Foundation PL Course

KAPPA

FOUNDATION
PRODUCTION LOG
INTERPRETATION
COURSE

Module #1 Introduction

Course Objective

COURSE MATERIAL COVERS:

- Tool theory of the most common Production Logging tools. (Flowmeter, Density, Temperature, Capacitance, Pressure)
- QA/QC Data quality, Pre-interpretation data editing
- Basics of PL interpretation
- Calibration and single-phase interpretation
- Simple multi-phase interpretation
- Application on real data, learning and using Emeraude

AFTER THE COURSE YOU SHOULD BE ABLE TO:

- Plan, coordinate and supervise a PL Job
- QAQC a PL data set
- Perform a spinner calibration
- Generate a simple multiphase PL interpretation

PL Objectives

Production logging encompasses a number of well logging techniques run on completed injection or production wells, with the goal being to evaluate the well itself or the reservoir performance.

SPE Monograph 14, "Production Logging", Hill A.D.

The purpose of production logging is to provide the most detailed knowledge possible of the nature and behavior of the fluids in the well during production or injection"

Production Log Interpretation, Schlumberger

What is PL?

A record of one or more in-situ measurements that describe the nature and behaviour of fluids in or around the borehole during production or injection.

Production logs are now run for the purpose of:

- Monitoring & controlling the reservoir
- Analyzing dynamic well performance
- Productivity or injectivity of different zones
- Diagnosing problem wells
- Monitoring the results of a stimulation or completion.

The term is sometimes extended to include logs run to measure the physical condition of the well, completion and reservoir properties.

- Cement bond
- Pulse neutron logs
- Corrosion logs
- Radioactive tracer logs
- Noise logs

History of PL

The earliest production logs consisted of:

- Temperature logs (1930s)
- Flowmeters (1940s)
- Fluid-density and capacitance logs (1950s).
- Array probe measurements (1980's)

Flow-rate measurements were gradually improved by:

- the development of tracer logs
- improvement to the basic spinner flowmeter.

Recent PL Developments

These tools were adequate for near-vertical wells with single or biphasic flow, but could be misleading in highly deviated, and especially in horizontal, wells.

New techniques were developed starting in the 1980s:

- Array tools to measure holdup at different points across the borehole
- Nuclear techniques to analyze the total holdup of all three phases. TPHI processing.
- Direct phase velocity measurements for the analysis of individual fluids. Oxygen Activation log.
- Complex flow structures and flow regimes have been studied more extensively using flow loops. **- Models & Correlations**

PL Applications

PL can be used in all stages through the life of a well.

- Initial Completions
- Natural Production Wells
- Secondary Recovery Production Wells
- Injection Wells

Classical PL Applications

- Determine production profile – flowmeter, fluid identity, temperature
- Check for completion integrity… tubing, casing and packer leaks – flowmeter & temperature
- Check for channelling – temperature, flowmeter & tracer
- Check for operation of gas-lift valves – temperature
- Identify leaks
- Evaluate stimulation effectiveness. PL before & after
- Establish baseline PL with well in good shape
  - Determine if all perforations are effective
  - Determine Productivity Index
  - Determine individual reservoir pressures

Injection Wells

Applications include:

- Check for tubing, casing & packer leaks – Flowmeter, Temperature, Tracer, PNL
- Determine injection profiles – Flowmeter, Tracer
  Are all the zones taking fluid?
- Check for channelling – Tracer, Temperature, PNL
- Check if regulator valves are working correctly – Flowmeter

PL in Reservoir Engineering

The task of the reservoir engineering is similar to a financial investor:

- **How are my assets doing**
- **How can I improve the performance**
- **How can I maximize the value of the resources I have**

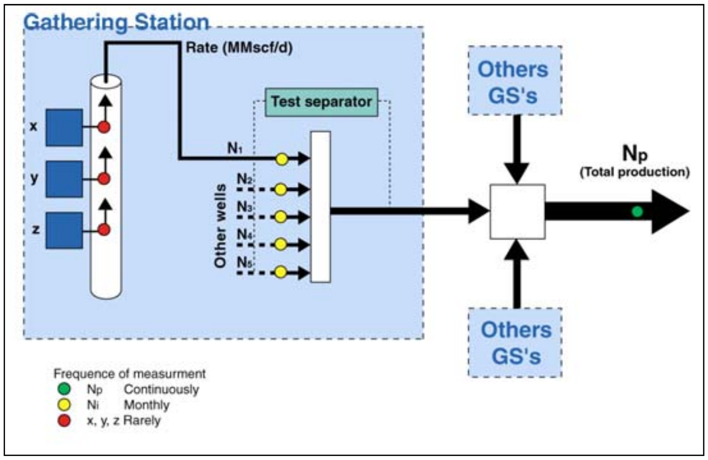
Condition for good asset management:

A Reservoir Model

Monitoring Total System

Surface Measurements: generally OK, but well produces from more layers.

Allocation: what is x, y, z for Oil, Gas and Water



Reservoir model

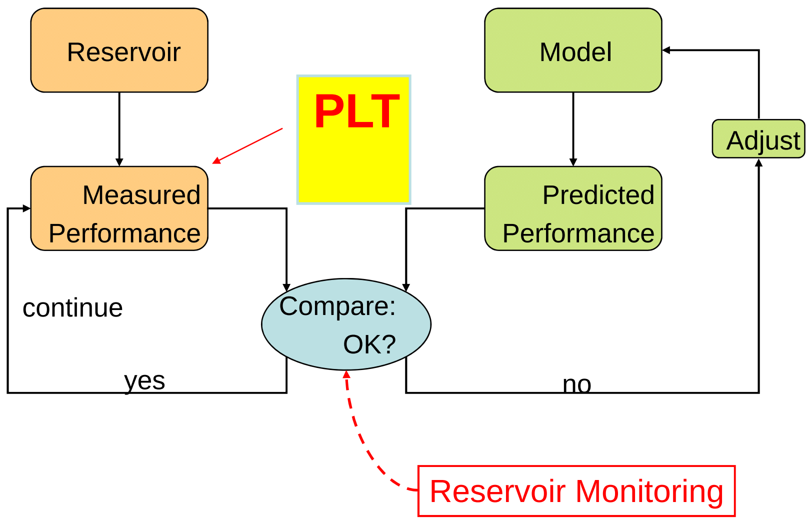
A reservoir model describes the performance of the reservoir as function of time and production policies

It describes the theoretical performance

The model needs to be:
- checked
- calibrated

and adjusted with real observations:
-reservoir/well monitoring

Modeling & Monitoring



Reservoir monitoring: PL

Production Logging:
Analysis of the well condition as function of depth, e.g. individual contribution of all reservoir layers

Multi-Rate Production Logging (MRPL):
Does this with the well flowing at different rates.

Potential source of information for:
- **Reservoir pressure**
- **Permeability/Completion efficiency: PI (productivity index) and Skin/Permeability (in coordination with PTA program)**

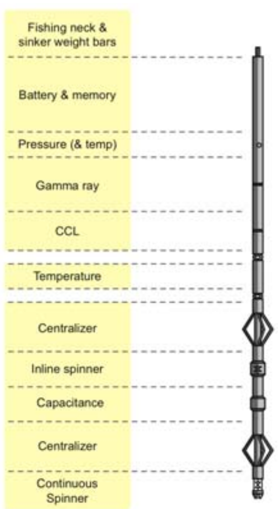
Why PL: Conclusion

Modern software and the affordability of high precision tools have transformed the use of PL:

- Most surveys are easy to run (memory tools on slickline)
- Interpretation done by the engineers. They know what they need, and realize that PL can give the answer.
- PL can give unique information, unobtainable via any other method
- The client (e.g. petroleum engineer) is now the driver

Production Logging is now a fully developed tool for Reservoir Monitoring

Typical PL Toolstring



No.	Tool Length (meters)	Outside Diameter (inches)
1	0.4670	1 11/16
2	0.476	1 11/16
3	0.306	1 11/16
4	0.675	1 11/16
5	0.468	1 11/16
6	0.171	1 11/16
7	0.316	1 11/16
8	0.171	1 11/16
9	0.613	1 11/16
10	0.440	2 1/8
11	0.664	2 1/8
12	0.613	1 11/16
13	0.557	2 1/8

Sondex MPLT string

Conveyance Methods: SRO

SURFACE READOUT: monoconductor cable etc.

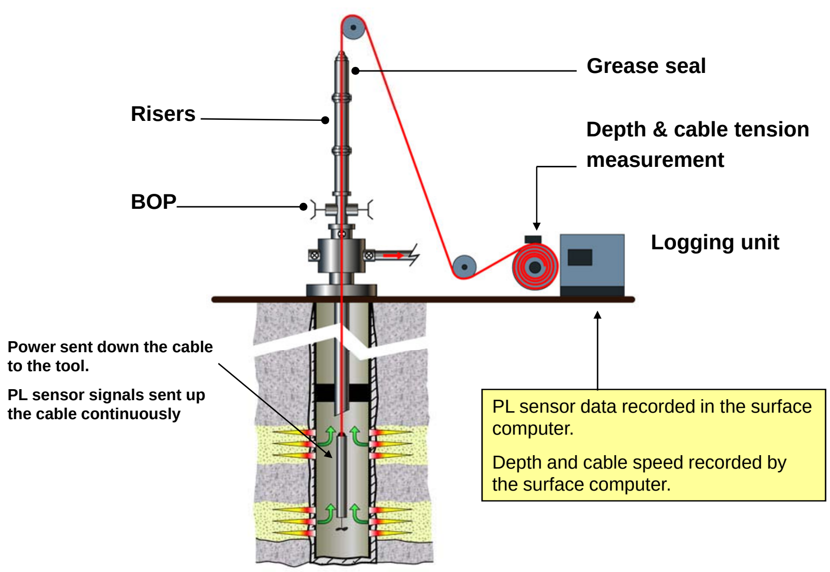
Advantages

- Reliable
- Real time quality control of data at surface
- Program can be adjusted depending on results
- Can log all tool types and combinations

Disadvantages

- Constraint in deviation ~60-70deg
- Usually more expensive than slickline in logistics
- Need surface data acquisition system (logging unit)

PL operations: Surface Read-Out



Conveyance Methods: Slickline

MEMORY: Slickline conveyed

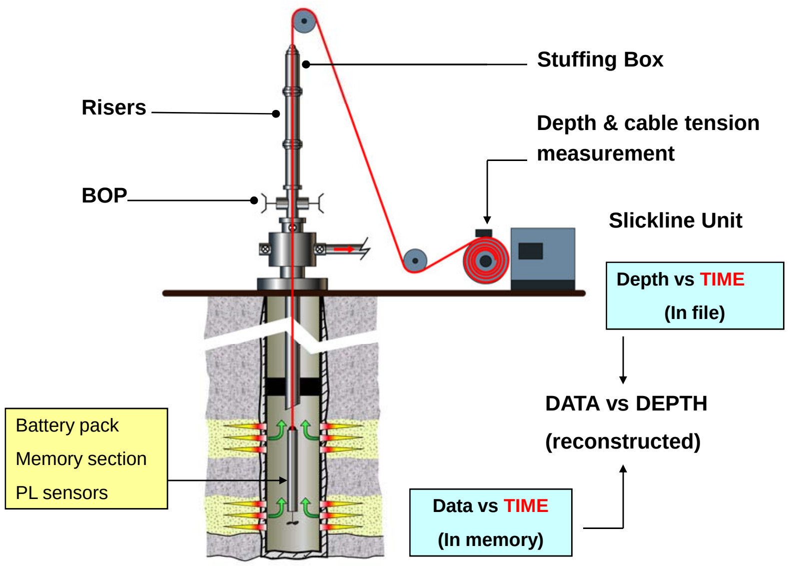
Advantages

- Less costs, especially in logistics.
- Fast – no need for grease injection
- Easy to run
- Slickline unit available on most offshore facilities
- Portability

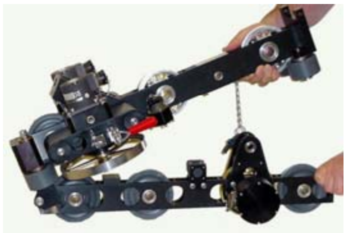
Disadvantages

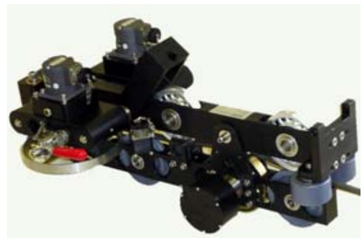
- Constraint in deviation ~60-70deg
- Once set, no change in acquisition mode
- No QA/QC at surface during acquisition
- Some limitations on sensors (power requirements)

PL operations: Memory



Depth Measurement

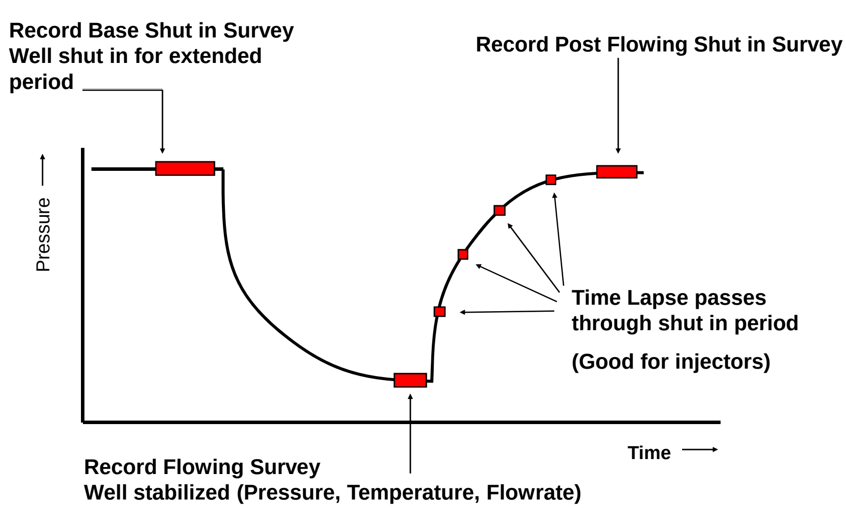




Courtesy : NOV ELMAR

- Spring-loaded measure wheels measure the amount of wireline cable passing through.
- The measure wheels drive 1200 pulse/rps (600 pulses/ft) optical encoders that transmit electrical signals, to the logging computer, for depth and cable speed.
- Often an independently powered magnetic encoder is used for back up depth indication.

Logging Sequence

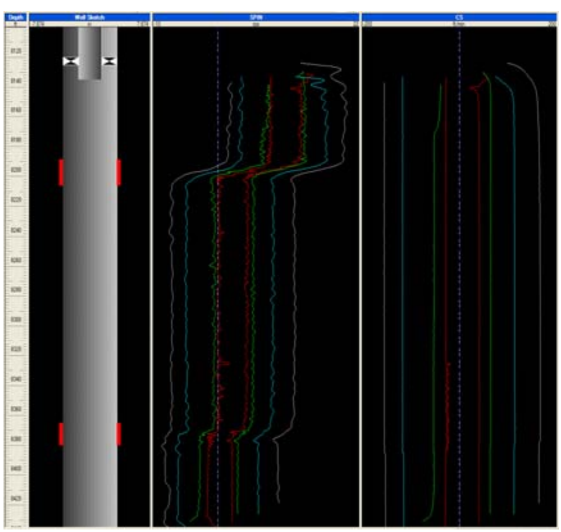


*Note: Various constraints may limit the recording or extent of some of the surveys above.

Shut in Survey: information

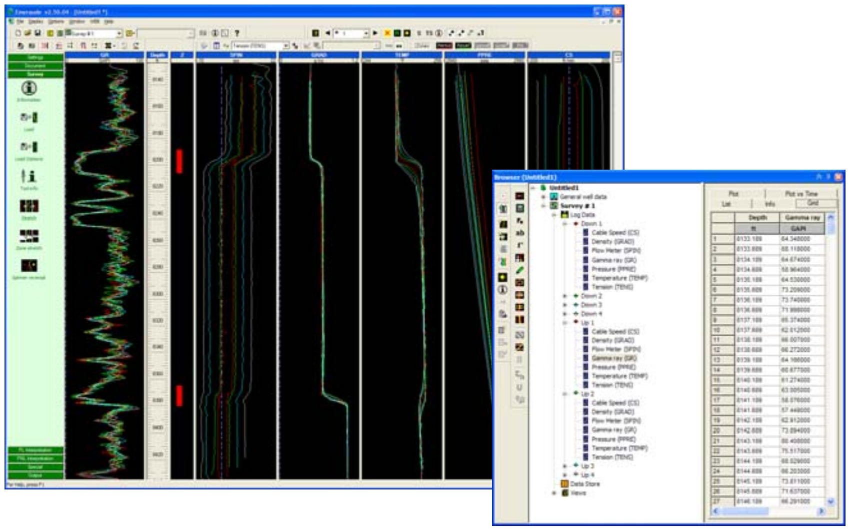
- **Identify fluid contacts in the wellbore**
  - could be useful for spinner calibration purposes
  - useful for Capacitance end point calibrations
- **Density reading of tool at downhole conditions**
  - possible PVT constraint values for interpreted phases
- **Shut in temperature profile**
  - for overlay with flowing temperature passes
  - establish geothermal temperature gradient
- **Identify crossflows**
  - for possible use in SIP and understanding of reservoir
- **Shut in bottom hole pressure profile**
  - and fluid pressure gradients

Typical PL Job

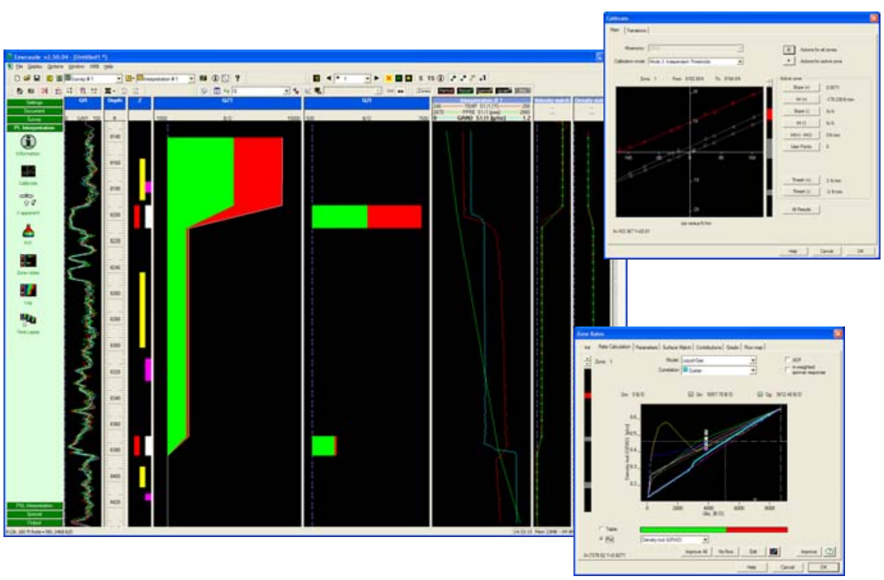


- How many passes are needed for an interpretation?
- Why do we log 3 or 4 up and down passes?
- Typical logging speeds
  (Oilfield) 30, 60, 90, 120 ft/m
  (Metric) 10, 20, 30, 40 m/min
- Normal logging sequence proceeds from slower to faster passes (order not critical)

PL data



PL data interpreted



Stations

Sensor data is usually independent of logging speed.
Data acquired from stations can be averaged and "merged" and used in exactly the same way as data from flowing passes.

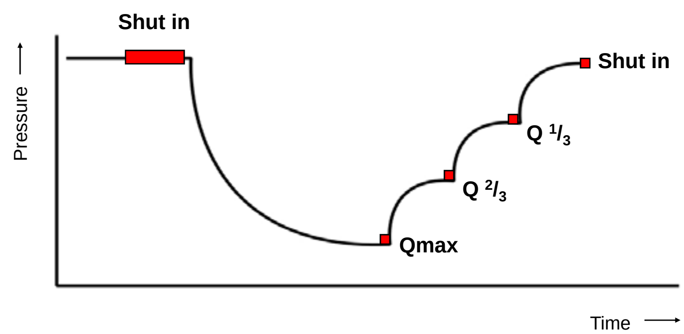
- If spinner calibration data is known, stations can give velocity information.
- Passes have better coverage than stations, as they span the total interval with continuous data.
- Some measurements require stations e.g. PVL, Radioactive tracer logging – velocity stations.
- Some sensors only achieve sufficient accuracy when logged for prolonged periods. E.g. Oxygen activation, WFL, Spectral Flow

Stations

REASONS FOR STATIONS:-

- Monitor stability of well
- Record stabilized pressure reading
- Record buildup or falloff for Pressure Transient analysis
- Evaluate for flow direction in low velocity areas (+/- spinner sign)
- Log vs time for flow regime evaluation
- Oxygen activation water velocity measurement
- Basket/Diverter Flowmeter
- Pressure Gradient stops
- Confirmation of log response observed on passes
- Density of fluids without friction effect caused by cable velocity
- Just because it is on the logging program.. ☺

Multirate PL: MRPL



- The sequence of rates can be adjusted to suit operational & reservoir requirements.
- Many clients prefer to perform Qmax first, to ensure best clean out of well, and best chance of clean stable flow.
- For SIP analysis, stabilized flowing periods should be of similar durations.

Factors Affecting Well Production

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Module #2
Factors Affecting Well Production

Factors Affecting Well Production

The following module is designed to stimulate thoughts about the relevance of additional information in the interpretation process.

e.g.

- Open hole logs
- Core data
- Reservoir history
- Reservoir model & simulation
- Other available log data
- Completion design

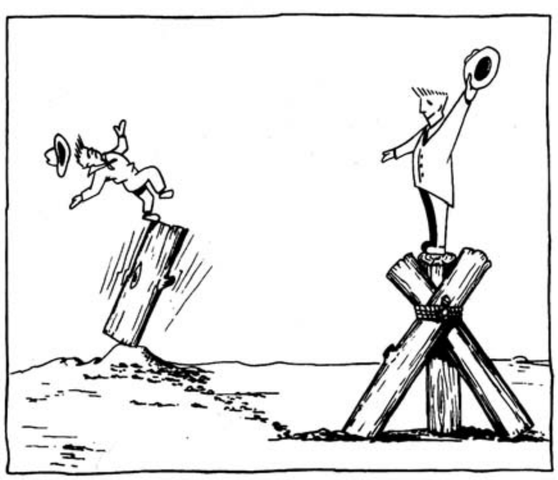
What Is PL Interpretation?

Production Logging is NOT just Flow Rate Measurements

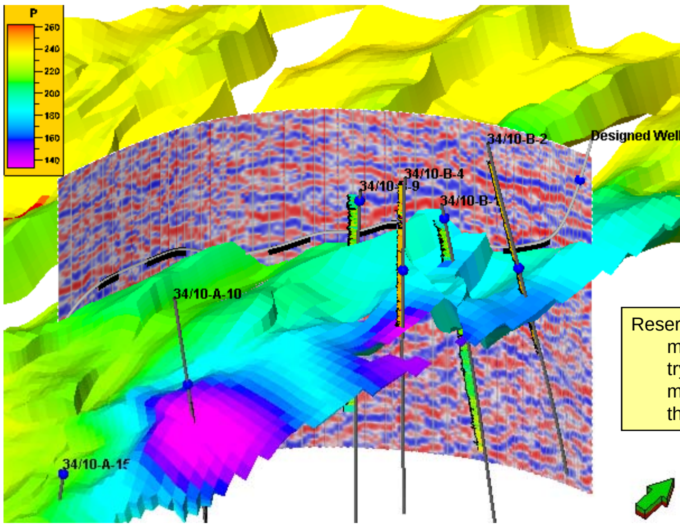
Flow Rates are accessed through a (complex) INTERPRETATION process

- Complex in mathematical analysis (iterations, models, correlations)
- Complex in the understanding of the completion, the reservoir, and it's history and behaviour.

PL INTERPRETATION?

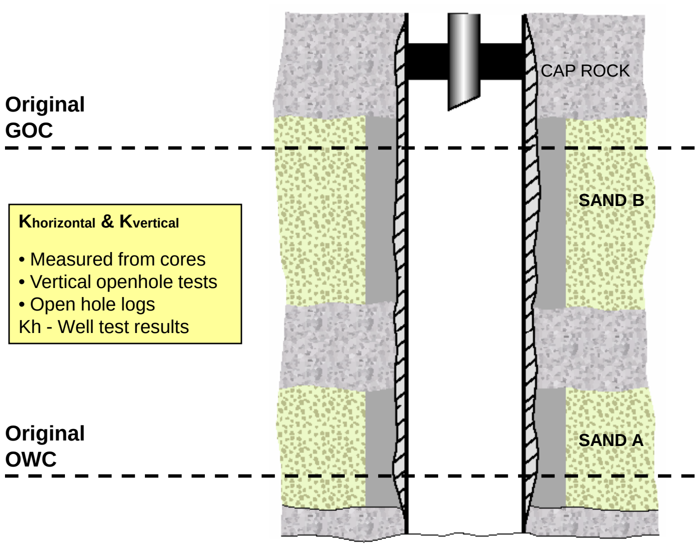


The Reservoir



Reservoirs are complex and must be considered when trying to interpret PL measurements taken in the wellbore.

The Well and Permeability

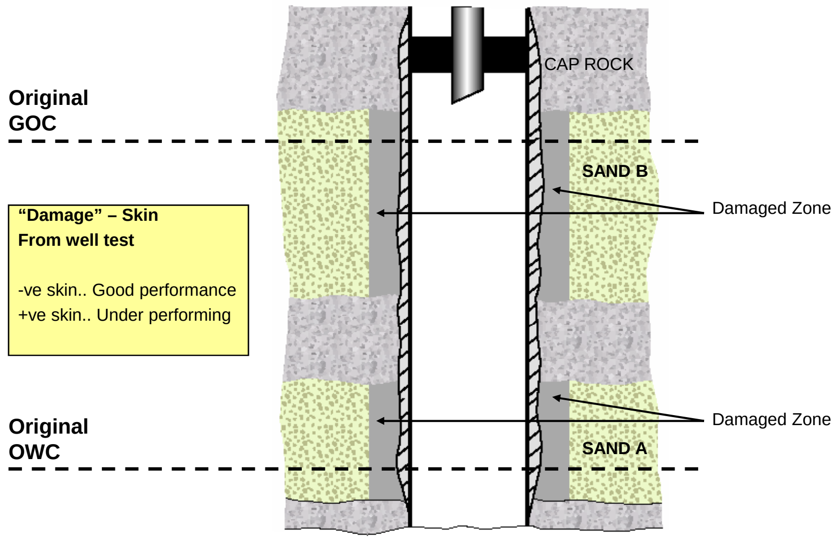


Khorizontal & **K**vertical

- Measured from cores
- Vertical openhole tests
- Open hole logs

Kh - Well test results

The Well Damage



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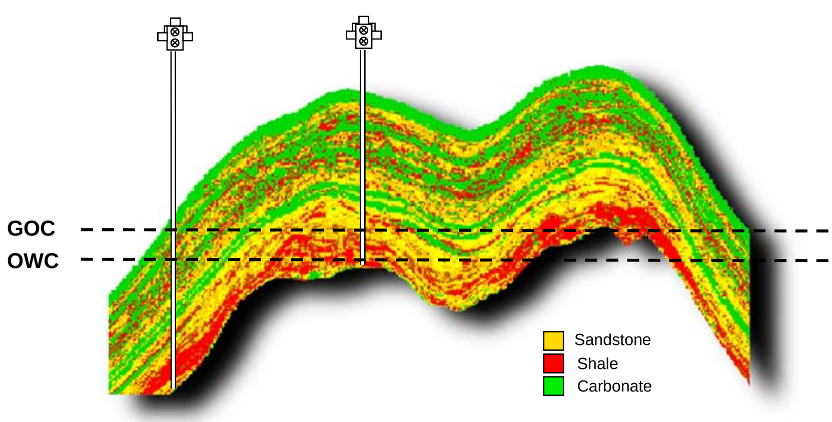
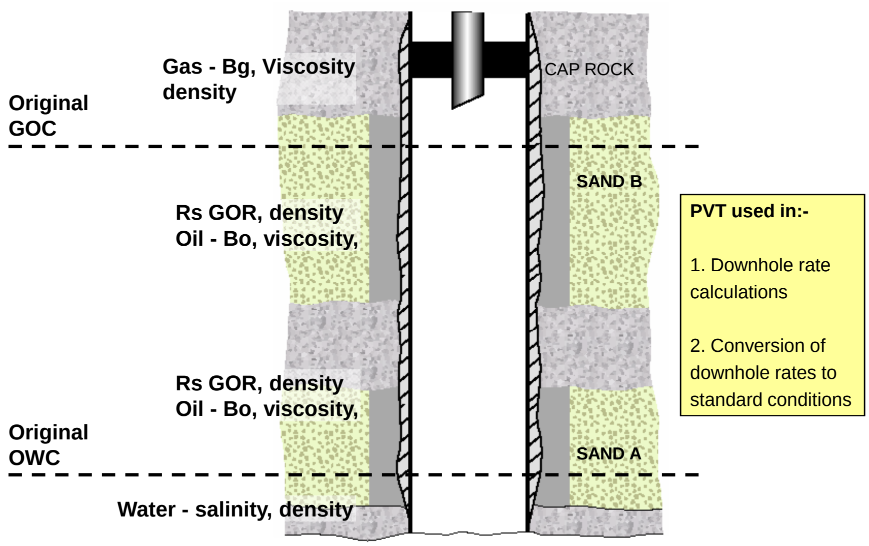
Reservoir Contacts



The location of the contacts in the reservoir are used to assist us in understanding our observations in the wellbore.

02

The Well Fluids



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The Well Fluids - PVT

Minimum PVT parameters required for EMERAUDE

WATER

- **Salinity ppm**

OIL

- **Gravity API**
- **Rs (Solution Gas-Oil Ratio).. Maybe not produced GOR!!!**

GAS

- **Specific gravity**

(Additional PVT parameters can be entered or derived from PVT correlations)

ALWAYS BE CAREFUL WITH YOUR UNITS!!

 02

Problems - Producers

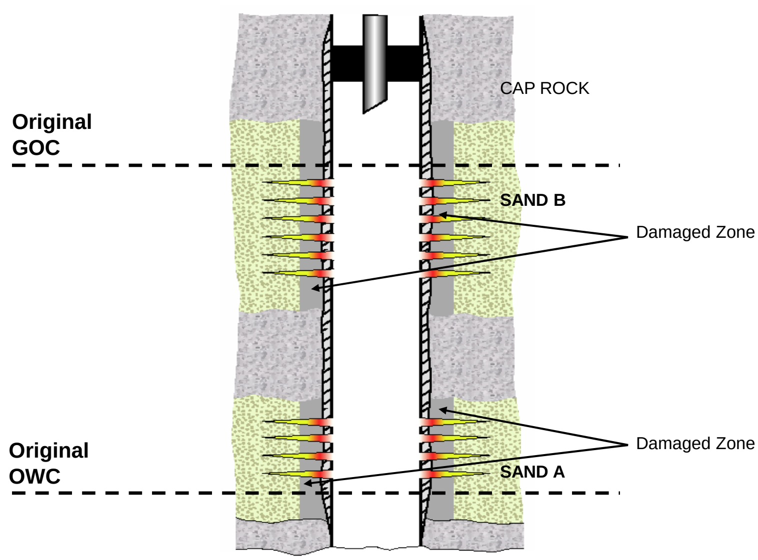
Measure well and reservoir performance

- Flow profile (generic)
- Multi-layer tests (specific methods, e.g. IPR per layer)

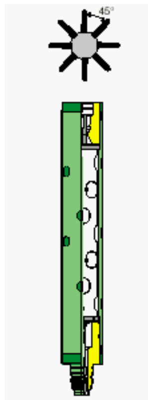
Diagnose well problems

- Perforations off depth / ineffective
- Crossflow
- Channeling
- Coning
- Leaks (casing, packer,etc)
- Zoned flows
- Fractures
- Early water/gas breakthrough

Perforations



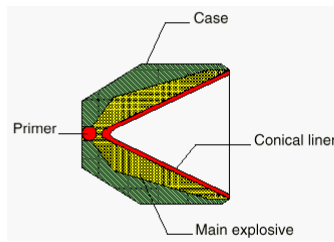
Perforation Gun



The perforating gun comes in a number of formats, density, phase

The common items are the detonator, prima cord and the shaped charge.

The gun used depends on the situation/local preferences.



15 million Psi!!!

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Perforation and PL

Perforating parameters are important in PL Interpretation.

Need to know:

- Perforation intervals

Nice to know:

- Shot density & phasing
- Charge type - big hole/deep penetrating
- Gun type – casing gun, through tubing gun
- Perforation performed overbalanced or under balanced
- Perforation history - timeline

Need to discover:

- Which perforations are producing
- Are the perforations on depth, or are they even there at all?

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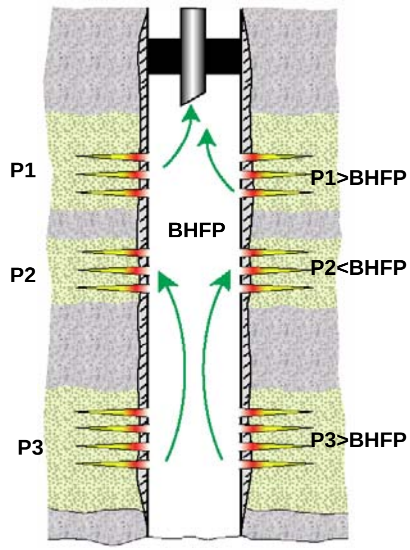
Crossflow



- Three layers were initially perforated
- Layer 2 pressure has somehow dropped. Possibly due to high permeability, therefore experiencing preferential production, and depleted faster. Or maybe it was just a smaller reservoir which has depleted prematurely.
- A point was reached where the pressure in layer 2 is lower than the BHFP
- The Crossflow behaviour in to layer 2 should increase during shut in

Solutions:
- Flow well at higher flowrate – lower BHFP
- Reperforate only layers 1 and 3
- Recomplete layer 3 through a different tubing than layer 2
- Close off, or somehow straddle layer 2

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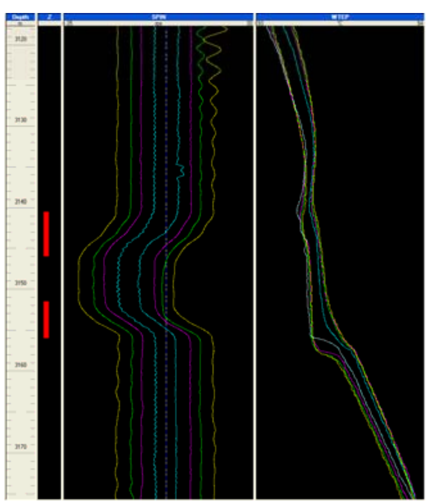
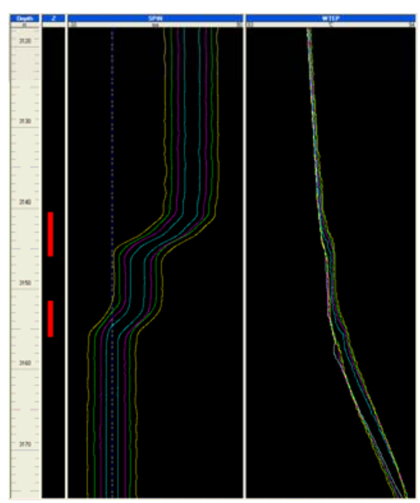
Crossflow

SHUT IN



FLOWING



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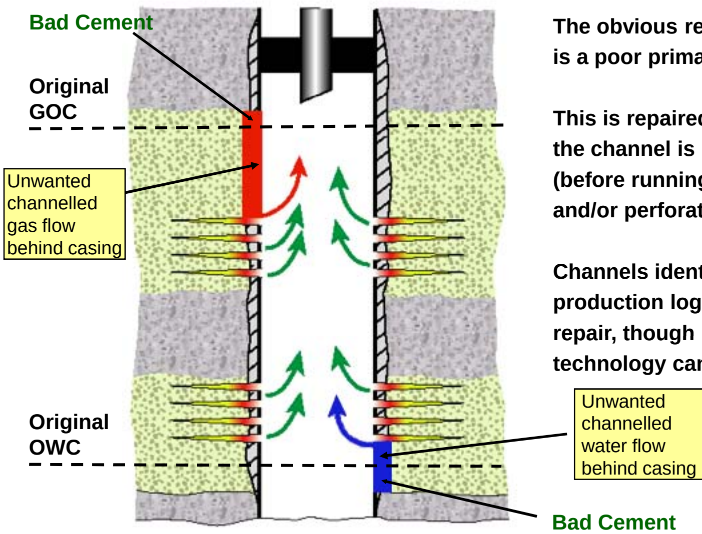
Channeling



The obvious reason for a channel is a poor primary cement job

This is repaired by a squeeze if the channel is identified in time (before running the completion and/or perforating)

Channels identified during production logging are difficult to repair, though modern cementing technology can help.

 02

Cementing

Cement quality is affected by many parameters

- Bottom hole temperature
- Pressures
- Formation stability
- Fluids present, especially gas
- Casing centralization
- Well deviation and doglegs

The most common cause of a poor cement job is poor centralization of the casing.

 02

Cement Evaluation

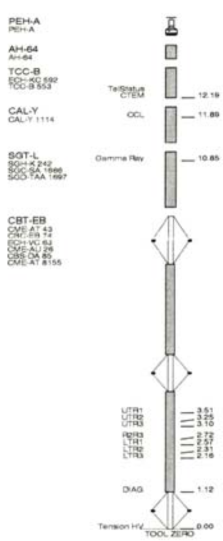
There are a number of tools capable of measuring the cement quality:

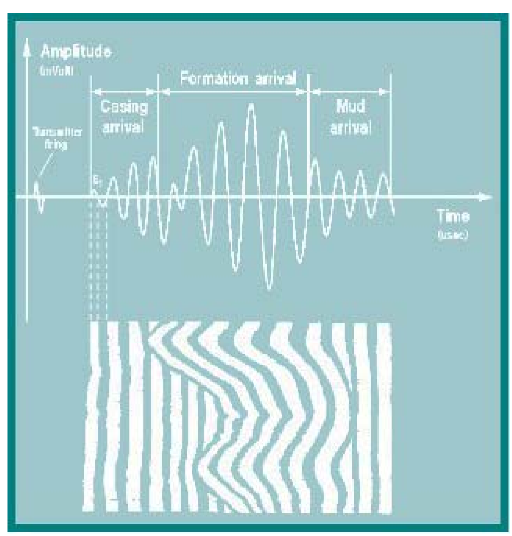
Cement Bond Logging – Acoustic
- transmitter & receiver
- looks at the average bond around the pipe (CBL)
- interpretation is difficult
- only tool to "see" the formation - cement bond (VDL)

Radial Cement Bond Logging - Acoustic
- as above but radially distributed transmitters/receivers

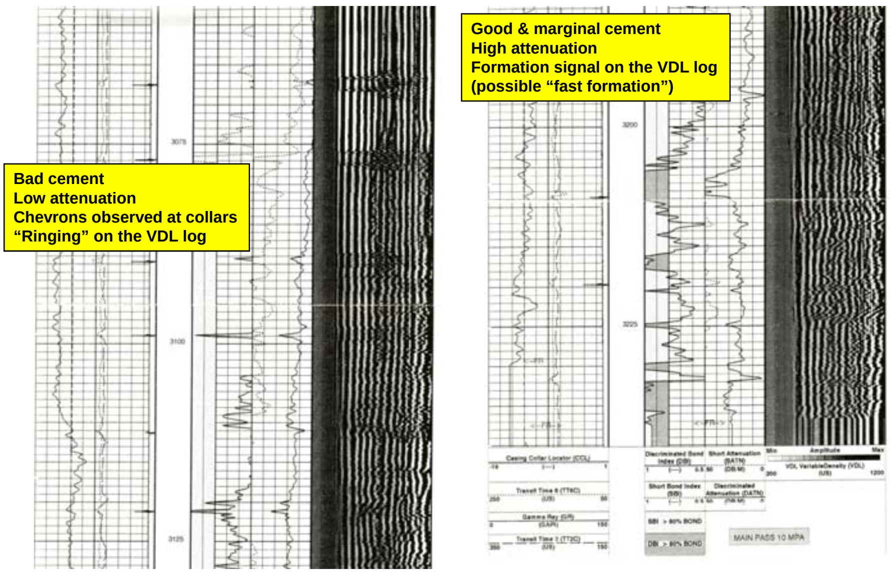
Pulse Echo Logging – Ultrasonic (CAST, USI)
- images all around the casing
- interpretation is simple
- has a corrosion measurement as well

CBL-VDL





CBL-VDL



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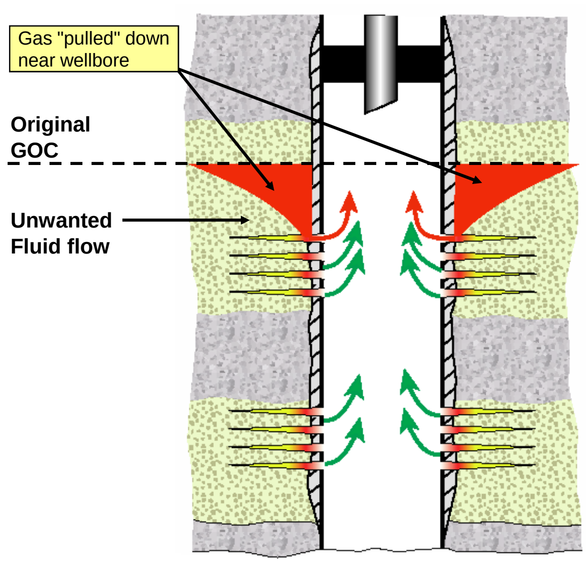
Cone Down



For coning interpretation we need:-

- Vertical flow path Kv/Kh
- Proof of good cement
- Proof of GO contact depth
- Source of fluid for coning
- High drawdown

Choking back the well may reduce this coning effect

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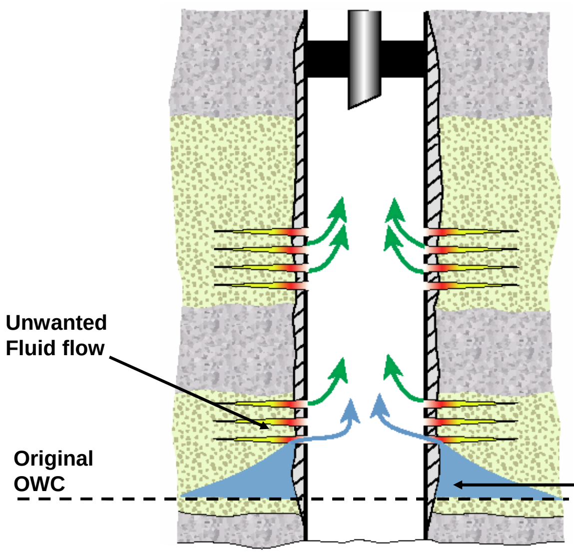
Cone Up



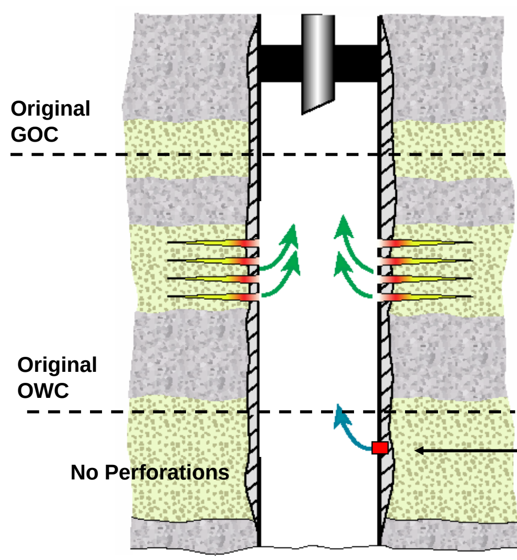
For coning interpretation we need:-

- Vertical flow path - Kv/Kh
- Proof of good cement
- Proof of OW contact depth
- Source of fluid for coning
- High drawdown

Choking back the well will probably not reduce this coning

The effect of the coned water is to "wet" the formation

Casing Leak

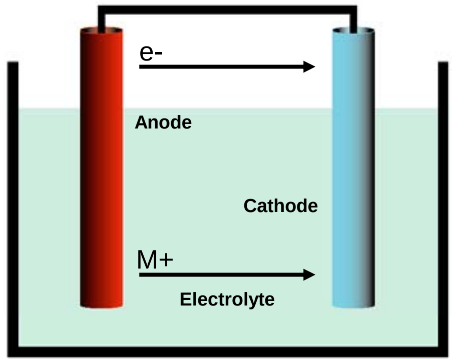


Leaks occur because of corrosion in the casing or tubing.

This can happen at any time in the life of the well.

Logs are used to identify corroded pipe

Corrosion Mechanisms



Two metals in an electrolyte act as a battery.

One is an anode the other the cathode.

Metal moves from the anode to the cathode.

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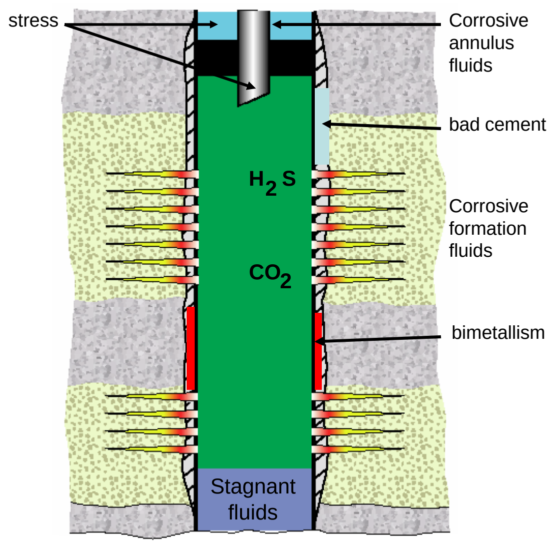
Corrosion



Several tools exist to measure corrosion

- Mechanical calipers
  internal corrosion only

- Imaging tools - ultrasonic
  internal and external

- Electromagnetic
  internal and external
  multiple strings

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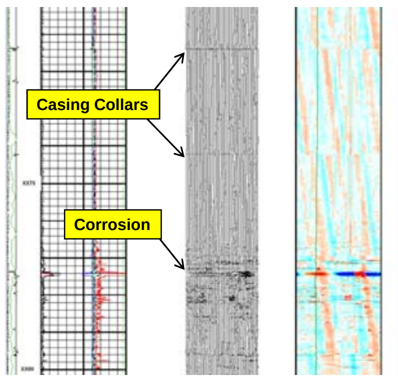
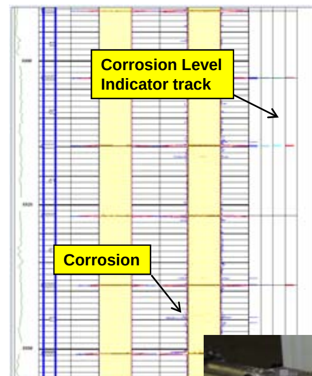
Corrosion Log - examples

Multifinger Caliper Log



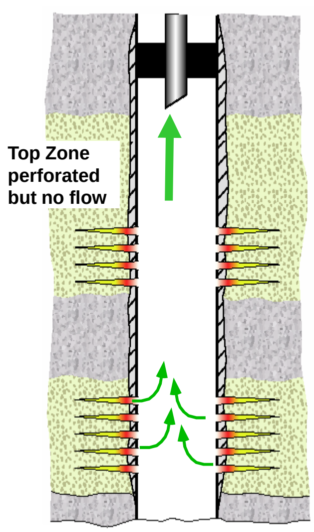
Magnetic Flux & Eddy Current Log



Courtesy
SCHLUMBERGER
SONDEX
SPARTEK

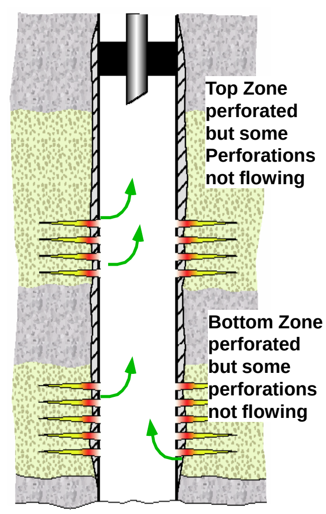
 02

Problem: Zoned Flow



- zones of widely differing permeability, high permeability will flow preferentially, low perm zones may not flow at all

- perforations plugged, debris from the perforation gun, mud entering while perforating overbalanced, crushed rock in the perforation tunnel



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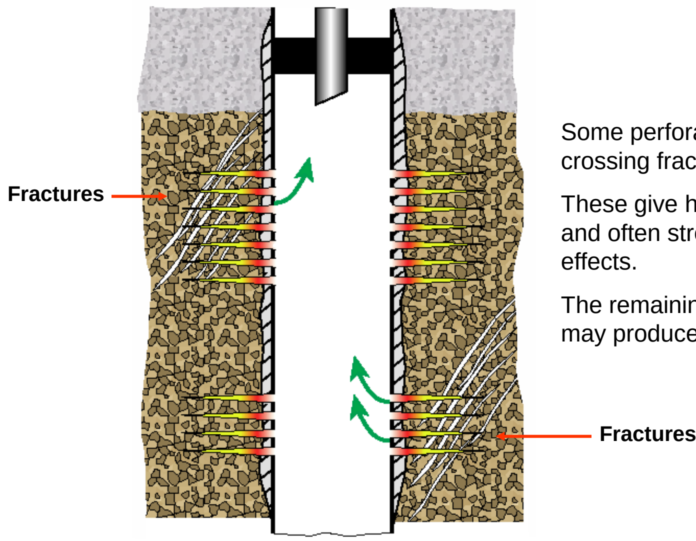
Fracture Production



Some perforations are crossing fractures

These give high flow rates, and often strong jetting effects.

The remaining perforations may produce nothing

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Fracture Topography

- Fractures occur primarily in carbonates and they are usually in a consistent direction.
- They may appear at random in the well
- They are the major flow paths for the reservoir
- They may connect with the gas above or the water below the oil zone and create unwanted fluid entries
- The fractures may conduct the flow of water, while the matrix still remains hydrocarbon saturated

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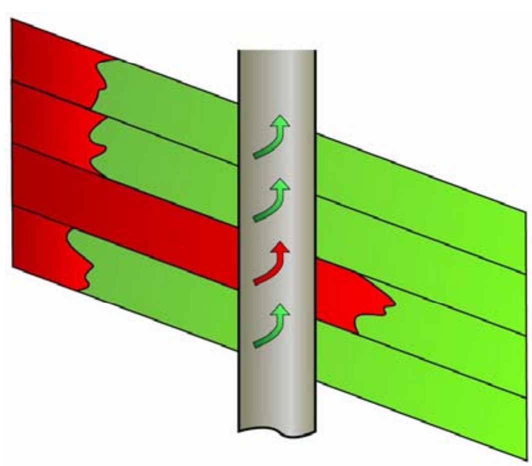
Fracture Evaluation

There are a number of methods of fractures detection during open hole logging.

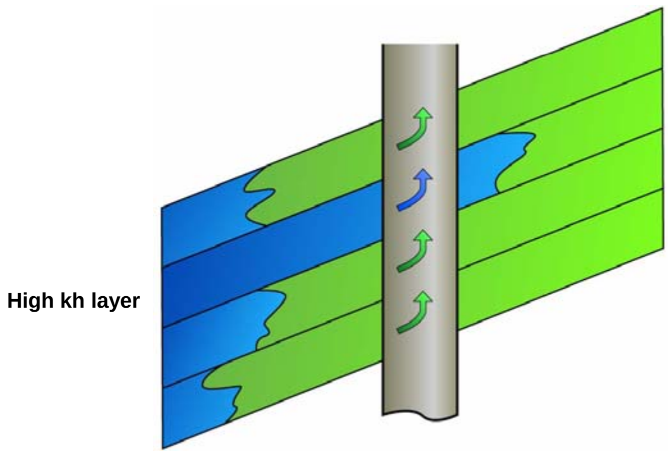
- Resistivity imaging
- Core sample analysis
  A detailed examination will give fracture density, exact location and possibly aperture.
- Well test interpretation will possibly be affected by the presence of fractures. (Often masked by the effect of wellbore storage)
- Drilling Records e.g. losses

Early gas breakthrough

High kh layer



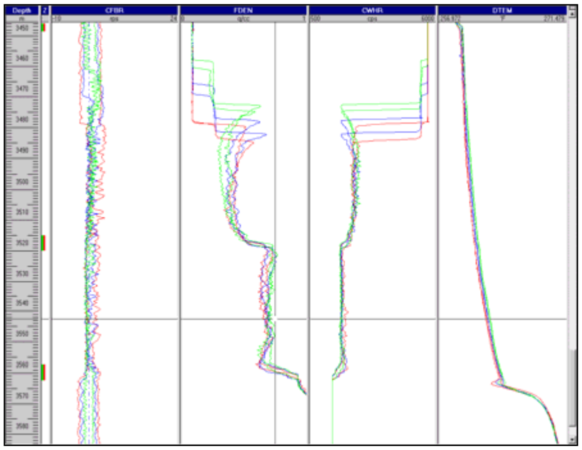
Early water breakthrough



02

Production Logging: More Info

There is often more information than just calculations:
Moving water column with changing BHP



Shut-in Pass: Water column moving up

02

Problems - Injectors

The objective of the injection well is to get the fluid into the selected zones.

Are all zones taking fluid – Injection Profile

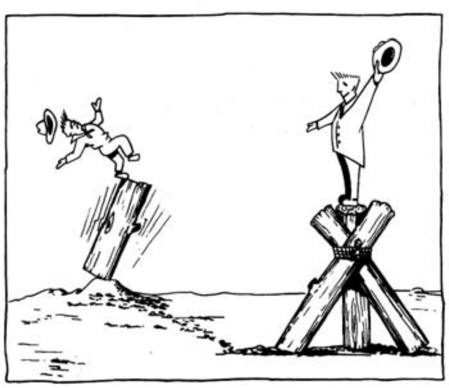
Is any zone taking “extra” fluid – Thief zone

Is fluid going into anywhere it shouldn’t
Casing leak, squeezed perfs?

Is there flow behind casing – channeling?

Is there crossflow?

PL INTERPRETATION?



Validate the interpretation against all known completion, and reservoir information.

PVT

KAPPA

FOUNDATION
PRODUCTION LOG
INTERPRETATION
COURSE

Module #3 PVT

PVT

PVT: Properties of Reservoir Fluids as function of

P ressure

V olume

T emperature

Use of PVT in Emeraude

1. **PVT properties are used as inputs to the calculation process, in generating the downhole solution. e.g.**
   - Reynolds number (Flowmeter VPCF & Gradio frictions)
   - Correlations (Flow regime & Slippage velocity)

2. **PVT properties are also used to convert the calculated downhole rates to standard conditions. (Bo, Bg, Bw)**

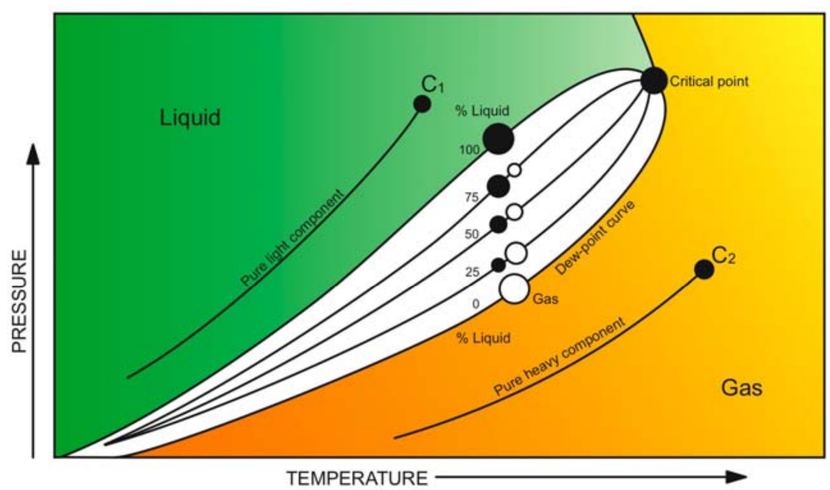
OBJECTIVE
We need the best PVT parameters that suit the uses described above.

NOTE: Errors in the PVT can introduce significant errors in the computed EMERAUDE results!

 03

Two Component System:

Pressure vs. Temperature



 03

PVT: Curve Definitions

Dew-Point Curve

Pressure – Temperature trajectory at which the saturated vapour starts to condense.

Bubble-Point Curve

Pressure – Temperature trajectory at which the liquid starts to boil.

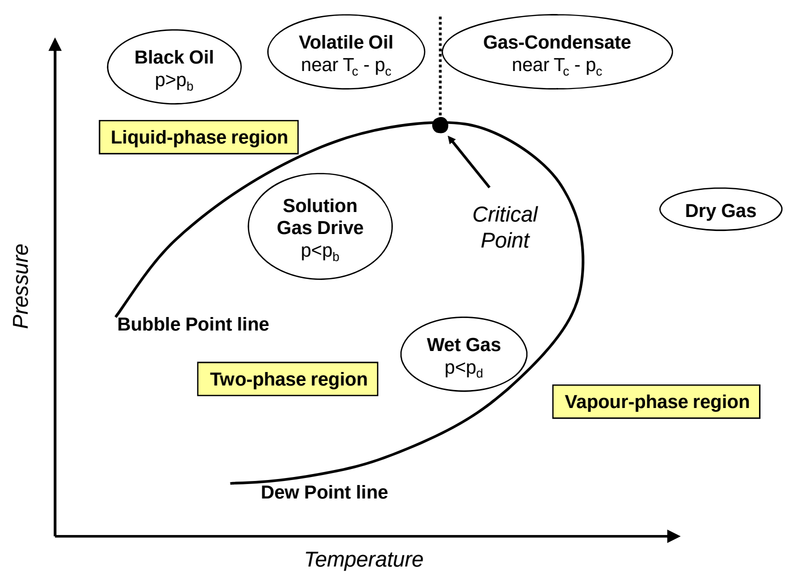
Critical Point

point where the ***bubble point and dew point curves meet***.

It is the point at which vapour and liquid phases become indistinguishable.

 03

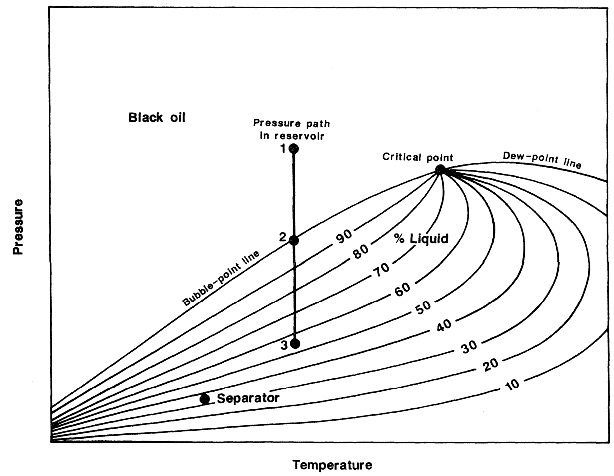
Reservoir Types



 03

Black Oil *p-T* Diagram

Black Oil



Typical values:

γ_o < 45ºAPI

GOR_i < 1,000 scf/stb

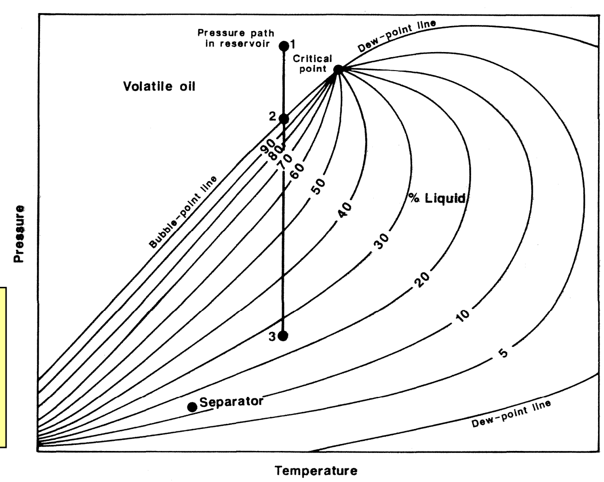
B_{oi} < 2.0 rb/stb

C_{7+} > 30 %

03

Volatile Oil *p-T* Diagram

Volatile Oil



Typical values

45º<γ_o<60ºAPI

1000 < GOR_i < 8000 scf/stb

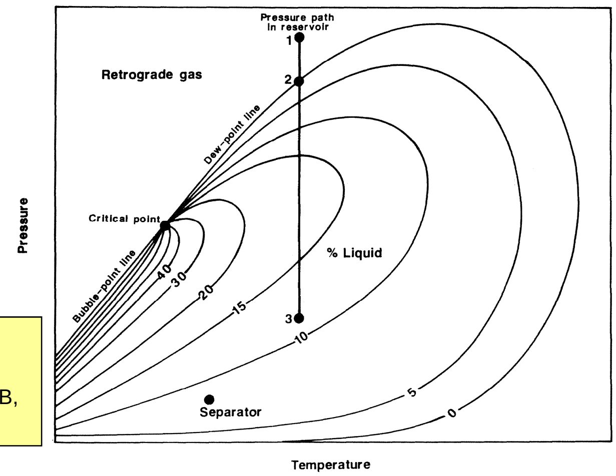
B_{oi} >2.0 v/v

C_{7+}>12.5%

03

Gas: Condensate *p-T* Diagram

Retrograde Gas

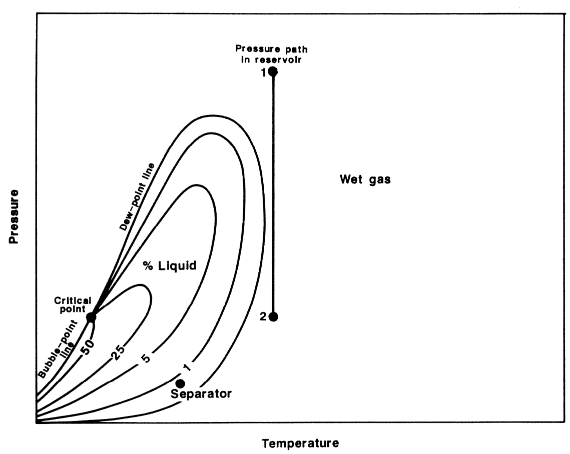


Typical values
γ_o>60º API,
70K < GOR_i < 150K scf/STB,
C_{7+} < 12.5 %.

03

Wet Gas *p-T* Diagram

Wet Gas

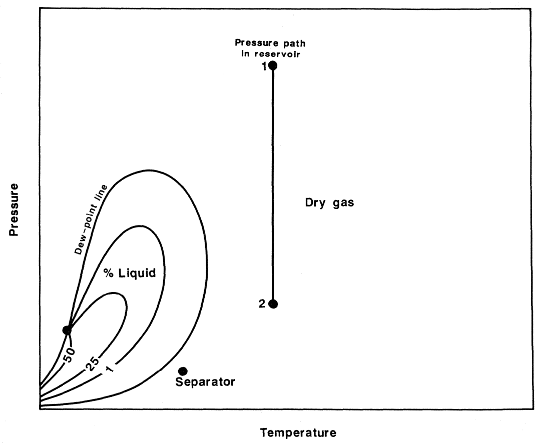


Typical values
GOR_i > 100,000 scf/STB.

03

Dry Gas *p-T* Diagram

Dry Gas



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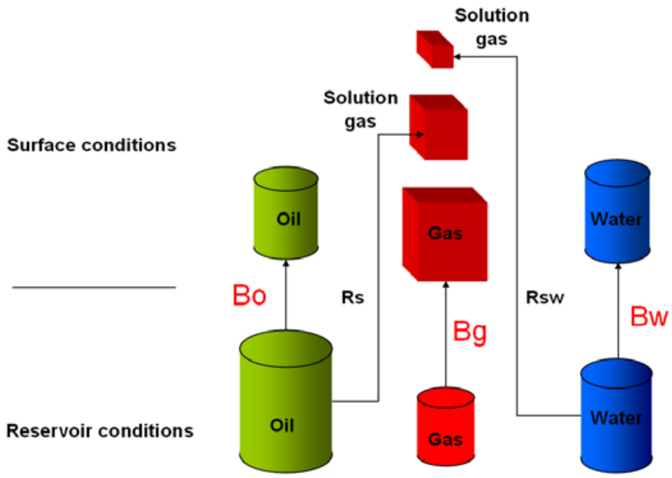
Summary of Classifications

	Oil		Gas		
	Black	Volatile	Condensate	Wet	Dry
GOR [kscf/b] CGR [kstb/MMscf]	< 1.75	1 – 8	70 – 100 14.3 - 10	>100 < 10	
API Gravity	< 45	45 - 60	> 60		
Bo	< 2	>2			
Color	dark green - black	light brown – green	light	clear	
Mole % C7+	> 30	>12.5	< 12.5		

After Barrufet's: Classification of the Hydrocarbon Stream (Texas A&M)

03

Formation Volume factors



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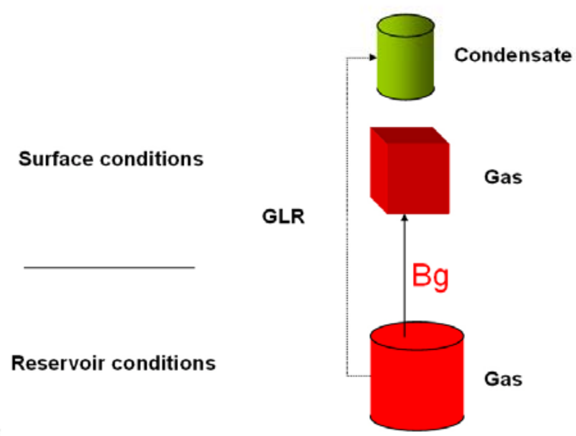
Retrograde Gas Condensate



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Formation Volume Factor

Formation Volume Factor: $B_{o,g,w}$

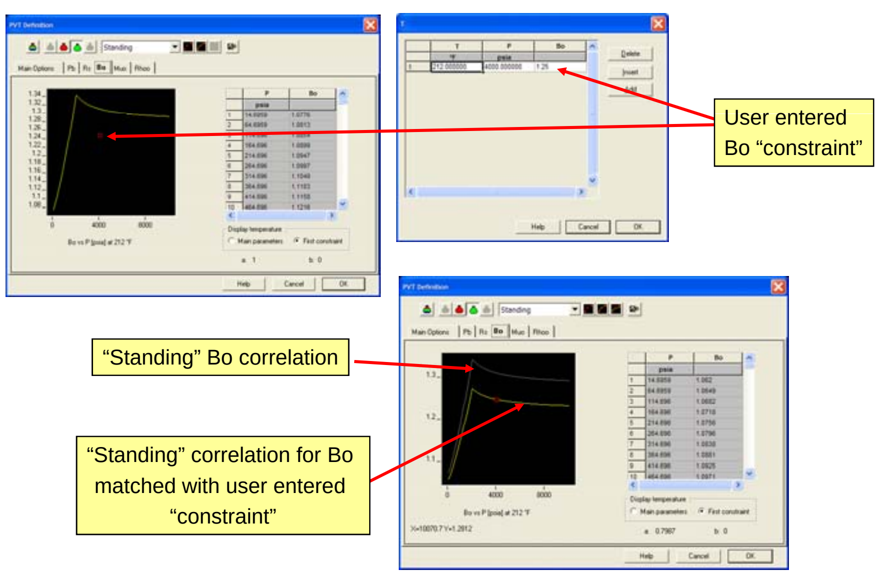
$$B_{o,g,w} = \frac{\text{Fluid volume at reservoir conditions}}{\text{Fluid volume at standard conditions}}$$

The *Formation Volume Factor* "converts" surface volumes to downhole conditions.

Typical values:

Oil:	1.2	to	2.4	RB/STB
Gas:	0.003	to	0.01	rcf/scf
	100	*to*	*333*	*scf/rcf (=expansion factor)*

Oil Volume factor - Constrained

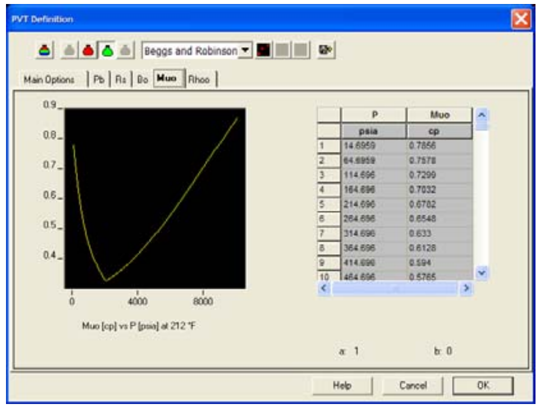


Viscosity

Fluid viscosity depends on pressure, temperature and composition.

Typical values:

- Oil: 0.2 - 30 cp
- Gas: 0.01 - 0.05 cp
- Water: 0.5 - 1 cp



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Fluid Correlations

Oil PVT Correlations used in Emeraude

	R_s/p_b	B_o	μ_o	c_o
Standing	☑	☑	-	-
Lasater	☐	-	-	-
Vasquez and Beggs	☐	☐	-	☑
Glaso	☐	☐	☐	-
Lasater- Standing	☐	-	-	-
Petrosky and Farshad	☐	☐	-	☐
Beggs and Robinson	☐	-	☑	-
Beal	-	-	☐	-

☑ generally used as default

 03

Gas

In order to keep the liquid flow equations linear, the variations in gas properties are accounted for by the real gas pseudo-pressure function

$$m(p) = \int_{p_0}^{p} \frac{2p.dp}{\mu(p).z(p)}$$

Pseudo-pressure available as a scaling option in Emeraude SIP plot

Gas Correlations

Gas PVT Correlations used in Emeraude

	z-factor	μ_g
Dranchuk, et al.	☐	-
Beggs and Brill	☑	-
Hall and Yarborough	☐	-
Lee, et al.	-	☑
Carr, et al.	-	☐

☑ generally used as default

Condensates

Two methods to define Condensates in Emeraude:

"Dry Gas" and Condensate.

"Dry gas" Condensate is added to the dry gas stream to get downhole properties.

- The recombination ratios are based on the total measured surface rates and densities.
- The analysis assumes single phase production (no oil phase)
- Can be used in low-medium CGR wells (mist flow, check your correlation)

Remark mist flow assumes no slippage

Condensates

Condensate Fluid is split into two components: gas and liquid

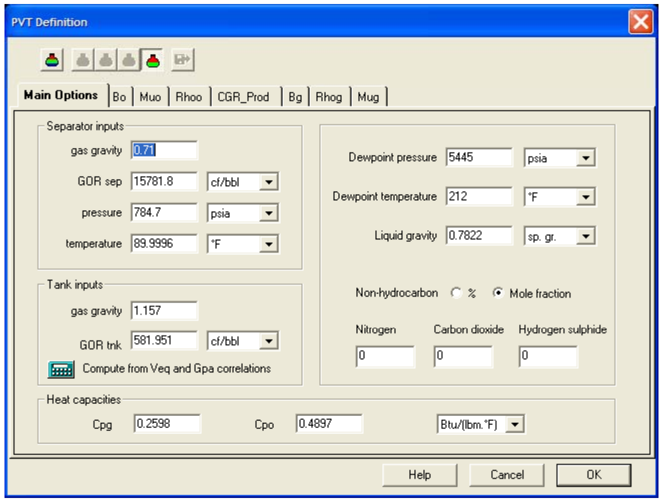
- Can distinguish between oil and gas downhole

Caution Split into two downhole phases is often difficult:

- Requires more detailed surface data and PVT properties are critical
- Holdups are often difficult to determine:
  - Uncertainties in densities gives wrong split (for instance the friction in gradio measurements)
  - GHOST: max fluid velocity is 9 m/s. And measurements are affected by presence of (small) water droplets)
  - In condensate wells part of the liquid flow is along the pipe: not measured

It is recommended to use the "Dry Gas" option where possible

Condensates



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PVT Parameter Source

Source of the PVT parameter values:

Laboratory
- Accurate, Expensive
- Time delay.
- Laboratory PVT results present a problem as they are often isothermal, derived at a single reservoir temperature.
- NOTE: **EMERAUDE** requires a non-isothermal PVT

Correlations
- Fast
- Built in to **EMERAUDE**
- Less accurate
- Oil viscosity often problematic.

The best solution is to use PVT Correlations, and constrained by Laboratory measurements (or in some cases density readings from the PL tool)

03

PVT: Lab Measurements

Examples of PVT Lab analysis:

******Flash Vaporization*:** in equilibrium during T&P traverse (tubing and separator)

***Differential Vaporization*:** Gas is removed at every step (reservoir)

Hydrocarbon Analysis of reservoir fluids

Additional and Special Analysis, such as detailed liquid drop-outs and accurate phase envelopes for volatile oils and gas-condensate reservoirs (LNG).

Essential PVT Inputs

Minimum PVT parameters required for EMERAUDE

WATER

- Salinity ppm

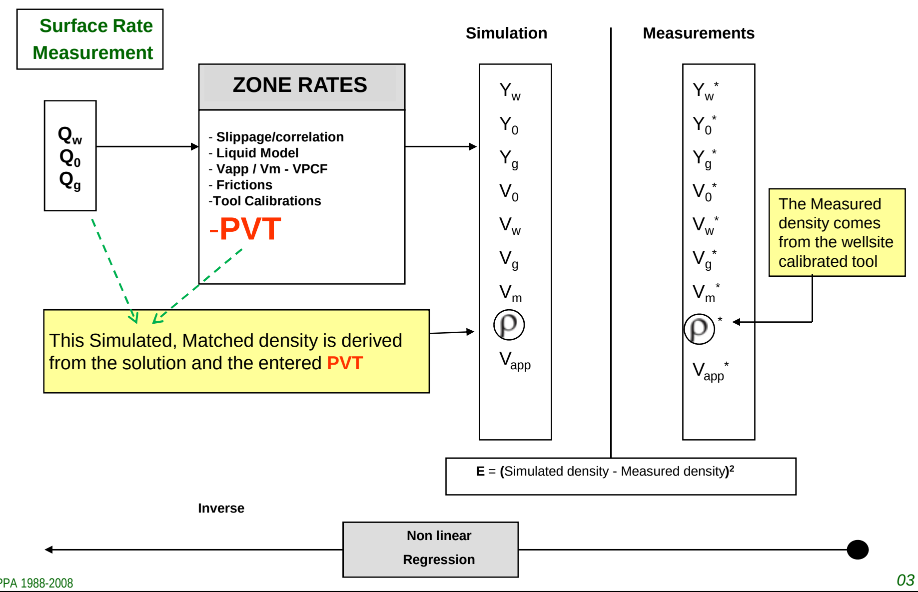
OIL

- Gravity API
- Rs (Solution Gas-Oil Ratio)..
- NOTE: Rs is not necessarily the produced GOR!!!

GAS

- Specific gravity

Importance of PVT - Density



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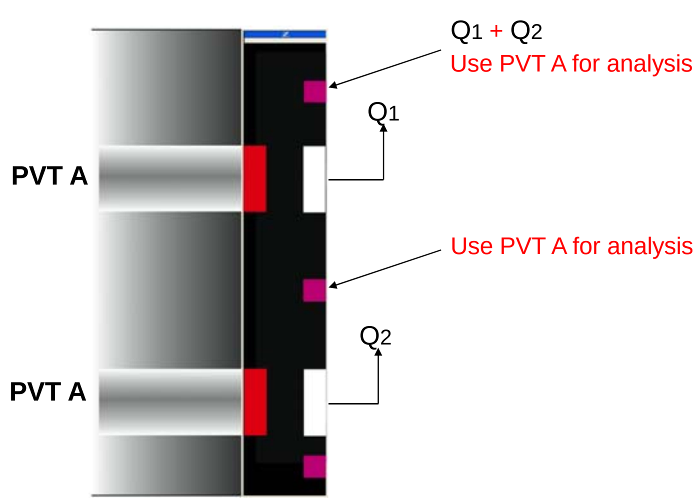
Zoned PVT



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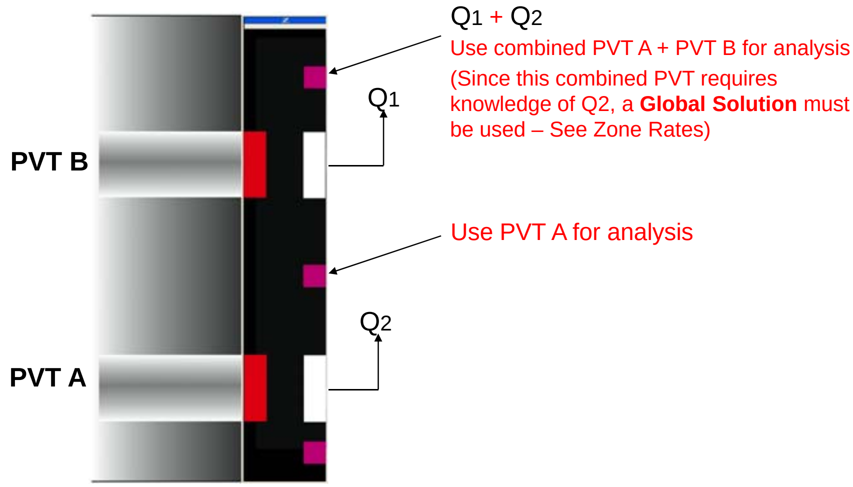
Zoned PVT



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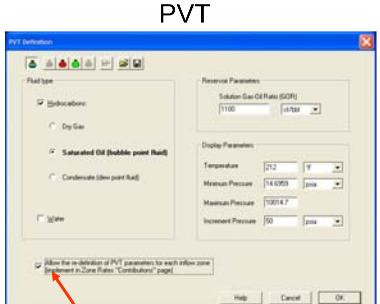
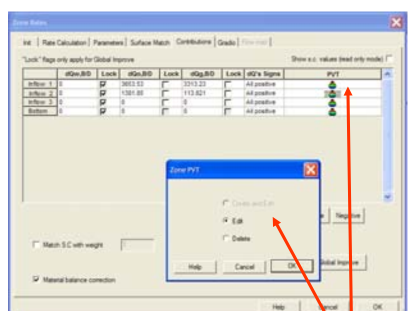
Zoned PVT

PVT



Zone Rates



Enable "Zoned PVT" option in the PVT dialogue

Initialise PVT for each inflow zone prior to Global Improve for simultaneous optimisation

03

PVT References

- Fundamentals of Reservoir Engineering — Calhoun (1953).
- Properties of Petroleum Fluids — McCain (1990).
- Reservoir classification Based on Fluid Types, Barrufet, PETE 323 Texas A&M
- Hydrocarbon Liquid Phase Definition, Determination and Allocation in Two-Phase Hydrocarbon Reservoir, A.N. Hamoodi et. al., SPE 78363 (2002)
- Fundamentals of Reservoir Engineering – L.P. Dake ISBN 0-444-41380-X Elsevier

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