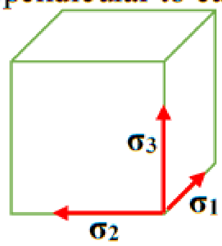
The Stress in the Earth *before* Drilling a Borehole:

Before we drill a borehole the rock in the earth is in a state of equilibrium.

In rock mechanics, we have 3 stresses in a material that are perpendicular to each other:



σ_1 Maximum Principal Stress

σ_2 Intermediate Principal Stress

σ_3 Minimum Principal Stress

These can act in any orientation in 3 dimensions.

Also (and independently from the above 3 stresses) the earth's principal stresses are defined as follows:

σ_v Principal stress acting in the vertical axis

σ_h Principal stress acting in the horizontal axis

σ_H Principal stress acting in the horizontal axis

σ_H is the maximum of the 2 horizontal stresses and σ_h is the minimum. (i.e. $\sigma_H > \sigma_h$).

The earth's stresses are related to a number of different variables including:

- Tectonic Setting
- Depth
- Pore pressure
- Lithology
- Temperature
- Structure

The relationship between stress and the above variables is complicated due to local geographical differences between basins and interdependence of the above variables. However, it can be seen that:
Intrabasin stress variations are correlated with lithology and pore pressure
Interbasin stress variations are correlated with tectonic setting and diagenesis (consolidation and cementation).
Tectonic Setting (Figure 1):

a) Normal fault regime, the vertical stress (σ_v) is the maximum principal stress (σ_1).
   $\sigma_v > \sigma_H > \sigma_h$
b) Thrust (reverse) fault regime, the horizontal stress (σ_H) is the maximum principal stress (σ_1).
   $\sigma_H > \sigma_h > \sigma_v$
c) Slip fault regime, the horizontal stress (σ_H) is the maximum principal stress (σ_1).
   $\sigma_H > \sigma_v > \sigma_h$

Depth:
In practice it is observed that at **shallow depths** the minimum principal stress is the vertical stress. Here a hydraulic fracture is most likely to occur in a *horizontal plane*.
At greater depths the principal stresses generally follow fault regimes described in Figure 1. For example, in a normally pressured sedimentary basin, the minimum stress σ_3 is most probably in the horizontal plane at depths greater than 3300 ft. (Plumb). This stress scenario is probably the most common to be found in the oilfield.

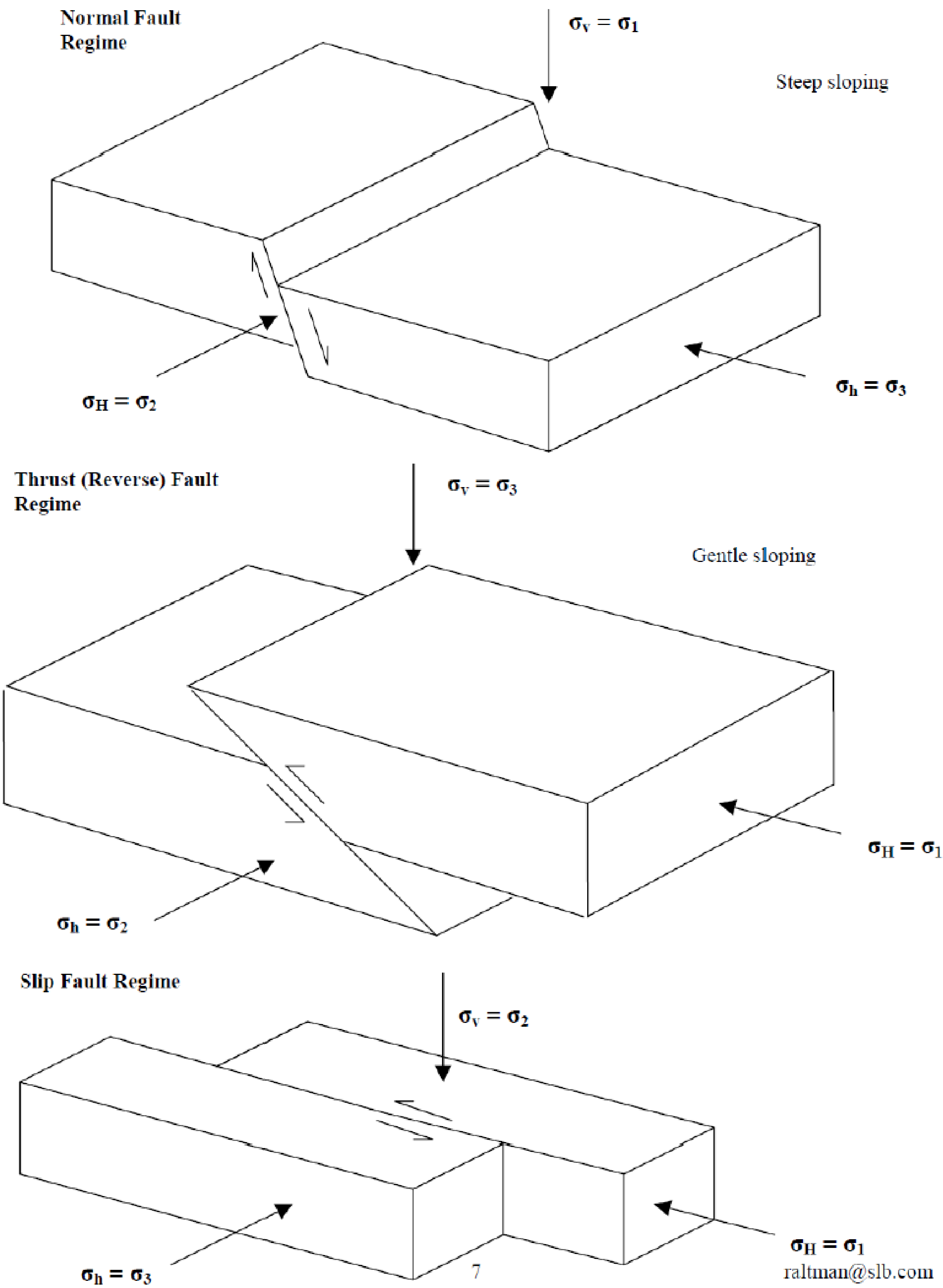


Figure 1: Tectonic dependence on earth stresses

Generally, the vertical stress is **depth dependent** and expressed as follows:

$$\sigma_v = \int_0^H \rho(H) g dH$$

$\rho(H)$ = density of rock at given depth H (from density log or core sample)

g = gravity

Hence the value of this stress component is obtained from the integration of a density log.

σ_v is known as the **Overburden Gradient** and varied from 0.8 psi/ft. in young, shallow formations (e.g. Gulf Coast) to 1.25 psi/ft. in high-density formations.

Given the density of quartz (1.65 g/cc) the overburden gradient ranges between 1.0 and 1.1 psi/ft. for brine saturated sandstone with porosity ranging between 20% and 7% respectively.

If tectonic loading is present yielding horizontal compressive forces, then we cannot use this expression for vertical stress.

Pore Pressure:

Pore Pressure supports a portion of the total applied stress in a rock.

In general:

Total stress (in given direction) = Effective Stress of Rock Grains (given direction) + Pore Pressure

If a formation is "normally pressured" the pore pressure mechanism can be described as following:

Sediment burial → full pore fluid escape → porosity decreases → effective rock stress increases → pore pressures are hydrostatic (normal)

A "Cam-Clay" law under these (normal) conditions shows how porosity evolves with depth:

$$\frac{\emptyset}{1-\emptyset} = \frac{\emptyset}{1-\emptyset_0} - \lambda \ln[gz(\rho_b - \rho_w)]$$

$\emptyset$ = Porosity at a given depth

$\emptyset_0$ = Initial porosity of material

λ = Compressibility coefficient (constant)

ρ_b = Density of rock

ρ_w = Density of water

z = Vertical Depth

(i.e. at surface z = 0 and ln0 = –∞, hence $\frac{\emptyset}{1-\emptyset} = +\infty$ and $\emptyset \to \infty$ or 100% porosity)

If a formation is "over-pressured" the pressure in the formation is greater than the pressure exerted by a column of water at that same depth.

3 mechanisms have been proposed:

a) *Loading mechanisms*:

Sediment burial → pore fluid escape fully restricted → porosity & effective stress are both constant → pore pressures increases at the same rate as the overburden (i.e. overpressure)

– Restricted fluid escape may occur in thick low-permeability shale sections.

– Depends on: rate of sediment compaction Vs rate at which fluid is expelled (higher this ratio the more likely that overpressure occurs).

– Also depends on: pore fluid compressibility. The lower the compressibility of the pore fluid, the worse the overpressure. This is because the overall rock is stiffer and this will lower the efficiency of pore fluid expulsion.

b) *Unloading mechanisms*:

When unloading occurs, stress is relieved and sediments do not revert to their original state.

2 natural mechanisms occur that can cause 'unloading'.

(I) Aquathermal expansion / hydrocarbon generation / mineral dehydration (smectite → illite) /osmosis → sealed formation → fluid-volume increase can result in rapid pore pressure increases that unload the rock grain matrix.

(ii) Uplift / Erosion → unloading rock grain matrix → sealed formation → formation has same pore pressure as before but due to closed system is abnormally pressured compared with neighbor formations at same depth.

c) *Tectonic Stress*:

Horizontal tectonic stress → Very low permeability seal (e.g. non-communicating fault) → rate of pore fluid escape cannot keep up with additional tectonic stress → system does not fracture / fault to relieve stress → pore pressure increases.

Terzaghi proposed the following relationship:

$$\sigma' = \sigma - p$$

σ'= Effective rock stress (in a given direction)

σ = Total applied stress (in a given direction)

p = Pore pressure

Biot proposed an equation to account for the following: any change in pore pressure is accompanied by variation in pore volume – this change in pore volume affects the overall mechanical response of the rock:

$$\sigma' = \sigma - \alpha p \qquad (1)$$

α = Biot's constant (varies between 0 and 1)

$\boldsymbol{\alpha}$ describes the efficiency of the fluid pressure in counteracting the total applied stress.

If $\boldsymbol{\alpha} = \mathbf{1}$ this means that the pore fluid has maximum efficiency in counteracting the total overburden stress ($\boldsymbol{\sigma_v}$) and therefore implies that the effective stress of the rock is lower, a pessimistic condition for rock failure.

If **α < 1** this means that the pore fluid is less efficient in counteracting the total overburden stress (**σ_v**) and the effective stress of the rock is greater.

α is close to 1 for stiff rocks and close to 0 for rocks with low stiffness

In Petroleum Rock Mechanics always ***effective rock stress*** σ' (not total rock stress) is used in calculations.

Lithology:

The effect of lithology on earth stresses is complicated.

To analyze the effect on horizontal stresses, we define **R_h**:

$$\mathbf{R_h = \sigma h / \sigma_v}$$

σ_h = horizontal stress

σ_v = vertical stress

R_h is merely the normalized horizontal stress - we cannot just compare horizontal stresses for the various lithologies. We need to remove the dependence of vertical stress **S_v**.

For example, if a lithology has a high **σ_h**, this could be due to there being a high **σ_v**. The high **σ_v** could have the effect of "squeezing out sediment laterally". Assuming there is a lateral force (at large distances) to counteract this, **σ_h** will then be higher.

Relaxed-state Basins:

R_h Carbonates < Rh Sandstones < R_h Siltstones < Rh Mudstones < R_h Shales

The Poisson's ratio **ν** for sands is generally **lower** than for shales. This implies that shales have greater affinity for lateral expansion.

The lateral expansion encounters lateral forces of resistance causing the greater lateral stress in shales.

Compressed-state Basins:

R_h Shales < R_h Sandstones

This is characterized by **higher** stress magnitudes in elastically stiffer rocks. Sandstones are generally stiffer than shales.

Pore pressure effects:

R_h generally **increases** for overpressured formations (in relaxed-state basins) due to the formation becoming more elastic.

Fractured rocks:

R_h **decreases** (is generally lower than 0.7) in naturally fractured lithologies (e.g. carbonates). These rocks are more brittle and lateral stresses are released as microfractures.

Temperature:

A reduction of temperature (e.g. injection of cooler injection fluid) causes a reduction in the rock stress.

The cooler temperature acts to contract the rock – if the rock is confined on all sides (which it always is) by a stress of some kind, the rock will contract leaving a ‘void space’ and weakness which could favor a tensile failure as a reduction in the rock stress.

Structure:

In a typical anticline structure the lowest stress magnitudes are found at the crest of the structure while greater stresses are found along the flanks.

The crest is usually under a greater tensile state whereas the flanks are under a greater compressive state.