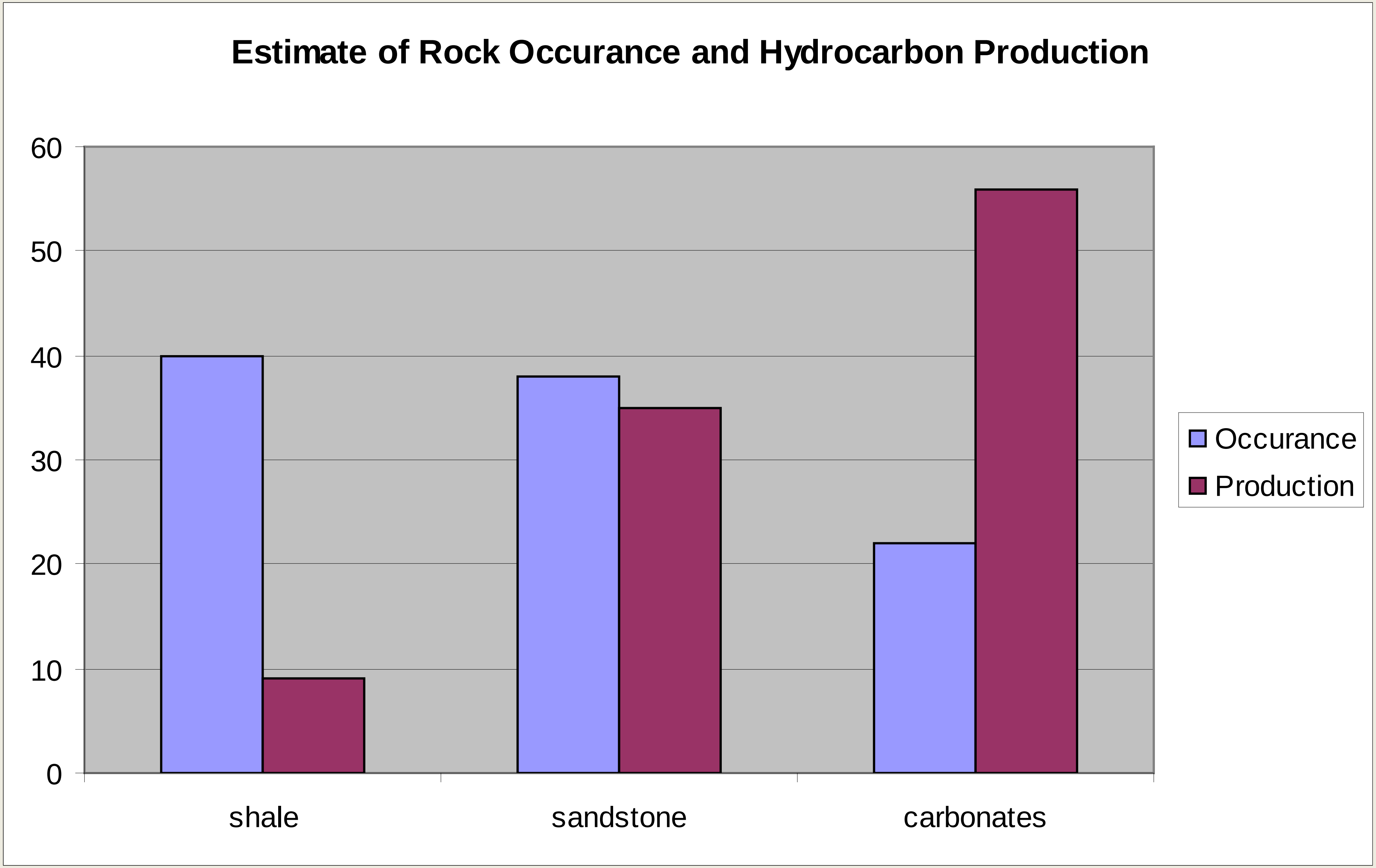
Rocks

- Igneous rocks – result from cooling and crystallization of magma (molten lava). No hydrocarbon storage potential unless it has been modified to create porosity. No organic generation within the rock since no organic content present.
- Metamorphic rock (including crystalline and evaporite deposits) is formed by effects of heat, pressure and other factors on or within existing rock. No hydrocarbon potential in most cases but can be a reservoir rock if weathered and/or fractured sufficiently to form interconnected porosity and sealed.
- Sedimentary rock forms from redeposited fragments of existing rock. Sandstone, shale and most carbonates are examples. All these rocks have porosity, although some are very low permeability and may require special completion techniques to produce hydrocarbon at economic rates and quantities.


Estimate of Rock Occurance and Hydrocarbon Production
60
50
40
30
20
10
0
shale
sandstone
carbonates
Occurance
Production

Depositional Environments

- Depositional environments are the conditions under which the rock was deposited.
- It significantly affects variables like permeability, porosity, organic content, thickness, aerial extent, layers, barriers, etc.
- The characteristics of the rock generated by the depositional environment can be changed for the better or worst by physical, chemical and biologic actions after depositions.

Deltas

- Mouth of river deposits, some of the larger sandstone deposits.
  - Enormous amount of natural organic material swept down the river systems - deltas are rich in hydrocarbons.
  - Quality of the reservoir rock deposits may vary widely because of the wide variations in the energy level of the depositional systems. Low energy systems have wide mixtures of sediment sizes and variable permeability. High energy environments sweep the smaller pieces away from the larger pieces creating higher permeability rocks.

Lagoon Deposits

- regionally extensive along shores of ancient seas.
  - usually low energy deposits that are hydrocarbon rich.
  - permeability will vary with the energy and amount of silt. Usually low energy and poor sorting generate low permeability rocks.
  - There are often variances in rock quality between ancient shore line areas and slightly deeper water where marine sediments may interlay the poorer sorted deposits.
  - reworking of sediments are very likely.

Stream beds

- Moderate to low energy deposit with some streaks of high energy along the fast flowing parts of the streams.
  - stream beds are known to wander extensively and chasing these deposits with wells requires very good geologic interpretation, plus a lot of luck.
  - deposit volumes are also limited and frequently deplete quickly.

Deep marine chalks

- Often the most massive deposits, built up at the bottom of ancient seas by the death of millions of generations of plankton-sized, calcium fixing organisms.
  - can be very consistent, thick deposits.
  - natural fracturing is common. Chalk reservoirs usually depend on natural fractures for permeability.
  - most chalks are high porosity but low permeability because of the very small size of materials in the sediments. Porosities of 25 to 30% may yield permeabilities of much less than 1 md.

Reefs

- Built in the same manner as modern reefs (animal secreted).
  - Because of the cavities remaining from the once living organisms, reefs that have not undergone extensive chemical modification are among the most permeable of the carbonate deposits.
  - Reefs are generally easy to see on seismic and are a favorite target of explorers.

Dunes

- The effects of winds (aeolian) on the sands have a shaping effect that can be seen in the arrangement of the grains.
  - deposits may be massive but are usually lower energy and often lower permeability.
  - permeability may vary considerably from top to bottom with changes in grain size sorting caused by energy of the system.

Alluvial fan

- Zones of heavy water run-off such as from mountains are extremely high energy runoffs.
  - components may range from pebbles to boulders. Conglomerates with particle size range of small grains to bus size boulders are possible. These formations are often very low permeability, but can have high permeability streaks.
  - cementation may be very weak.
  - granite washes are in this classification.

Flood plains

- Occur along lower energy rivers and form during flood stages when the rivers overflow the banks and spill into adjacent low areas.
  - flood plain deposits are mostly silt and mud.
  - Streaks of permeability may exist in high energy areas but may be isolated by lower perm deposits.
  - low and highly variable permeabilities are common.

OK – you've got the rock, but what makes it a reservoir?

- To make a rock a potential reservoir, it must be able to collect and trap fluids and be produced.
- Some requirements for a hydrocarbon reservoir:
  1. Connection to a source rock that generates hydrocarbons.
  2. A seal or system of seals that keep fluids from leaving.
  3. Conditions over geologic time that do not destroy the hydrocarbon or the capability to produce.
  4. Ability to economically access and produce the hydrocarbons in commercial quantities.

Source Rocks

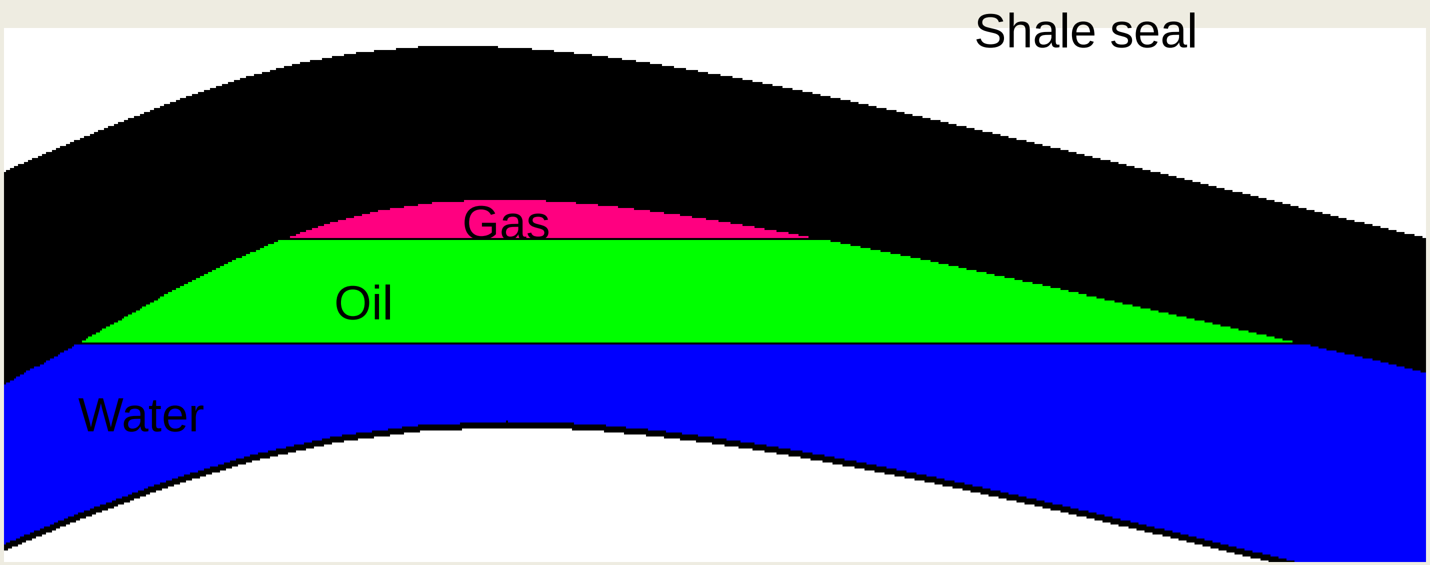
- Shales, carbonates and other rocks that:
  - are rich in organic content,
  - Have the "right" type of organics,
  - Have been heated by burial to a temperature that creates hydrocarbon fluids from the organics.
  - Have not overcooked and destroyed the hydrocarbons.

Traps

- Faulted rock that forms a trap and seals in hydrocarbon in rosk below it,
- Folds,
- Sealing layers (shales) over topographical highs such as dunes, reefs, etc.,
- Salt seals over porous and permeable rock,
- Stratagraphic traps (permeability pinchouts)

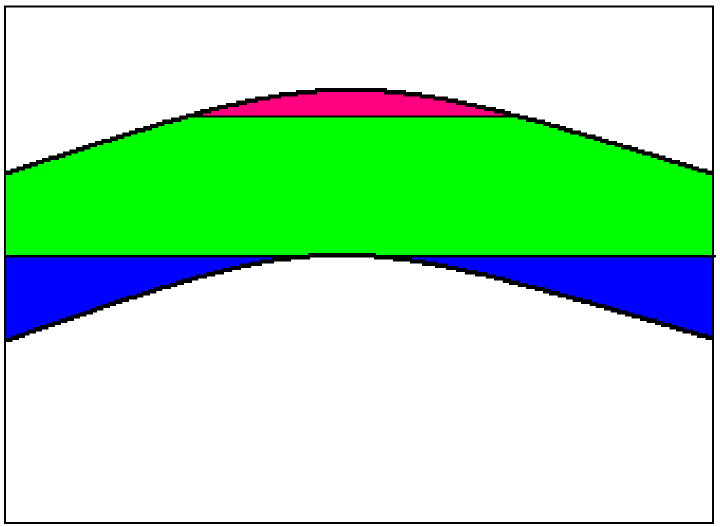
- Many of these seals are in combination with other seals.

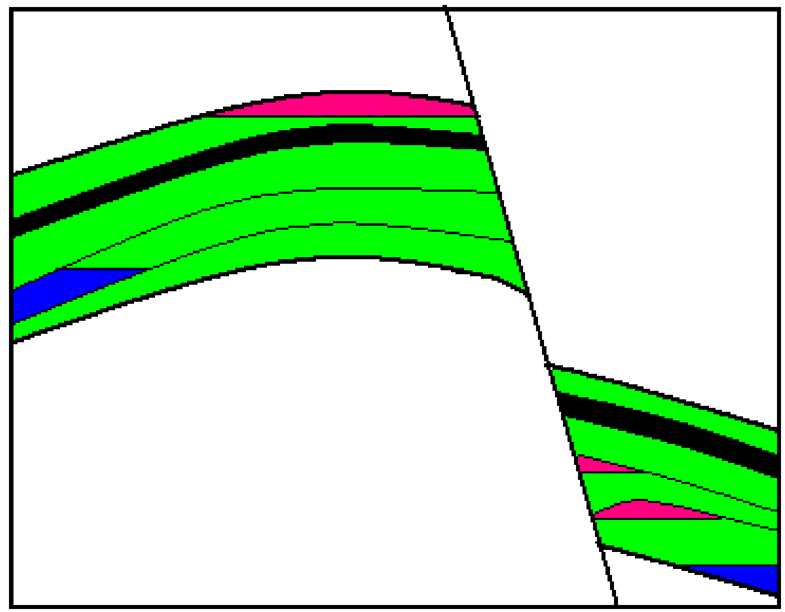
A Simple Reservoir



What is missing? Channels, permeability variances, layers, barriers, faults, pinchouts….. – all these can form compartments within the reservoir.

Complexity in the Reservoir





Simple Reservoir ? Only in a text book.

Most reservoirs have some degree of compartmentalization.

How can this reservoir be produced? What type of completions and what flexibility are needed to effectively deplete the reserves.

Does a reservoir change with time?

- Phase dropouts (bubble pont, dewpoint, floods) that create relative permeability barriers,
- Encroachment of water that isolates and traps oil in the pores (depends a lot on rock wettability),
- Fracture (natural and stimulated) closure as reservoir pressure is drawn down,
- Bacterial modification
- Tar layer movement with pressure depletion.
- Other damage factors

One other thing…..

- Understanding of the reservoir radically changes with time. The more wells that are drilled and logged the better the understanding of the subsurface (well control).
- Drilling, reservoir engineering and production assessment changes understanding of the reservoir – sometimes very significantly.

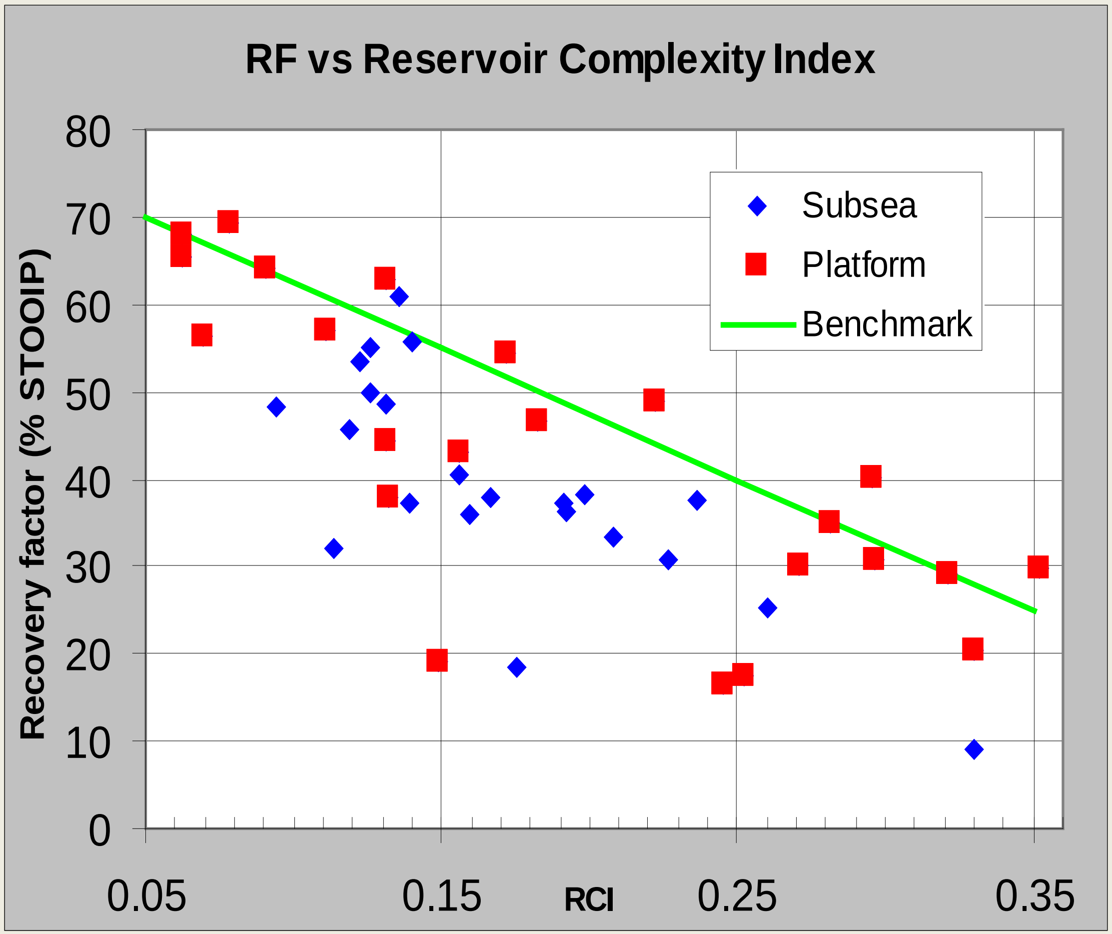
Integrating Geology with Production Information

- Compartments and the boundaries and barriers within the reservoir are usually not completely identified or mapped with pre-completion data such as seismic, log correlations, or analogs projections. Production data is one of the best methods to prove and refine subsurface models.
- The evaluation cycle is very valuable as long as the right data is being continuously collected and evaluated.
- The key to evaluation is in comparing geologic knowledge of the flowing units and the barriers with performance data of pressure, fluid types and rates, cumulative production and any other data from production to predict and describe the possible geologic controls.
- There are examples of good surveillance leading to a better description of the subsurface, however, the key to continuously collect and evaluate the data.

Geologic Control	Effect	Methods
Faults	compartments and connection, stimulation	MDT, Mbal, OHL CHL
Pressure barriers	compartments, sweep, res. limits	MDT, SBHP, OHL, CHL
Channels and Pinchouts	conformance, sweep, compartments	SBHP, MDT, PLT
High Perm zones	Sweep bypass, conformance, stim.	CHL, RFT, PLT, LIL, tracers,
Presence of Layers	Sweep, conformance, recovery	SBHP, MDT, interference
Areal extent of flow unit	Sweep monitoring, recovery factor,	interference & fluid tests
Conductive fracs and faults	Recovery factor, sweep, by-passed pay	Temp logs, PLT, tracers, core
Rock stresses	Conformance, recovery, stim., rock stability	Sonic logs, core,
Fluid	Sources, compartments, sweep, recovery	NMR, tracers, geochem, core

Benchmark for recovery factor

- Ongoing activity to establish a benchmark for the recovery factor of oil reservoirs.
- The Reservoir Complexity Index is derived from 17 factors characterizing a reservoir
- The plot depicts a preliminary analysis of most oil reservoirs on the NCS (+ a few others)



Average permeability
Permeability contrast
Fractures
Structural complexity
Lateral stratigraphic continuity
Vertical communication
Reservoir dip
Original oil in place (STOOIP)
STOOIP density
Oil viscosity [cP]
Coning tendency
External drive
Compaction and sol'gas drive
Reservoir pressure/lift
Flow assurance issues
Temperature
Water depth

Statoil Recovery Tool Box Slide

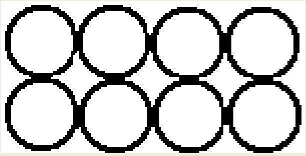
Porosity

- Porosity is the ratio of voids to volume of rock.
- Porosity = $\frac{\text{Volume of pores}}{\text{Total volume of rock}}$
- The amount of porosity is a measure of the amount of fluid that a rock will hold, but may or may not be producable.
- Effective porosity is amount of void space that is interconnected and able to transmit fluids.
- Secondary porosity is that porosity added by events after deposition (natural fractures, solution porosity)

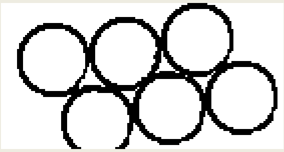
Source – AAPG Basic Well Log Analysis, Asquith. G., Krygowski, S.

Porosity

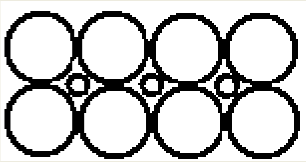
- Primary porosity is formed when grains are cemented together.



High porosity (48%), but unlikely in nature, except with rare cases in a few chalks.



More likely arrangement (26%), but single sized grains

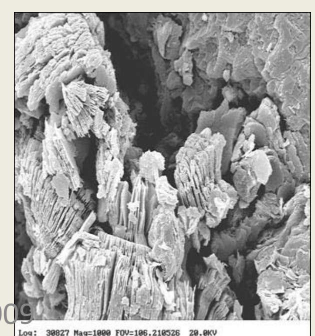


When various sized grains, cementation, stress, clays and rearrangements are added, porosity drops: 5% to 15% is normal

- Secondary porosity caused by reworking, solution removal of rock or fracturing – usually only 2% of porosity but significant influence on connection (permeability).

Rock Structure

- Lithology or mineralogy – describes the solid or matrix portion of the rock, generally the primary mineralogy, e.g., sandstone, limestone, etc.
- Mineralogy analysis often describes the chemical composition of the components of the rock: sand (SiO_2), limestone ($CaCO_3$), dolomite ($CaMgCO_3$), anhydrite ($CaSO_4$), clays, etc.
- SEM (Scanning Electron Microscope) analysis shows the shape and form of the minerals and some information about location.



A Few Definitions

- Stress and Strain
- Young's Modulus
- Poisson's Ratio
- Biot's Equation

Stress and Strainc

- Stress, σ, – a load, F, applied over an area, A.
- Effective stress = total stress less an offsetting force provided by support of the pore pressure.

  $\alpha' = \sigma - \alpha P$
- Strain, ε, the change in length under an applied end strain as compared to the initial length at no stress.

Poisson's and Young's

- Poisson's ratio is the ratio of lateral strain to axial strain (perpendicular deformation to parallel deformation). Poisson's ratio values are 0.1 to 0.35 depending on the formation.
- Young's Modulus or Modulus of Elasticity is stress over strain.
  – Shale: 1 to 3mm psi or 6,900 to 20,670 MPa
  – Sandstone: 5mm psi or 3,445 MPa
  – Limestone: 8 to 10mm psi or 55,000 to 68,900 MPa.

Biot’s Constant

- Biot’s constant describes the relationship between pore pressure and stress:
  $a = (1/C_g/C_b)$
  - C_g = compressibility of the grains
  - C_b = bulk rock compressibility (dry)

Now, will it flow?

- Permeability,
- Interconnected porosity,
- Pore throat and capillary pressure,
- Fluid type,
- Pressure differential – to the wellbore and to the surface,
- Formation stability, etc.

Permeability

- Permeability, k, is the ability of the rock to transmit fluids.
- Permeability is controlled by the size of the connecting passages between the pores.
- Secondary porosity, particularly natural fractures and solution vugs dominate permeability – often are 100x the matrix permeability.
- Permeability is NOT a constant – it changes with stress, fluid saturation, produced fluid deposition, stimulations, damage from fluids, etc.

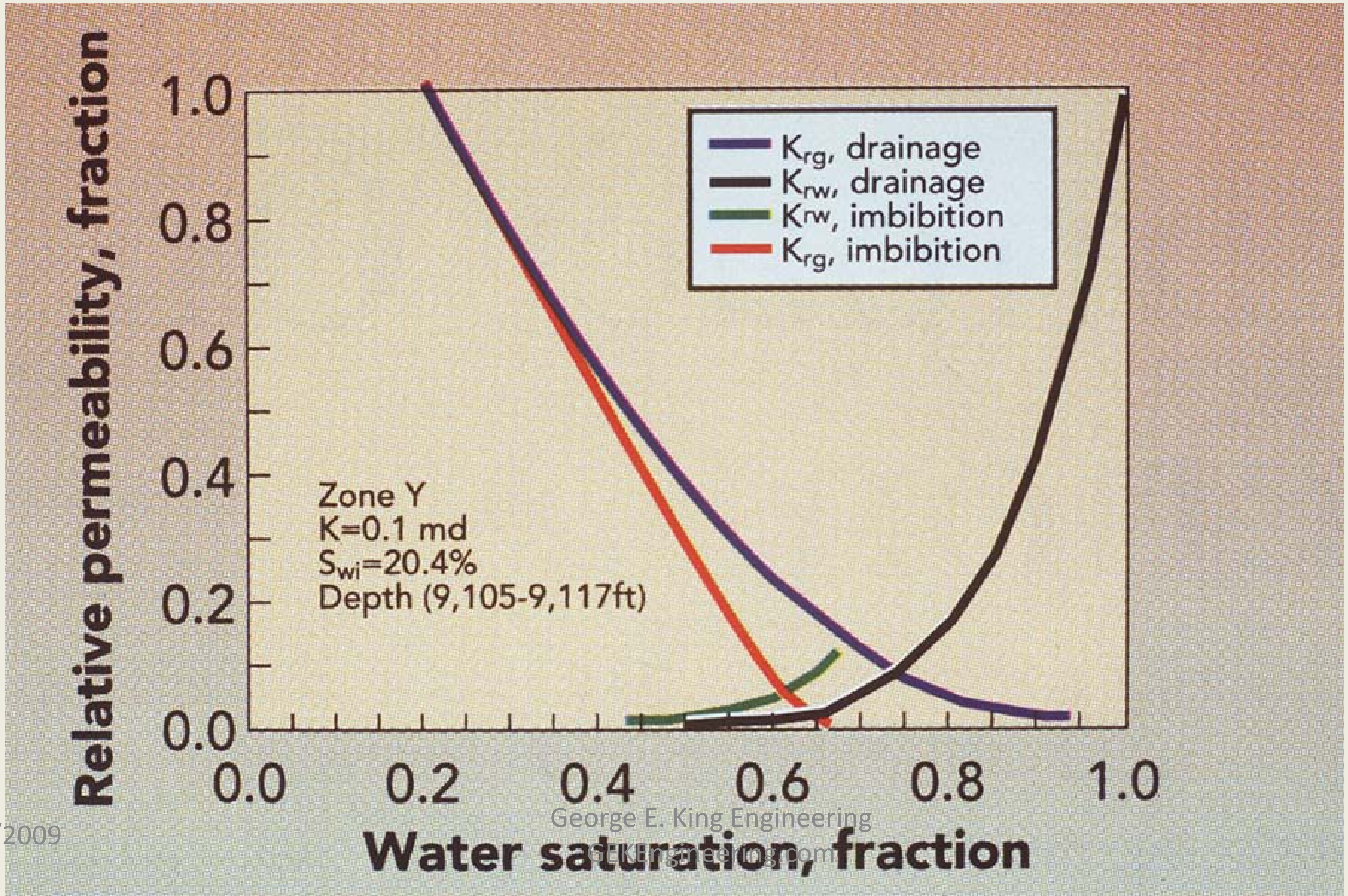
Permeability Measurements

- Absolute Permeability – the ability of a rock to transmit a single fluid when it is saturated with that fluid.
- Effective Permeability – the ability of the rock to transmit one fluid in the presence of another when the two fluids are immiscible.
- Relative permeability – the ratio between effective permeability to a specific fluid at partial saturation and the absolute permeability.

Source – AAPG Basic Well Log Analysis, Asquith. G., Krygowski, S.

Relative Permeability

Note that the permeability to the starting fluid decreases with invasion of a second phase, and that permeability to the invading phase gradually increases with saturation of that phase.



Water Saturation

- Water saturation (initial) is the amount pore volume in a rock that is occupied by formation water.
- Irreducible water saturation, $S_{w\ irr}$ is the water saturation at which all the water is adsorbed on the grains in the rocks or is held in the capillaries by capillary pressure.

Source – AAPG Basic Well Log Analysis, Asquith. G., Krygowski, S.

Resistivity

- Resistivity is the inherent property of all materials to resist the flow of electrical current. Different materials have different abilities to resist the flow of electrical current.
- Conductivity is the reciprocal of resistivity.

Borehole Environment

- Hole diameter (d_h)
- Drilling mud resistivity (R_m)
- Invaded Zone – zone where some of the original fluid is flushed or displaced.
- Flushed zone resistivity (R_{xo}) -

Four Most Fundamental Rock Properties For A Petroleum Engineer

- Porosity
- Permeability
- Water Saturations
- Lithology

What is needed from logging?

- Does the zone contain hydrocarbons?
- Is there a commercial hydrocarbon deposit?
- Is the zone permeable?
- Are the hydrocarbons movable?
- Is the water saturation low enough to manage the water production?