinars

QUESTIONS?

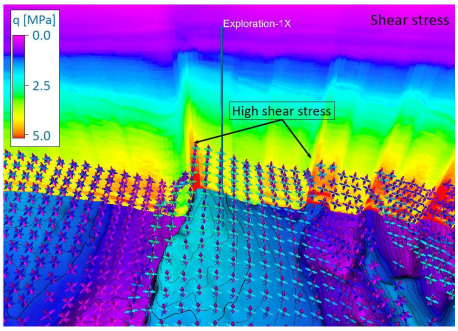
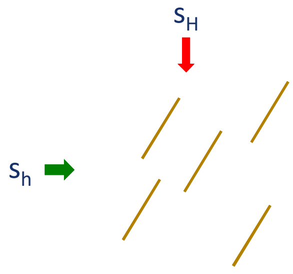


Image courtesy J. Herwanger, used with permission, EAGE Conference and Exhibition, 2010

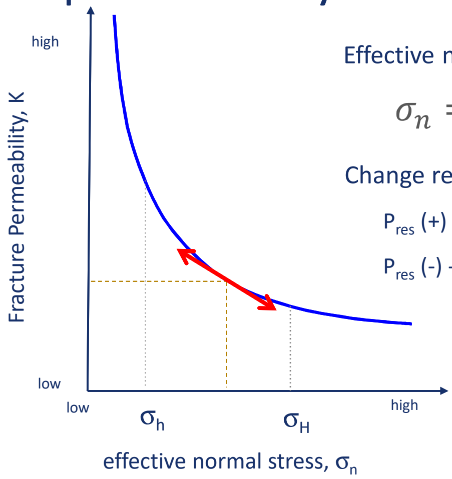
A Geomechanical model can help reduce risk and cost of unplanned events.

SPE International

Effect of stress and reservoir pressure on fracture permeability



Natural fractures-map view



Effective normal stress on fracture

$$\sigma_n = S_n - P_{res}$$

Change reservoir pressure:

P_{res} (+) -> K (+)

P_{res} (-) -> K (-)

Assumes un-cemented fractures

Important data to collect when measuring stress

- Location of the test with respect to geologic structure
- Lithology of rock where stress is measured
- S_v (from integrated density profile)
- Pore pressure (measured or estimated from min well pressure)
- Azimuth of breakouts and extension fractures (borehole images)
- Pressure and pump rate vs. time from injection tests (LOP, ISIP, P_c,)
- Rock strength (from lab measurements on cores or log-based estimates)

Nomenclature

Rock Mechanics (stress analysis)

- Principle stress σ
- Effective stress σ

Earth stress:

- Principle total stresses: S_v, S_H or S_{Hmax}, S_h or S_{hmin}
- Pore pressure: P_p
- Well Pressure: P_w or P_m