

PETE4313 – Drilling Engineering and Well Completion

Course Program

Introduction to drilling; duties of the drilling engineer; overview of petroleum engineering geology; fluid flow in porous media with emphasis on wellbore pressures and control and basic rock properties.

Drilling; rig types, components and selection; overview of drilling operations; planning and cost control; drilling optimization, drilling fluids and mud systems with lab; drilling hydraulics; well control and directional drilling.

Well design; casing design and casing seat selections; cementing and formation damage.

Introduction to well completions.

Well stimulation - hydraulic fracturing and matrix acidizing.

Special drilling and completion topics.



ENGR4313 Handout#1

“Introduction to Drilling”

1. Introduce the duties of the drilling engineer
2. Oil and Gas Wells (Nature and Entrapment of Oil and Gas)
3. Introduction to the physics of flow in porous media with pressure concerns in designing an oil well drilling operation
4. Solid Mechanics/Rock Properties



Drilling a Well!

Why do we drill wells?

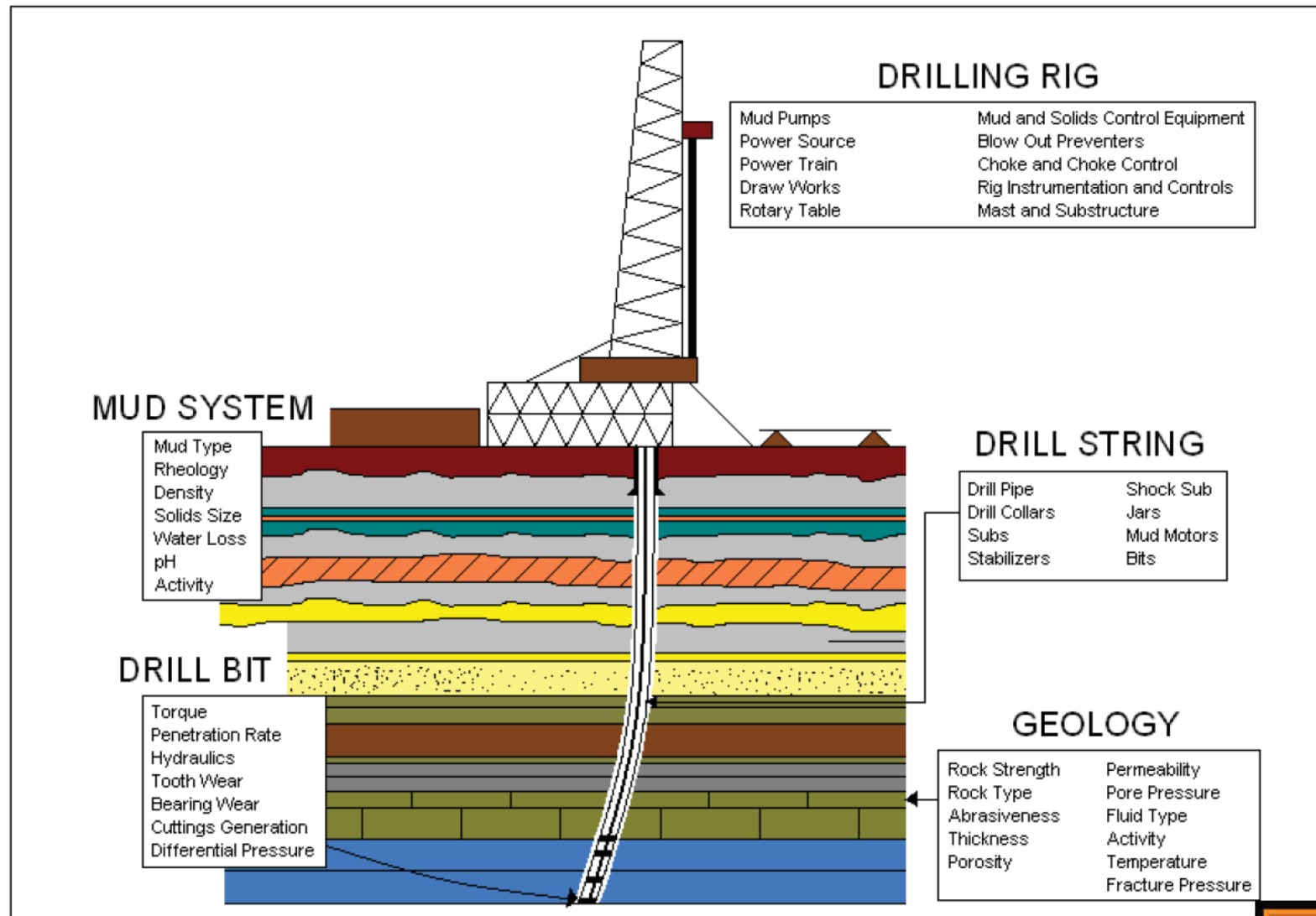
How do we drill wells?

Duties of an engineer?

Drilling engineers duties?



The Drilling System



Drilling Engineering

“Duties of the Drilling Engineer”

Some Specific Duties

1. Collection of offset data
2. Pore pressure plots and prediction
3. Casing point selection and design, manual calculation and computer application of casing design criteria
4. Cement design, properties for primary cementing and squeeze cementing, mixing and placement techniques, spacer design etc.
5. Drilling fluid (Mud) design (water-based and oil-based systems)
6. Directional drilling (tools and mechanics)
7. Drill bit selection, hydraulics and recommended WOB and RPM. (mud motor, rotary steerable or turbine based on economics)
8. Solid control equipment and optimization

Drilling Engineering

“Duties of the Drilling Engineer”

Some Specific Duties (cont.)

9. Mud logging requirements
10. Wireline logging requirements
11. Well control procedures and equipment
(diverters, annular bag preventers, ram type preventers, manifolds, chokes etc. BOP (Blow Out Prevention) school certification)
12. Wellhead equipment and design
13. Pre-spud presentation of drilling program
14. Daily review of well status, field personnel and contractors
15. Rules and regulations

Kristen - Drilling Engineer - Oklahoma

<https://www.youtube.com/watch?v=0NZFokQsj8E>

Cindy – Drilling Engineer - Canada

<https://www.youtube.com/watch?v=c83CvjQ6nYE>



Drilling Engineering

“Duties of the Drilling Engineer”

Scoping Well Cost Estimates

Well plans and associated “scoping” well cost estimate drilling and typically completions cost

“Drilling and Completion Program”

Complete the “Drilling and Completion Program” plan, circulate for approval and distribute

Monitor Drilling Operations (Daily progress and rig communication)

1. Analysis of mud trends, recommended treatments
2. Tracking of directional progress, inclination and azimuth
3. Analysis of pore pressure trend, recommended mud weight
- Hole conditions i.e. gains/losses, gas trends; recommended course of action
- Troubleshoot all deviations from plan

Pason System – Login – Well Demo! www.pason.com



Drilling Engineering

“Duties of the Drilling Engineer”

Prepare Engineering Material Requests

1. Prepare detailed material requests for approval by drilling superintendent (mud, casing, etc.)
2. Specification of necessary certification requirements to be included

Equipment Evaluation

1. Bits, turbines, motors, coring equipment, drillstring, BOPs, liner hangers, float equipment, etc.
2. Rig evaluation

Tubular Forecasting

1. Design and forecast tubular needs for drilling and completion operation
2. Computer application of spreadsheets

Special Projects

Report on implementation of new technologies, rig selection criteria, long range planning and design work, evaluation of other operator's designs and procedures i.e. casing design, shallow gas philosophy, oily cuttings discharge, etc.



Drilling Engineering

“Duties of the Drilling Engineer”

Special Projects

Report on implementation of new technologies, rig selection criteria, long range planning and design work, evaluation of other operator's designs and procedures i.e. casing design, shallow gas philosophy, oily cuttings discharge, etc.

Post Analysis

1. Post appraisal of non-typical events, input to final well report, drilling curves and cost comparisons
2. Computer application of drilling database and PC spreadsheet



General Petroleum Introduction

- What is the purpose of drilling?

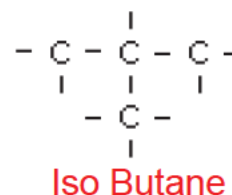
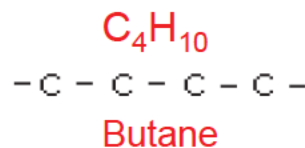
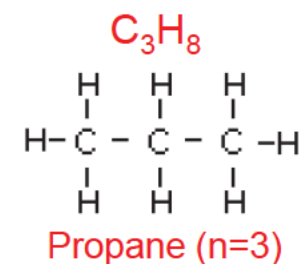
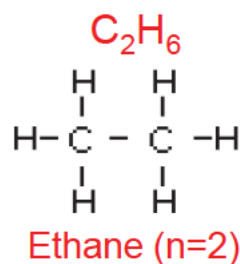
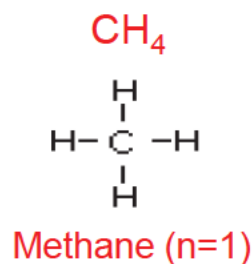
To discover natural resources such as oil, gas, coal, water and brine (water saturated with or containing large amount of salt, NaCl)

- What does the term "Petroleum" mean?

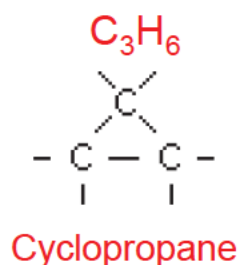
Petroleum: Mixture of hydrocarbons which may be either gas, liquid or solids, depending upon temperature, pressure and composition.

- What is the three basic types of hydrocarbons?

1. Paraffin - group of saturated hydrocarbons having the general formula C_nH_{2n+2} the simplest and most abundant of which is methane.

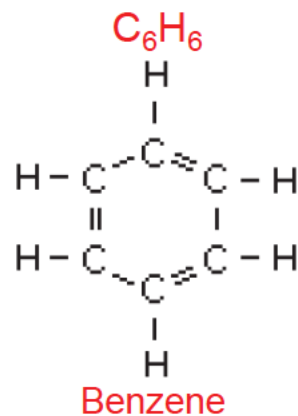


2. Cycloparaffin - class of hydrocarbons, in which at least three carbon atoms per molecule are joined in a ring structure and each such carbon in the ring is bonded to two hydrogen atoms or alkyl (C_nH_{2n}) groups having the general formula: C_nH_{2n}



3. Aromatic - class of hydrocarbons, containing the six carbon ring characteristics of benzene series or related organic groups.

General formula: C_nH_{2n-6}



- What is a typical composition of “Dry” Natural Gas?

	<u>Vol %</u>
Methane (CH ₄)	90.12
Ethane (C ₂ H ₆)	4.03
Propane (C ₃ H ₈)	1.52
n_Butane (C ₄ H ₁₀)	.73
iso_Butane (C ₄ H ₁₀)	.36
Pentane (C ₅ H ₁₂)	.50
Hexane (C ₆ H ₁₄)	.16
Heptane (C ₇ H ₁₆)	.25
CO ₂	.60
Nitrogen (N ₂)	1.73



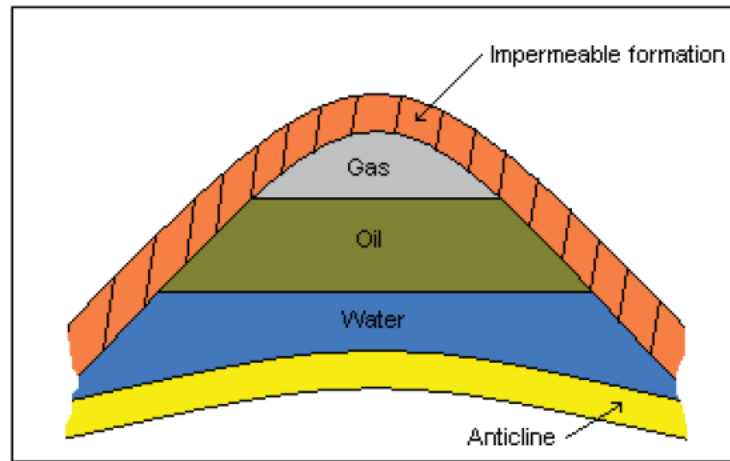
Origin of Petroleum

- Animals and plants have been altered by heat, bacterial action, pressure and other agents over long periods of time
- Petroleum is most often formed in shales, always in sedimentary rock
- Petroleum migrates to isolated rock (usually sedimentary) under gravity and pressure forces
- Usually oil migrates from less permeable rock to more permeable rock
- Petroleum almost always has a specific gravity less than water
- Petroleum reservoir is the rock region where the petroleum is deposited
- Classical geological features needed to accumulate petroleum are:
 - a permeable, porous stratum which is the reservoir (or container) for the petroleum
 - an overlying impermeable bed (sealing)
 - a trap for the petroleum, which prevents further migration (structure or permeable barrier)
- Unconventional oil and gas entrapment in rock matrix (but we access rock matrix oil and gas through “fracking” not necessary drainage through pressure drive mechanism)



Classification of Reservoirs

- Structural trap (deformed)

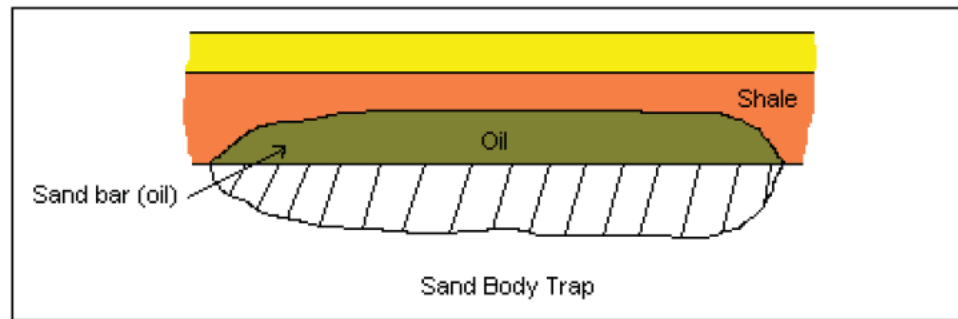


An anticline is a simple fold that traps hydrocarbon in its crest

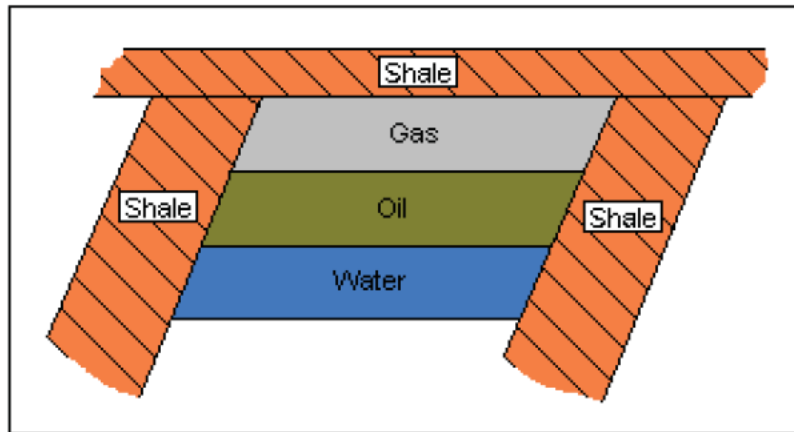
Where would you land a horizontal well in this structure?

- Other types: Fault, salt related

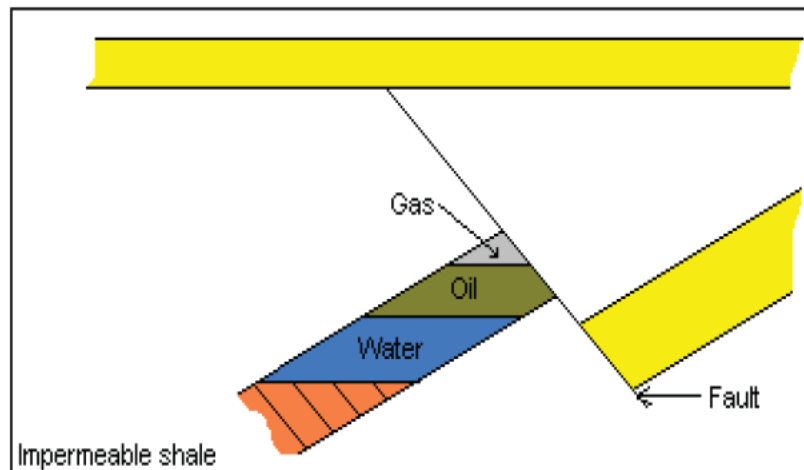
- stratigraphic trap (formed by depositional and sedimentary factors)



- Angular unconformity trap

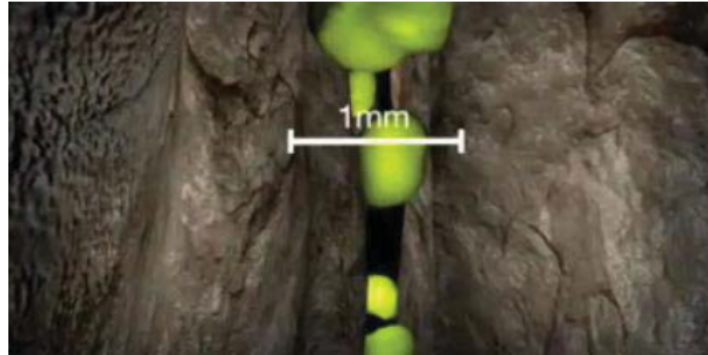


- Combination trap



Shale Oil/Gas

- oil/gas trapped in the rock matrix

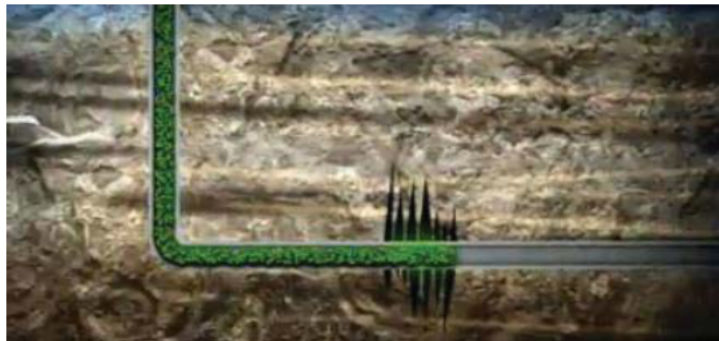


- use fracking

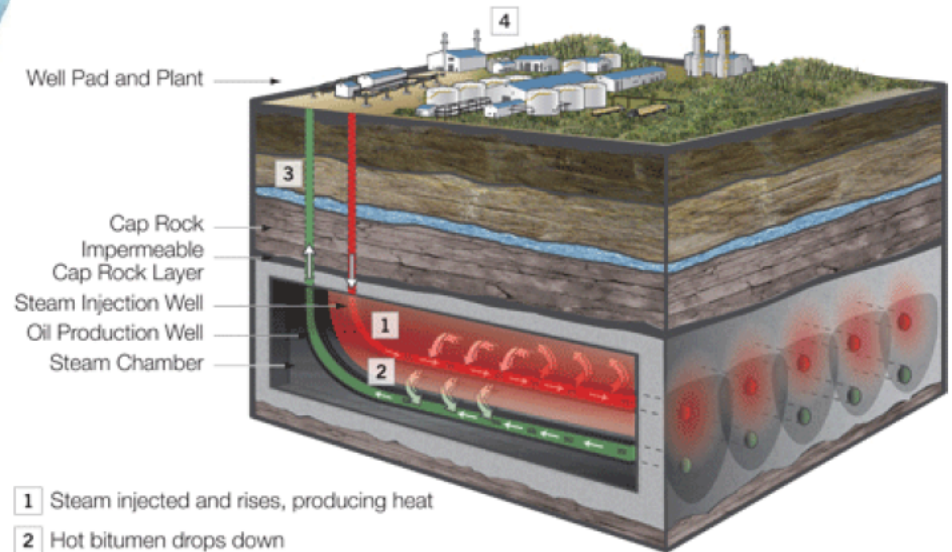
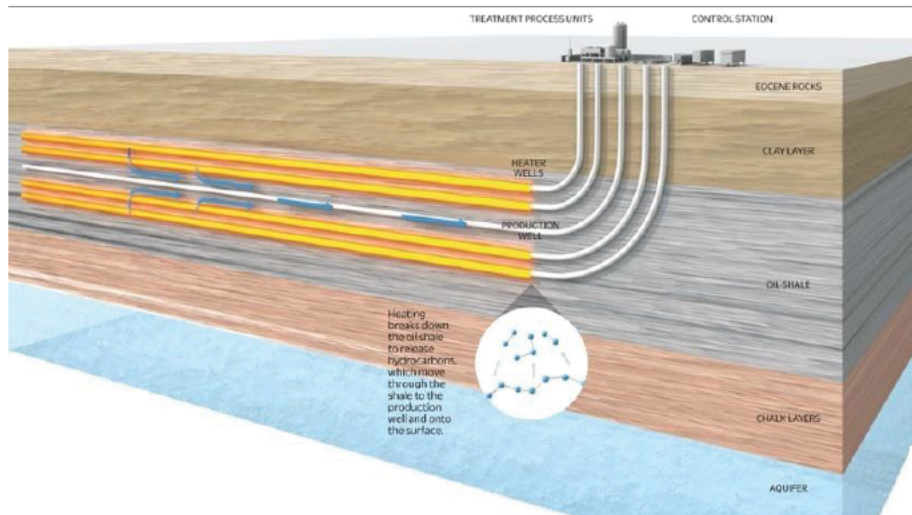
Perforate



Frack



Unconventional Oil (SAGD - Steam Assisted Gravity Drainage)



- 1 Steam injected and rises, producing heat
- 2 Hot bitumen drops down
- 3 Hot bitumen emulsion produced from lower well
- 4 Bitumen and hot water separated at surface; dilbit sold, water cleaned and recycled



Common Types of Reservoir Drive Mechanisms

- Gas Cap Drive: The pressure exerted upon the fluids in a reservoir by a gas cap above the oil can produce the oil as well as the gas. As the gas is under pressure, it is compressed and expands when the reservoir is produced. Pressure reduction is slower than with dissolved gas drive
- Water Drive: Expansion of reservoir formation water is responsible for production of oil by a formation water drive
- Solution Drive: When reservoir pressure drop because of production gas dissolved in the oil expands and is released, forming a gas phase. As expansion occurs, fluids remaining in the reservoir are swept toward the wellbore, accompanying the characteristically rapid pressure decline

Types of Drilling Wells

- Wildcat: New well in area unknown for production
- Production: Well drilled in area or field with known production

Abbreviations

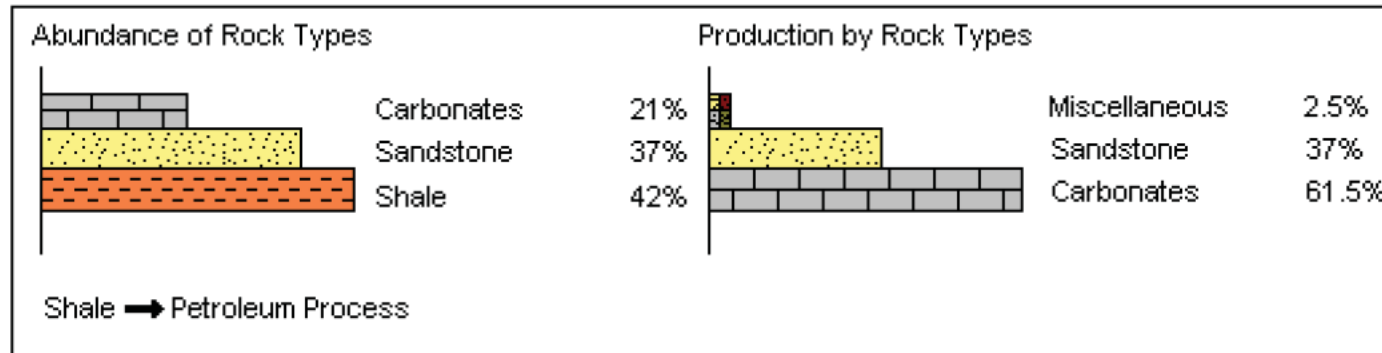
SPE, IADC, API, AADE



The Habitat of Oil and Gas (excluding shale oil/gas) mainly due to Migration

Although most origin theories use shale as origination for oil and gas

- ❑ - Oil and gas occurs in sandstone, carbonates (limestone and dolomite) and shale
- ❑ - Production reservoirs are almost all sandstone and carbonates



- ❑ - Note that this was before the shale oil/gas boom due to fracking!
 - ❑ - Shale oil/gas is now the main onshore contributor to the production in the US and Canada.
 - ❑ - Today US produces onshore mainly from shale (like Marcellus, Eagle Ford)
 - ❑ - We are also producing unconventionally from tight carbonates.
-
- Oklahoma examples are the Woodford/Haynesville/Springer Shale and Mississippian Lime
 - SCOOP (South Central Oklahoma Oil Province)
 - STACK (Sooner Trend Anadarko Basin Canadian and Kingfisher)



Shale → Petroleum

Material Matter > 99% 1%

Source

90% Kerogen which releases petroleum when heated - Organic Matter

10% Bitumen - Occurs in: asphalt and tar

- Use: surface roads, waterproofing

Generally, shales are deposited in near coastal waters of oceans or inland seas. In such regions the marine life flourishes and there is less vegetation. Closer to shore are larger clastic (broken) rocks, but with higher percentage of vegetation

<https://www.youtube.com/watch?v=8YHsxXEVb1M> (3 Min)

https://www.youtube.com/watch?v=_PDOD_FEnNk (2 Min)



Definition of Sedimentary Rocks

- Shale: A fissile (capable of being split) rock composed of laminated layers of clay-like, fine grains
- Sandstone: Sedimentary rocks composed predominantly of sand-like quartz grains cemented by lime, silica or other materials
Quartz: hard, crystalline, vitreous (glassy) mineral, silicone dioxide (SiO_2), in sandstone, granite (i.e. pure: chert, opal)
- Dolomite: A light-tinted, gray, pink or white mineral, especially $\text{CaMg}(\text{CO}_3)_2$ (resembling limestone)
- Limestone: Chiefly CaCO_3 containing magnesium, carbonate and quartz
Ex. Building stone - manufacturing of lime, carbon dioxide and cement

Diagenesis Process (Kerogen to Petroleum)

The process of chemical and physical change in deposited sediment during its conversion to rock.

- Pressure
- Temperature
- Time
- Possibly bacterial action



Properties of Liquid Petroleum

$$\text{API Gravity (degrees)} = \frac{141.5}{\text{SP.GR}} - 131.5$$

* API 10 ° is equivalent to SP. Gr. of 1.0

- Price on product (from well head) is dependent on gravity
 - higher gravity, more \$ (more valuables like gasoline)
 - lower gravity, less \$ (more asphalt etc.)

Oil at reservoir condition always contains in solution some components which would be gases at standard temperature and pressure (60 ° F, 14.7 PSI)

As oil is produced, the reservoir temperature and pressure is reduced. This reduction causes:

- Vaporization, which causes
- Liquid volume to shrink
- Liquid viscosity to increase



Basic Rock Properties

Porous and Permeable Beds (Reservoir rock)

After formation of petroleum the fluid will migrate into other porous and permeable beds. This migration will continue until the petroleum is trapped

Factors causing migration:

- **Compaction** of sediments as depth of burial increase
- **Tectonics**; movement of the crust causes a differential pressure and subsequent fluid movement.
- **Capillary** forces causes oil to be expelled from fine pore by the preferential entry of water.
- **Gravity** which promotes fluid segregation according to density differences

Porosity is the measure of the void space within a rock expressed as a fraction of the bulk volume of the rock

In general:

$$\phi = \frac{V_{\text{bulk}} - V_{\text{struct}}}{V_{\text{bulk}}} = \frac{V_p}{V_{\text{bulk}}}$$

- | | |
|---------------------|---------------------------------------|
| ϕ | - porosity |
| V_{bulk} | - bulk volume of rock |
| V_{struct} | - net volume by solids (grain volume) |
| V_p | - pore volume |



Basic Rock Properties

Absolute Porosity - Total porosity of rock regardless of whether or not the pores are connected

Effective Porosity - Only the porosity due to voids which are interconnected

Effective porosity is of interest to the petroleum industry. In most oil reservoirs the absolute porosity is the same

Permeability (Darcy's Equation)

Henry D'arcy - French Hydrologist, studied flow of water through unconsolidated sands, and formulated:

$$V = -\frac{k}{\mu} \cdot \frac{\Delta p}{\Delta l} = \frac{Q}{A}$$

where,

V = apparent flow velocity (m/s)

μ = viscosity of flowing fluid (Pa-s)

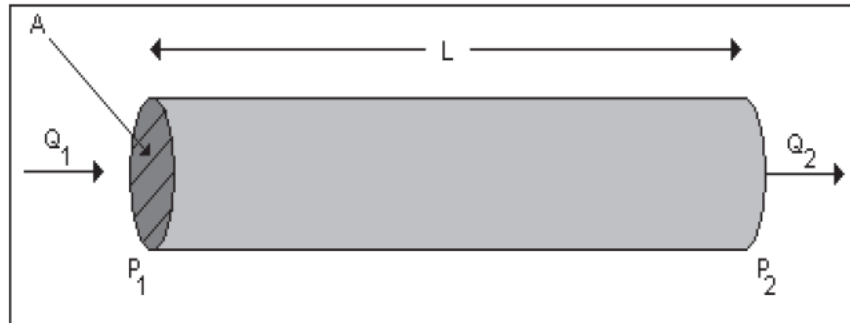
$\frac{\Delta p}{\Delta l}$ = pressure gradient in the direction of flow (Pa/m)

k = permeability of porous media (m^2)



Volumetric Flow (Rock Core Sample)

$$Q = A \cdot V$$



$$Q_1 = Q_2$$

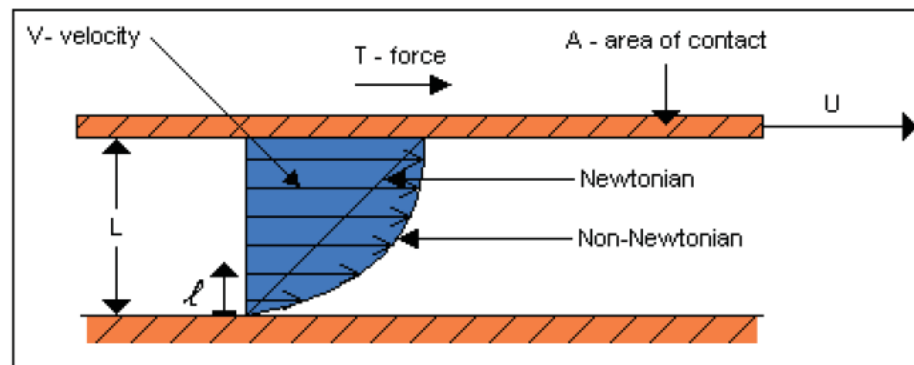
$$\frac{Q}{A} = -\frac{k}{\mu} \cdot \frac{\Delta p}{\Delta L} \quad \text{Darcy's Law}$$

$$\frac{Q}{A} \int_0^L dL = -\frac{k}{\mu} \int_{P_1}^{P_2} dP$$

$$Q = \frac{k \cdot A (P_2 - P_1)}{\mu \cdot L} \Rightarrow \text{or } k = \frac{Q \cdot \mu \cdot L}{A (P_2 - P_1)}$$

Viscosity

$$\mu = \frac{\text{shearing stress}}{\text{rate of shearing strain}}$$



Geologically (porosity)

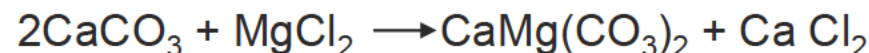
❑ Primary Porosity (intergranular): Porosity formed at the time the sediments are deposited

- Clastic Rocks (made up of rock fragments)
- Erosion fragments from other rocks
- Typical clastic rocks are common reservoir rocks like sandstone, conglomerate and limestone

❑ Secondary Porosity

- Solution porosity: voids formed by the solution of the more soluble portion of the rock in percolating (i.e. coffee filter) surface and/or subsurface waters containing carbonic and organic acids
- Fractures, fissures and where porosity or voids are formed by structural failure of the rock under loads caused by various tectonics such as folding or faults
- Dolomitization: process by which limestone CaCO_3 is transferred to

$\text{Ca}(\text{Mg})(\text{CO}_3)_2$:



dolomite is more porous than limestone



Typical Porosity Magnitudes

Sandstone (uniform clean and packed)

~20%

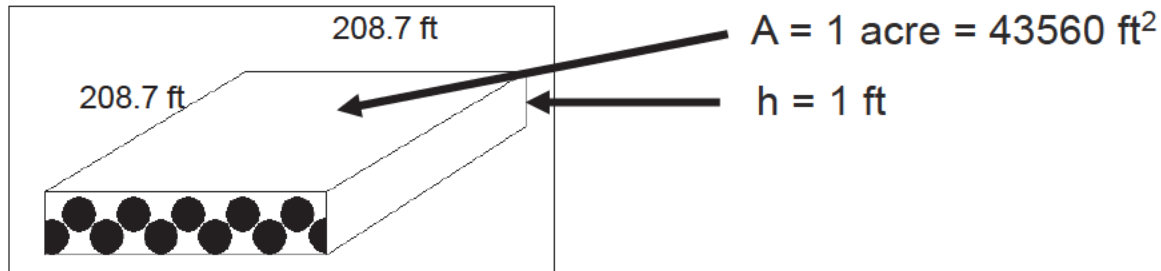
Limestone and Dolomites

~10%

Facts affecting porosity (mechanical)

- uniformity of grain size
- degree of cementation
- packing
- particle shape

Quantitative use of Porosity



1. One acre foot = 43560 ft³
2. 1 bbl = 42 gal = 5.61 ft³
3. 1 acre - ft = (43560/5.61) = 7758 bbls

Then, $V_{\text{pore}} \text{ (bbls/acre - ft)} = 7758 \times \phi$ (ϕ = porosity of rock)



Volumetric Equation of Oil in Place

$$N = \frac{7758 \cdot \phi \cdot S_o}{\beta_o} = \frac{7758 \cdot \phi \cdot (1 - S_w - S_g)}{\beta_o}$$

N = tank oil in place, bbl/acre-ft

S_o = fraction of pore space occupied by oil (oil saturation)

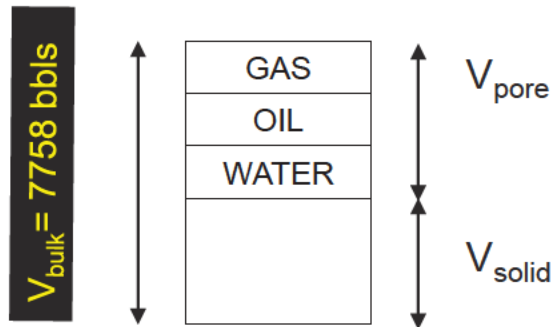
S_g = fraction of pore space occupied by gas

S_w = water saturation

β_o = oil formation volume factor, reservoir volume/tank volume

Note: S_o , S_g , S_w are very difficult to determine, harder than ϕ

$N = 7758 \cdot \phi \cdot S_o$ is bbls of ground oil



$$V_{\text{pore}} = 7758 \cdot \phi \text{ (bbls)}$$

$$\text{Water volume} = 7758 \cdot \phi \cdot S_w$$

$$\text{Oil volume} = 7758 \cdot \phi \cdot S_o$$

$$\begin{aligned} 1. \quad S_o &= \frac{V_o}{V_p} \\ 2. \quad S_w &= \frac{V_w}{V_p} \\ 3. \quad S_g &= \frac{V_g}{V_p} \\ 4. \quad V_p &= V_o + V_w + V_g \\ 5. \quad N &= \frac{7758 \cdot \phi \cdot S_o}{\beta_o} = \frac{7758 \cdot \phi \cdot (1 - S_w - S_g)}{\beta_o} \end{aligned}$$



Subsurface Temperature

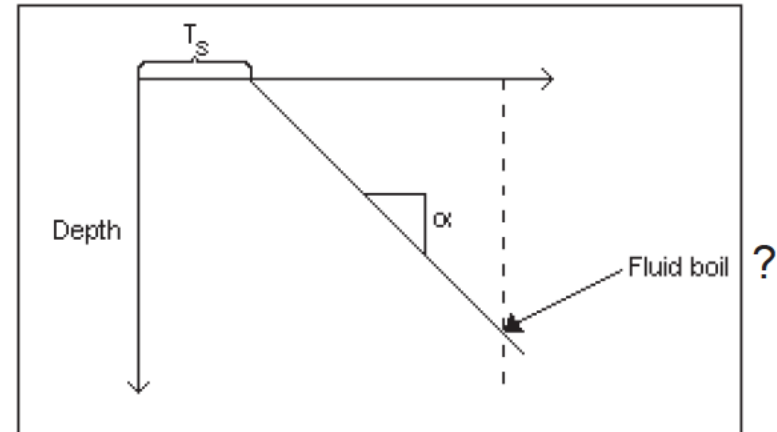
$$T_D = T_s + \alpha D$$

$\alpha = 1.6^\circ\text{F}/100\text{ ft}$, temperature gradient

D = depth, hundreds of feet

T_s = average surface temperature

T_D = temperature at depth



Subsurface Pressure

1. Hydrostatic pressure imposed by weight of fluid (mostly water) which fill voids of rocks above and near the reservoir

2. Overburden pressure due to weight of rocks

- Pore pressure - $62.4/144.0 = 0.433$ psi/ft (usually $0.46 \sim 0.48$ psi/ft)

- Overburden - $0.95 \sim 1.1$ psi/ft

* Pore pressure is important to drilling because of kicks

* Pore pressure could be increased

What causes abnormally high pore pressure?

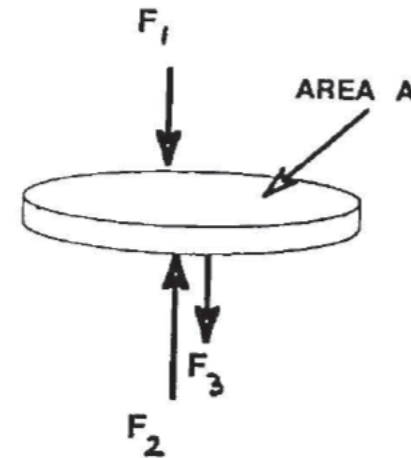
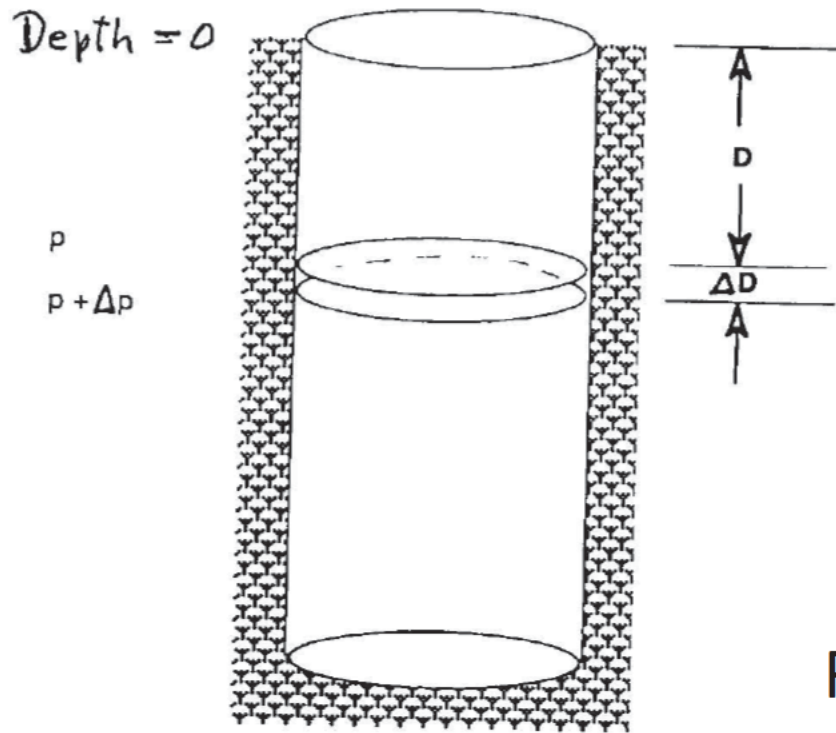
1. Mechanical

2. Chemical/Mechanical

(montmorillonite clay converted to illite)



Forces Acting on a Fluid Element



F_{wv} = specific wt.
of the fluid

$$F_1 = pA$$

$$F_2 = \left(p + \frac{dp}{dD} \Delta D\right) A$$

$$F_3 = F_{wv} A \Delta D$$



Pressures in a Fluid Column

- At equilibrium, $\Sigma F = 0$



$$0 = F_1 + F_2 + F_3$$

$$\Sigma F = 0 = pA - (p + \frac{dp}{dD} \Delta D)A + F_{wv} A \Delta D$$

$$\therefore dp = F_{wv} dD$$



Incompressible Fluids

$$dp = F_{w\ v} dD$$

Integrating,

$$p = F_{w\ v} D + p_0$$

$$[p = p_0 \text{ when } D = 0]$$



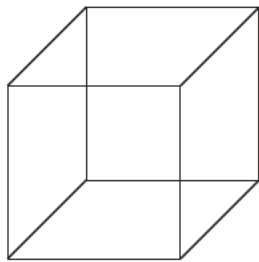
Incompressible Fluids

Density of Water is 62.4 (lbs/ft³)

In field units,
$$F_{wv} = \frac{62.4}{144} * \frac{\rho}{8.33}$$

(lbs/ft³)/(144 in²/ft²) gives psi/ft for water

$$= 0.433 * \frac{\rho}{8.33}$$



1' x 1' x 1'
cube

Water Density is 8.33 ppg - or 1 SG - or 0.433 psi/ft equivalent

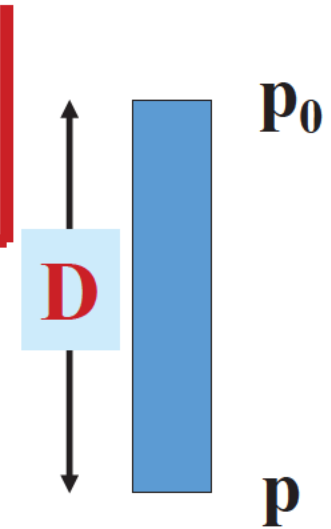
$$F_{wv} = 0.052 \rho$$



Incompressible fluids

\therefore

$$p = 0.052 \rho D + p_0$$



If $p_0 = 0$ (usually the case except during well control or cementing procedures)

\therefore

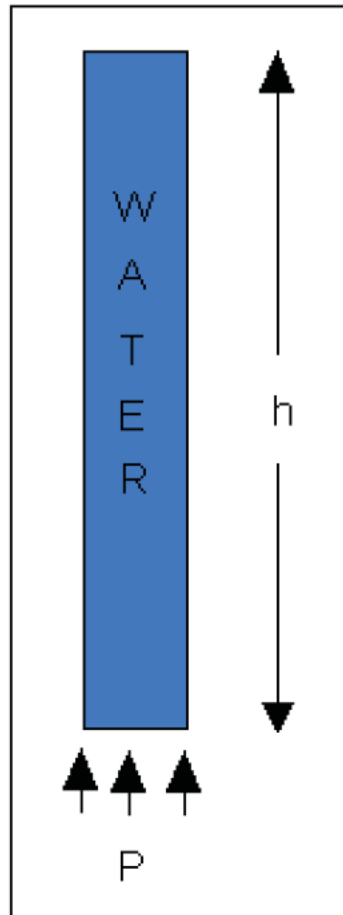
then,

$$p = 0.052 \rho D \quad \{\text{psig, lbm/gal, ft}\}$$

$$\rho = \frac{p}{0.052 D}$$



The Pressure at 10 ft with water?



$$\gamma = 62.4 \text{ lbs/ft}^3 - \text{water}$$

$$1 \text{ ft}^3 = 7.48 \text{ gal}$$

$$\text{fluid pressure} = P = \gamma \cdot h$$

$$P = \gamma \cdot h$$

$$= 62.4 \times 10 \text{ lbs/ft}^2 = 624 \text{ lbs/ft}^2$$

$$= \frac{624}{144} = 4.33 \text{ psi}$$





**The pressure at 10,000 ft in a column
with 10 ppg mud weight?**

$$\begin{aligned}P_{bh} &= 0.052 \times \rho \times D \\&= 0.052 \times 10 \text{ ppg} \times 10,000 \text{ ft} \\&= 5,200 \text{ psi}\end{aligned}$$

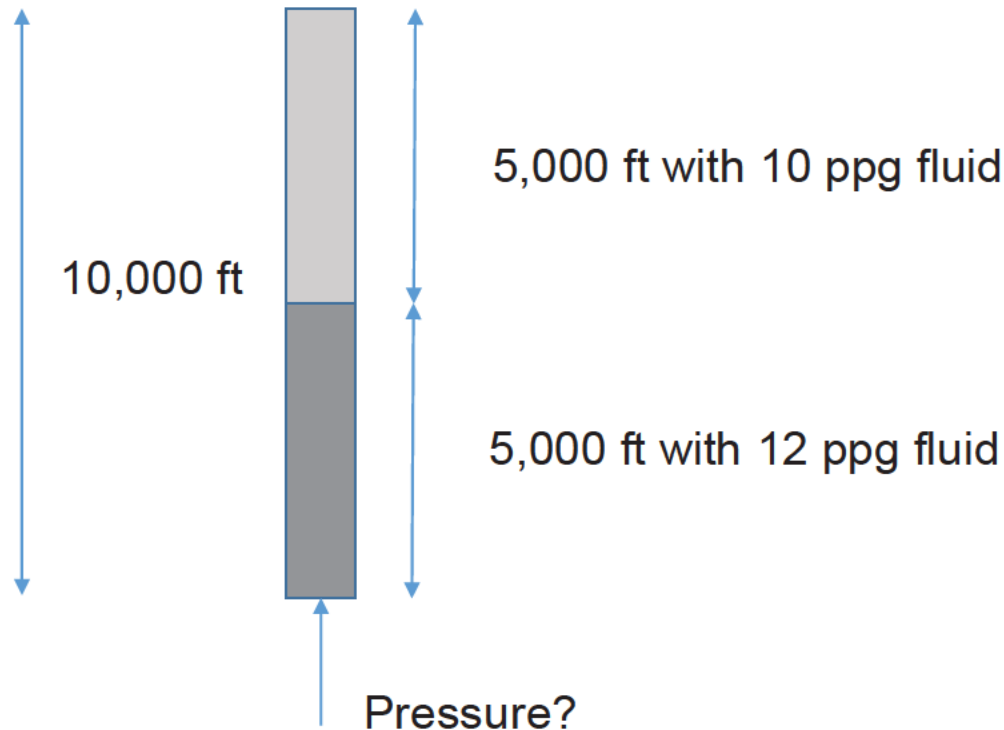
where,

ρ - ppg

D - ft



Calculate the pressure at 10,000 ft with a column of two different density fluids as below!

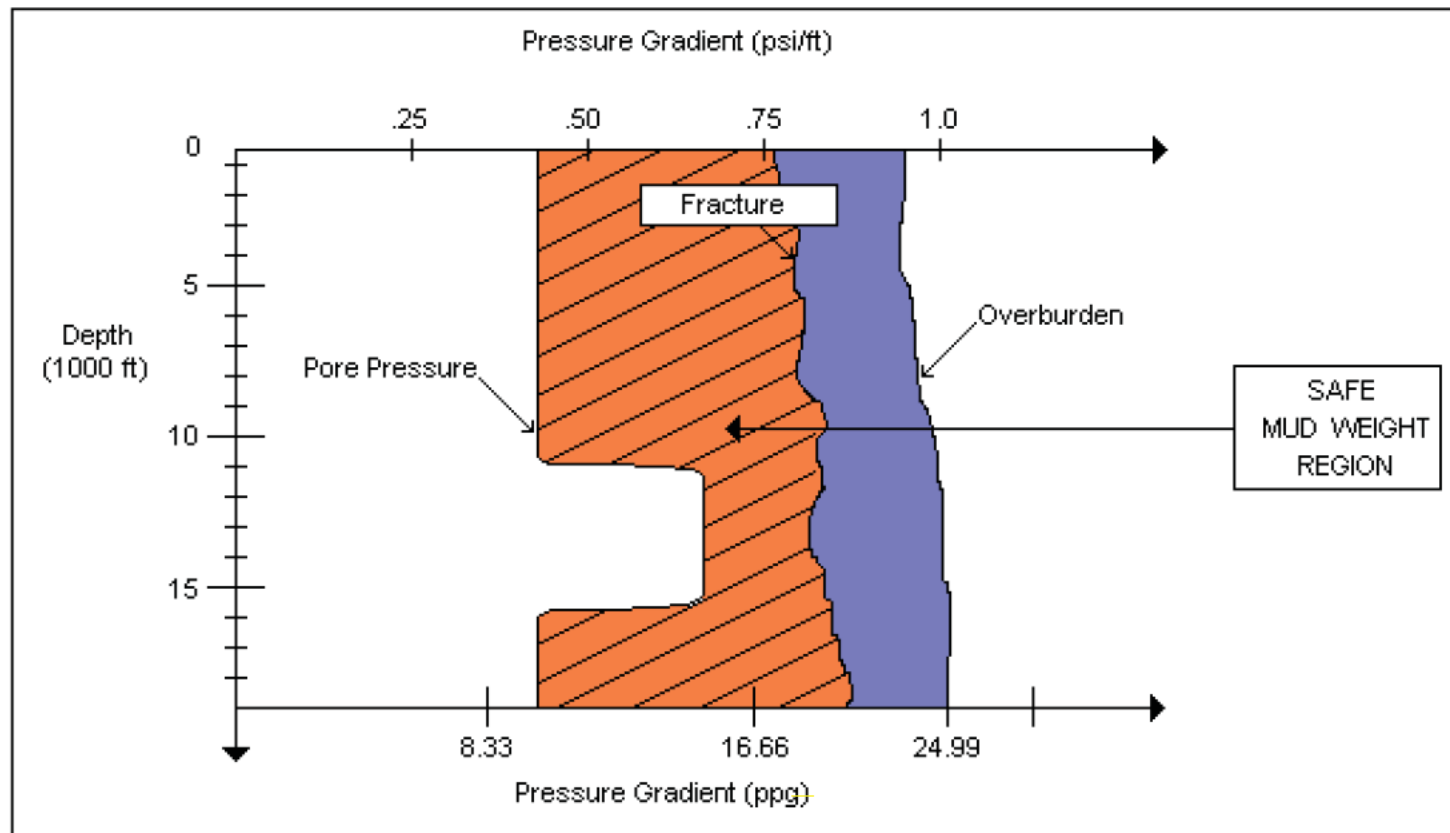


**Work in groups of two
and calculate in class!**

I
F

Factors Affecting Initial Mud Weight Selection

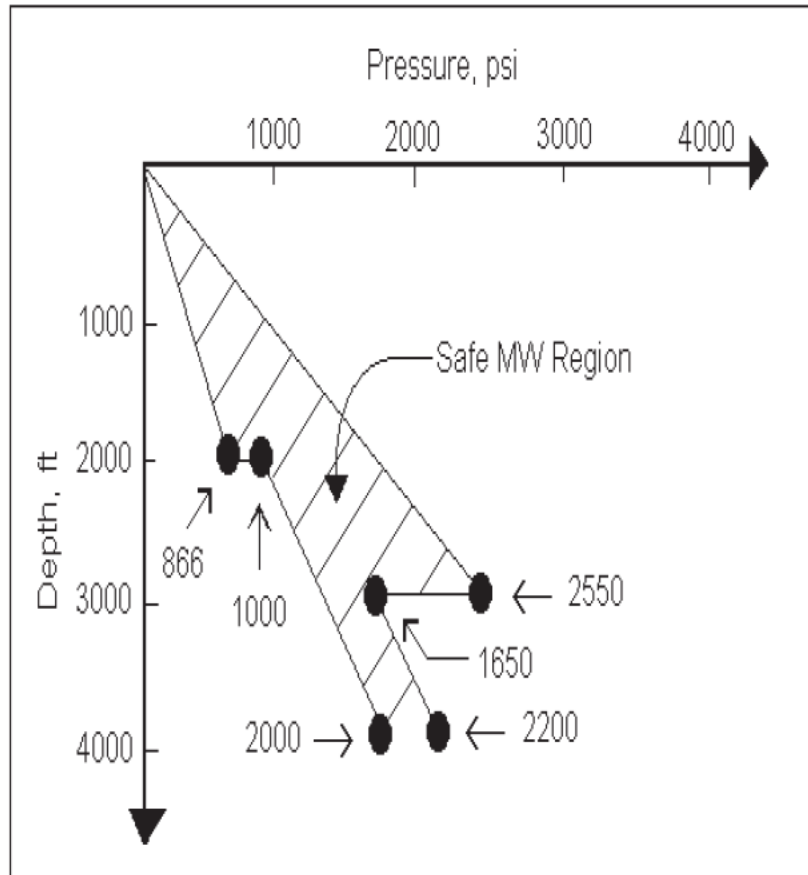
1. Fracture Gradient (Vertical, Horizontal)
2. Pore Pressure



$$MWE(ppg) = \frac{\bar{P}}{0.052D}$$



Example - Depth versus Mud Weight in (psi)



GIVEN:

Pore Pressure, 0-2000 ft, 0.433
2-4000 ft, 0.5

$\frac{\text{psi}}{\text{ft}}$
 $\frac{\text{psi}}{\text{ft}}$

Fracture Gradient, 0-3000 ft, 0.85
3-4000 ft, 0.55

$\frac{\text{psi}}{\text{ft}}$
 $\frac{\text{psi}}{\text{ft}}$

Mud weight - over pore pressure (200-500 psi)

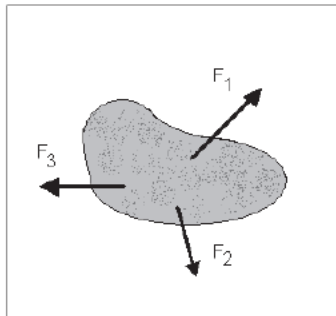
Differential pressure – $(P_{\text{MW}} - P_{\text{p}})$, $(P_{\text{hydrostatic}} - P_{\text{pore}})$

Lower differential pressure increases rate of penetration (ROP)



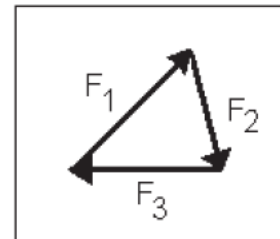
Solid Mechanics (Basic Concept)

Body is Static



$$\begin{aligned}\bar{\mathbf{F}} &= m\bar{\mathbf{a}} \\ \therefore \text{static } \bar{\mathbf{a}} &= 0 \\ \sum_{i=1}^3 \bar{\mathbf{F}}_i &= 0\end{aligned}$$

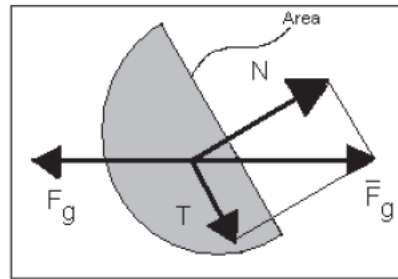
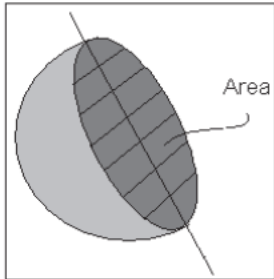
Vector Diagram



$$(F_1 + F_2) + F_3, \sum_{i=1}^3 F_i = 0$$



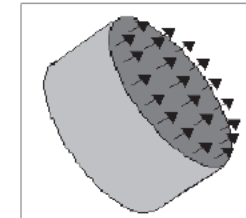
Define Simple State of Stress



N - Normal force
T - Tangential force

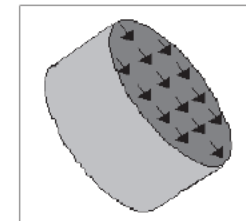
Uniaxial stress

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



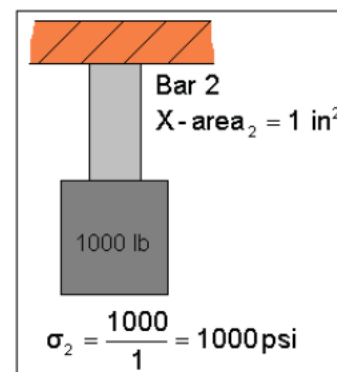
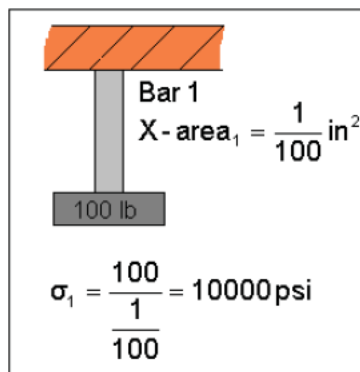
Shear stress

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

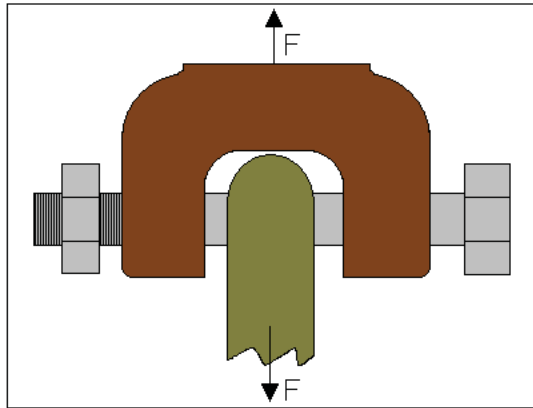


Example - Uniaxial stress

Which bar has the larger uniaxial stress?



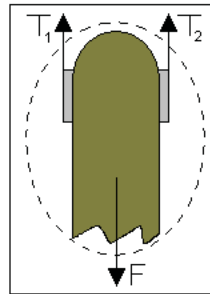
Shear Stress



Example: Shear stress in bolt

$F = 50,000 \text{ lb}$

$1/2'' \text{ Bolt}$



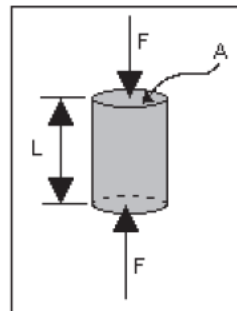
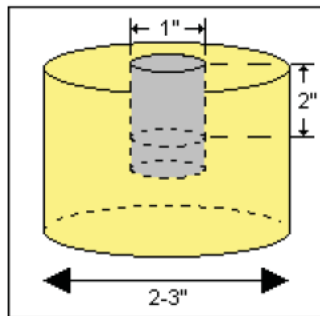
$$A_b = \pi \cdot r^2 = \pi \cdot \left(\frac{1}{4}\right)^2 = 0.1964 \text{ in}^2$$

$$T_1 = T_2 = F/2$$

$$\tau = \frac{T_1}{A_b} = \frac{T_2}{A_b} = \frac{25,000 \text{ lb}}{0.1964 \text{ in}^2} = 127271 \text{ psi}$$

Mechanical Rock Properties

Typically during drilling operations, sections of a well is cored



$$\sigma = \frac{F}{A} \quad \text{compressive stress (uniaxial)}$$

$$\epsilon = \frac{\Delta L}{L} \quad \text{strain}$$

$$\dot{\epsilon} = \frac{\Delta \epsilon}{\Delta t} \quad \text{strain rate}$$

Section of core re-drilled
for 1" dia. 2" long



Rock Uniaxial or Triaxial Test – (Stress-Strain curve)

Young Modulus

E_{steel}

$30 \times 10^6 \text{ psi}$

E_{aluminum}

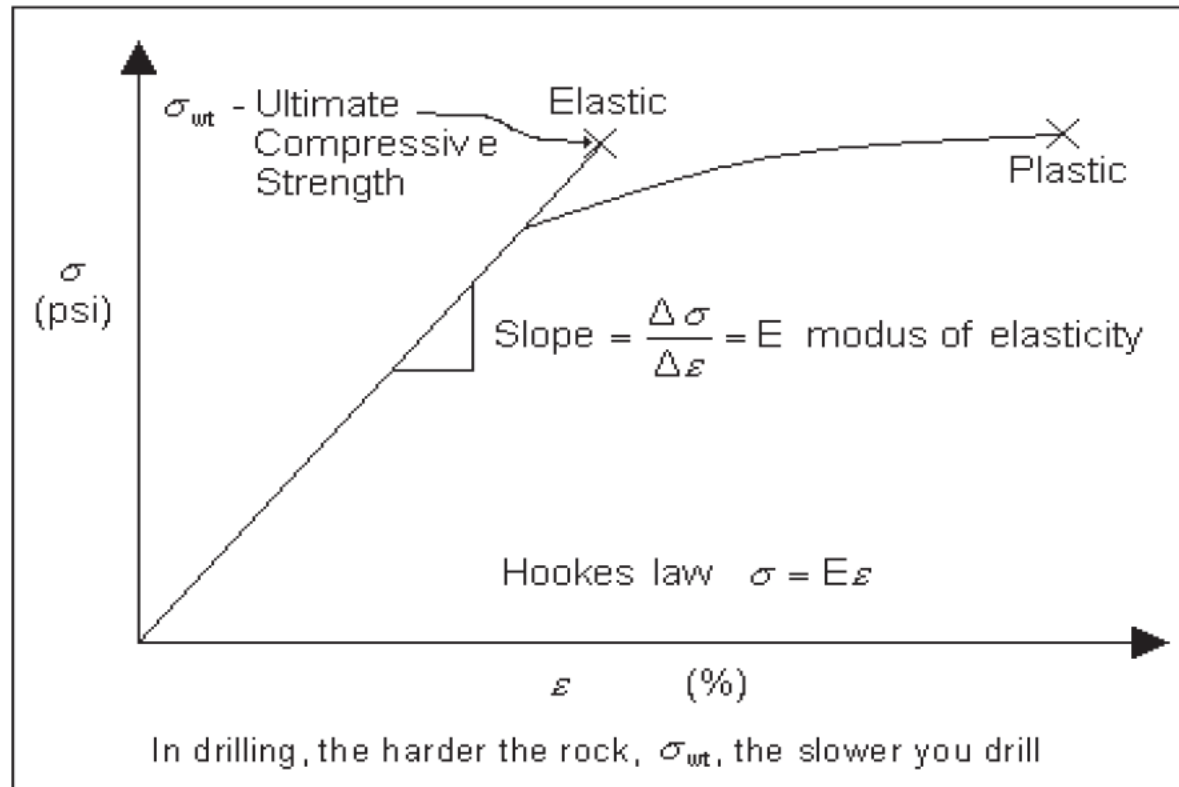
$10 \times 10^6 \text{ psi}$

E_{concrete}

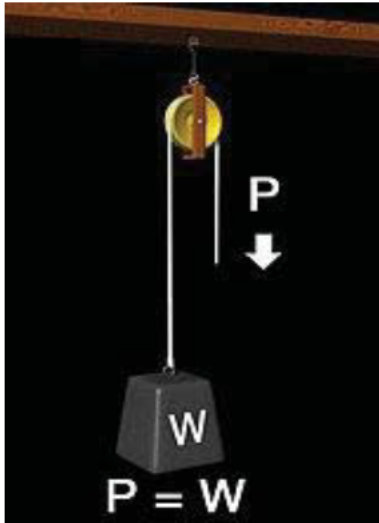
$2 \times 10^6 \text{ psi}$

$E_{\text{rock typical}}$

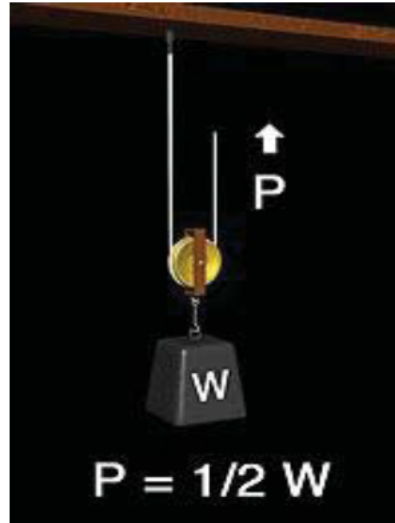
$3 \text{ to } 10 \times 10^6 \text{ psi}$



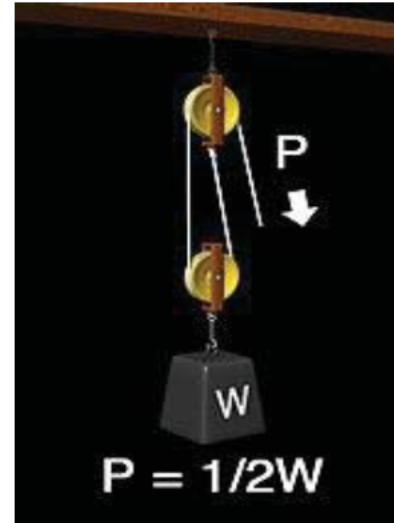
Pulley - the Rig Hoisting System Uses a System of Pulleys



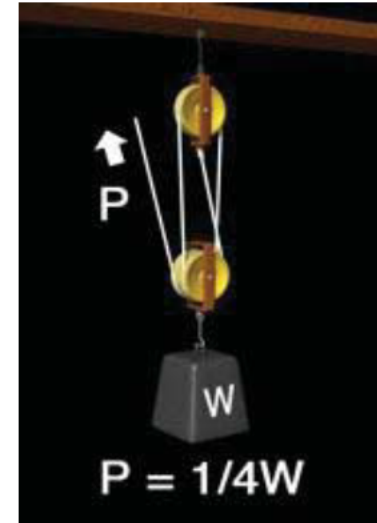
a



b



c



d

What if you had a system with the line going between the lower and upper “blocks” 4 times or 8 lines?



What if you had a system with the line going between the lower (traveling) and upper (crown) “blocks” 4 times or 8 lines?

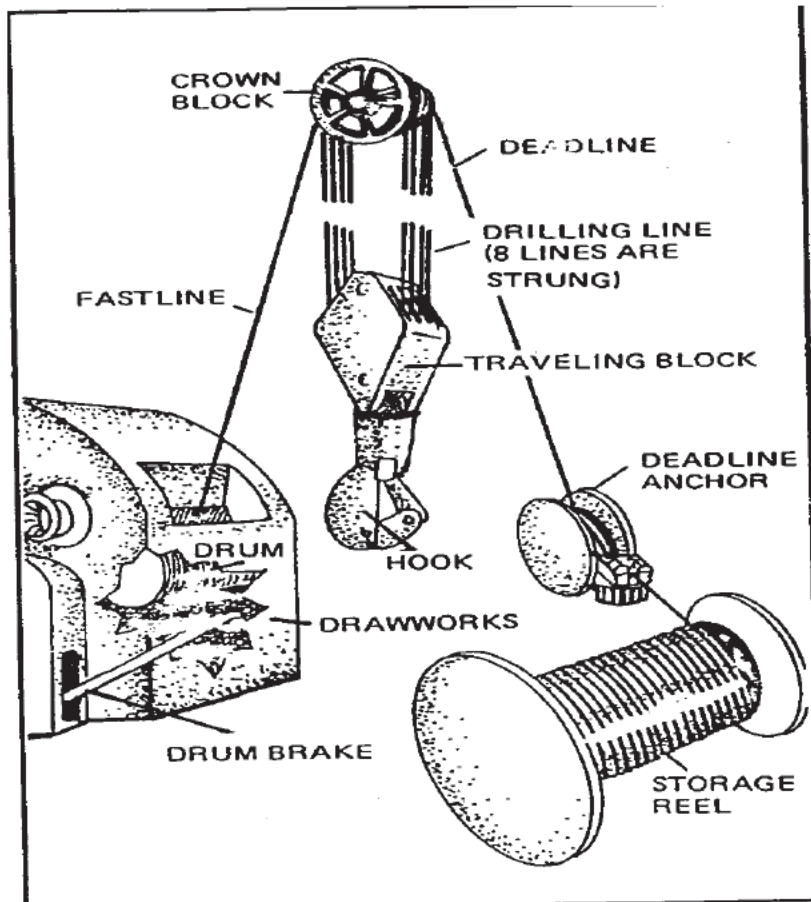


FIGURE 9. A ROTARY RIG HOISTING SYSTEM

- So 8 lines between the travel and crown block
- 1 anchored
- 1 goes into the drawworks
- This is how we get the needed mechanical hoisting advantage on the rig!
- Will be covered in more detail later

<https://www.youtube.com/watch?v=S9TU-4OKMuE> (Makin'Hole-20Min)

