SECTION 2

Open Hole Logs

- Wireline and alternative conveyancing
- Major types of tools
- The problem of invasion
- Specific logging tools used for reservoir description and evaluation
  - Gamma Ray, Spontaneous Potential
  - Density, Neutron
  - Sonic
  - Archie's Equation and Resistivity
  - Wireline Formation Testing
- Log Exercises in Formation Evaluation
  - Calculate net/gross, porosity, Sw, identify fluid contacts, fluid content and pay zones

Session overview

Objective: learn how to evaluate basic open hole logs

- **Petrophysics introduction**
- **Log data acquisition**
- **Quicklook openhole log evaluation**
  - **Gamma-ray**
  - **Density/Neutron**
  - **Resistivity** *(qualitative interpretation)*
  - **Resistivity** *(quantitative interpretation):* **the Archie equations**
- **Quicklook summary**
- **Quicklook exercise**

Discipline mission for petrophysics

- Objectives of Petrophysics

  Identify and quantify hydrocarbon resources in the subsurface and evaluate fluid & rock properties.

- Deliverables:

  Static & Dynamic reservoir description and fluid distribution at and away from the wellbore.

Hydrocarbon volume

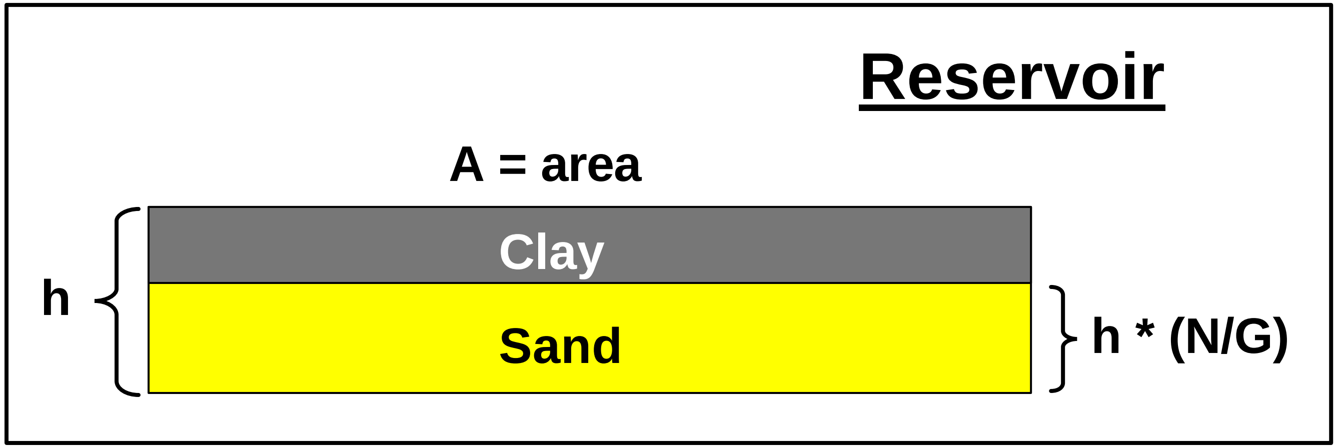
$$HCVOL = \underbrace{A * h}_{\text{Reservoir volume}} * (N/G) * f * (1 - S_w)$$

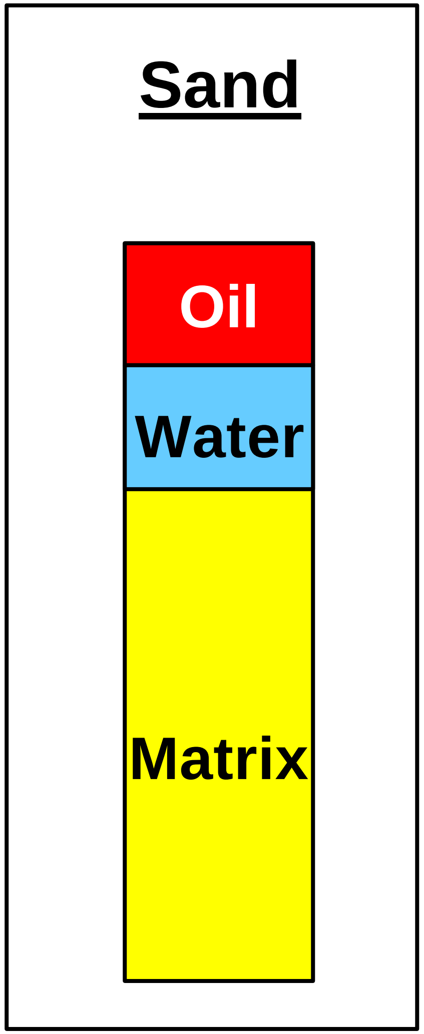
Hydrocarbon volume

Net over gross

Porosity

Water saturation



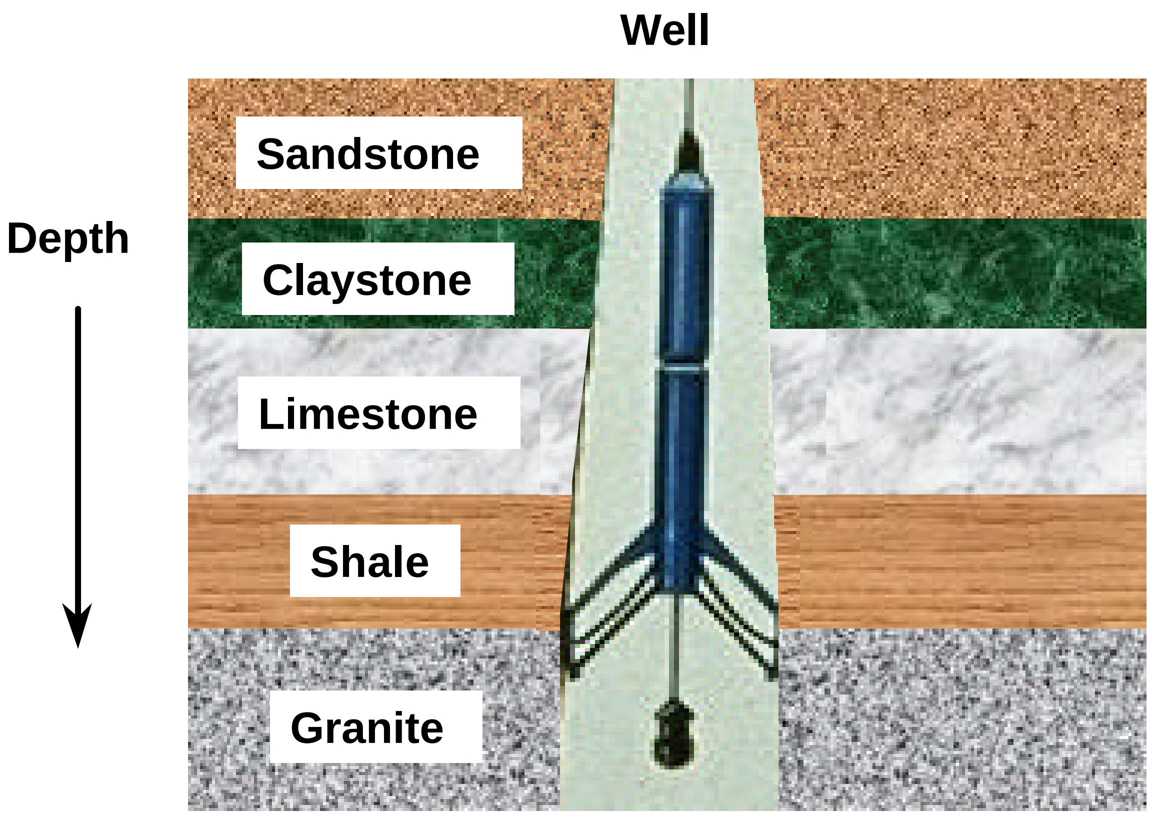


Direct & indirect measurements

- **Direct measurements:**
  direct comparison
  (e.g. ruler, weighing scales)

- **Indirect measurements:**
  via the effect on something else
  (e.g. temperature via Hg expansion)

Calibration is always required !



Open Hole Logs

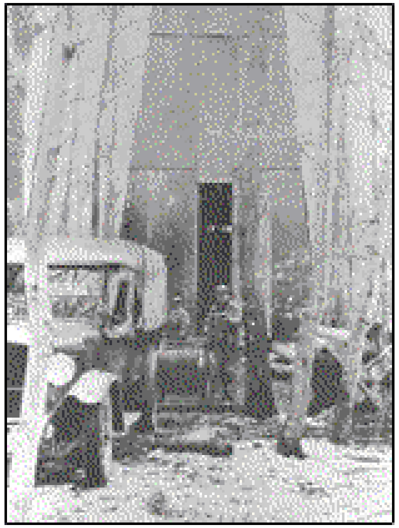
- Resistivity
- Nuclear
- Acoustic
- Nuclear Magnetic Resonance
- Sampling

Formation Properties

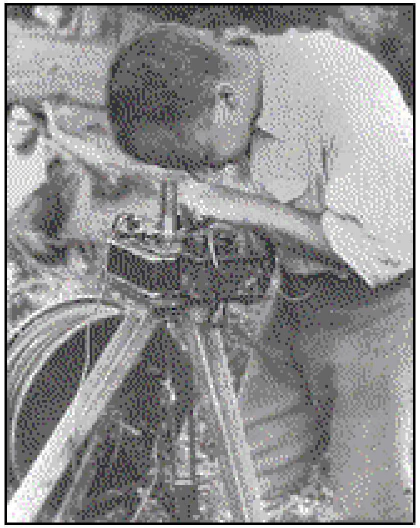
- Rock type
- Porosity
- Permeability
- Fluid type
- Fluid volume
- Formation tops
- Fractures

“Acquisition in 1927 ……”

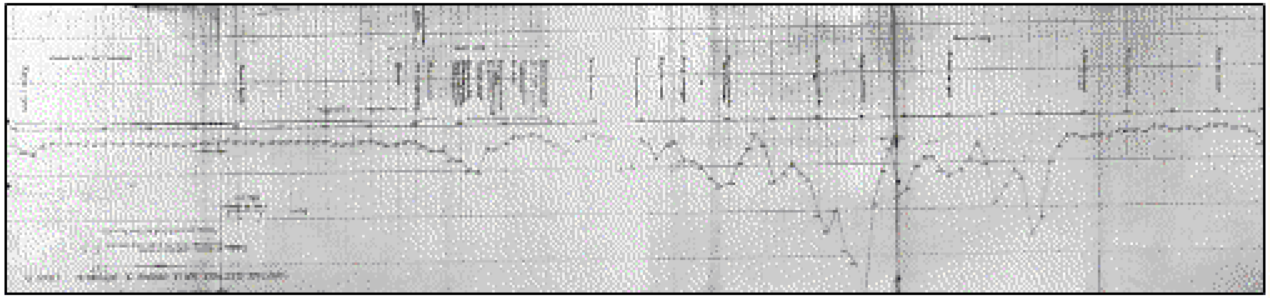
The First Log



Well in Pechelbronn - France



Surface Recording Instrument



The “First” Log recorded in 1927

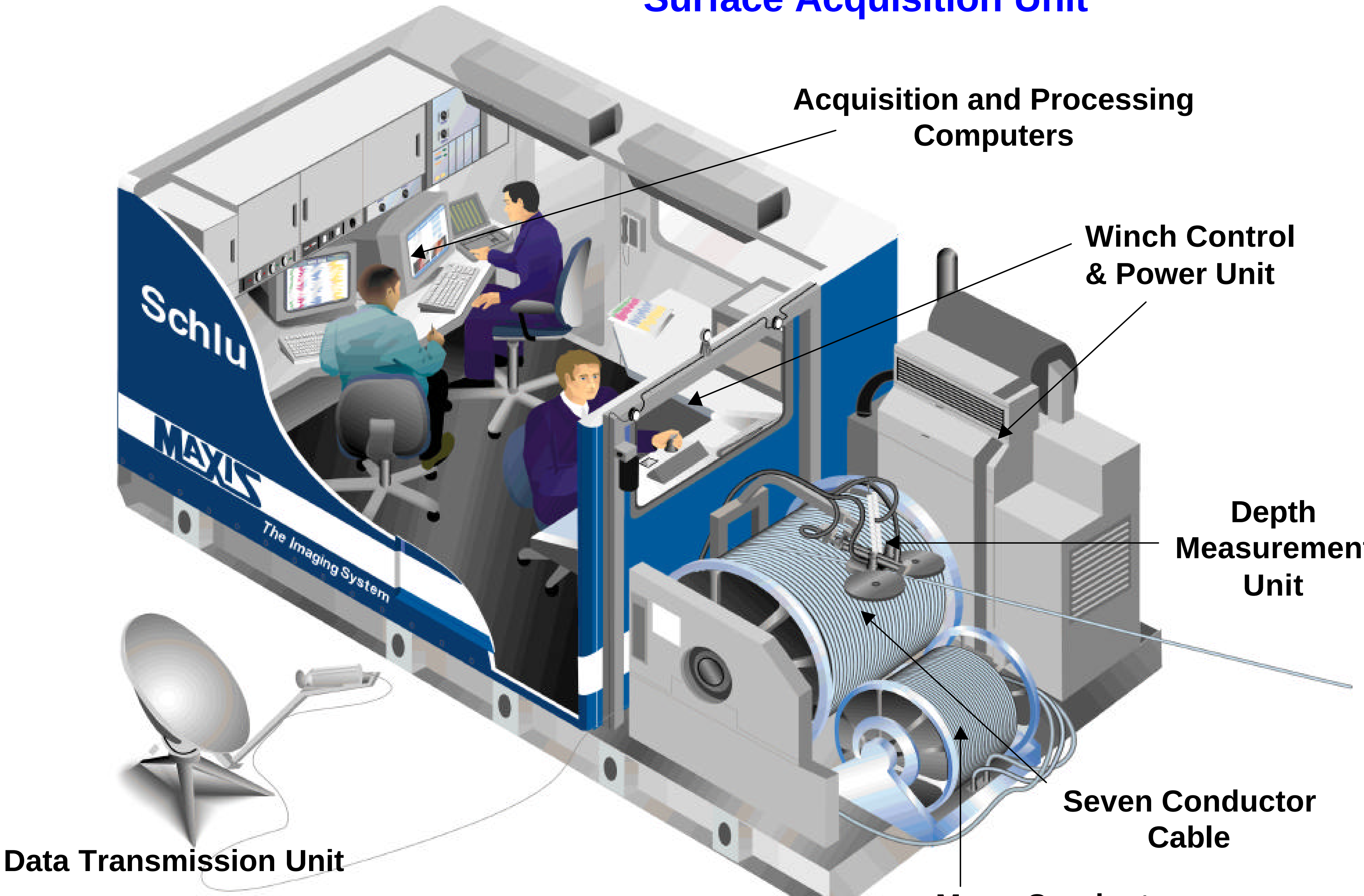
The first log was recorded by Schlumberger in 1927 in a 500m deep well in France. Only one curve was recorded, a Resistivity curve, through a point-by-point system. The instrument was stopped at a point in the hole. A measured amount of current was sent into the formation and the resulting potential was noted. The Resistivity recordings proved to be perfectly repeatable in neighboring wells, enabling precise correlation of formations across an entire field.

"..............Data Acquisition Now"

Typical Land Wireline Unit

Typical off-shore Wireline Unit

Surface Acquisition Unit



Courtesy: Schlumberger

Logging companies

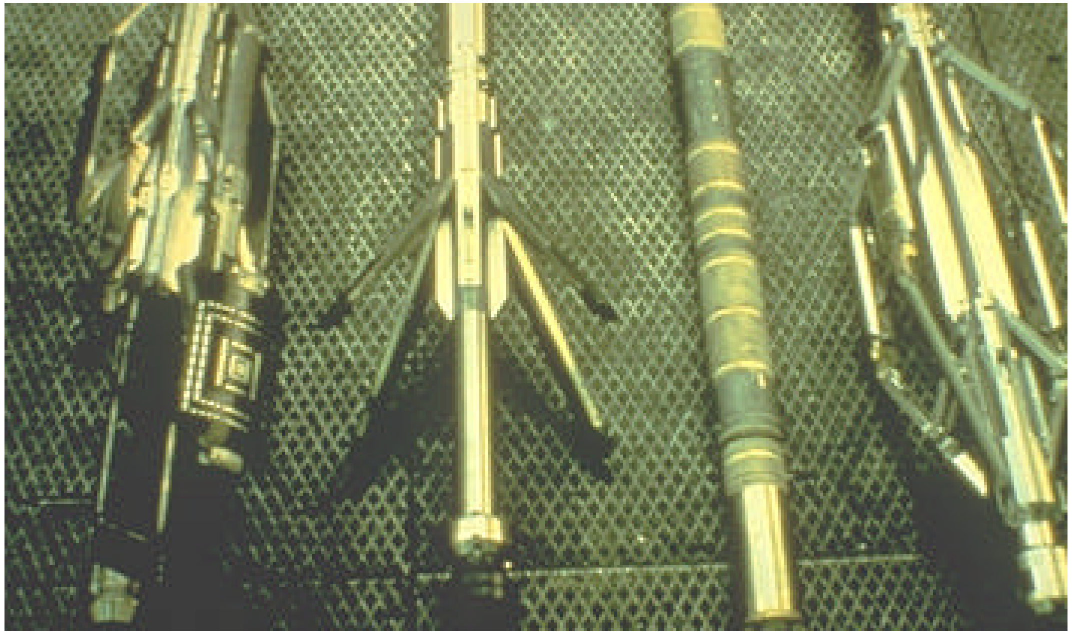
- **Wireline:**
  - **Schlumberger**
  - **Baker - Atlas**
  - **Halliburton**
  - **Reeves (was BPB)**

- **Logging while drilling**
  - **Anadrill** *(Schlumberger)*
  - **Baker-Hughes Inteq** *(incl. Teleco)*
  - **Halliburton (incl. Sperry Sun)**

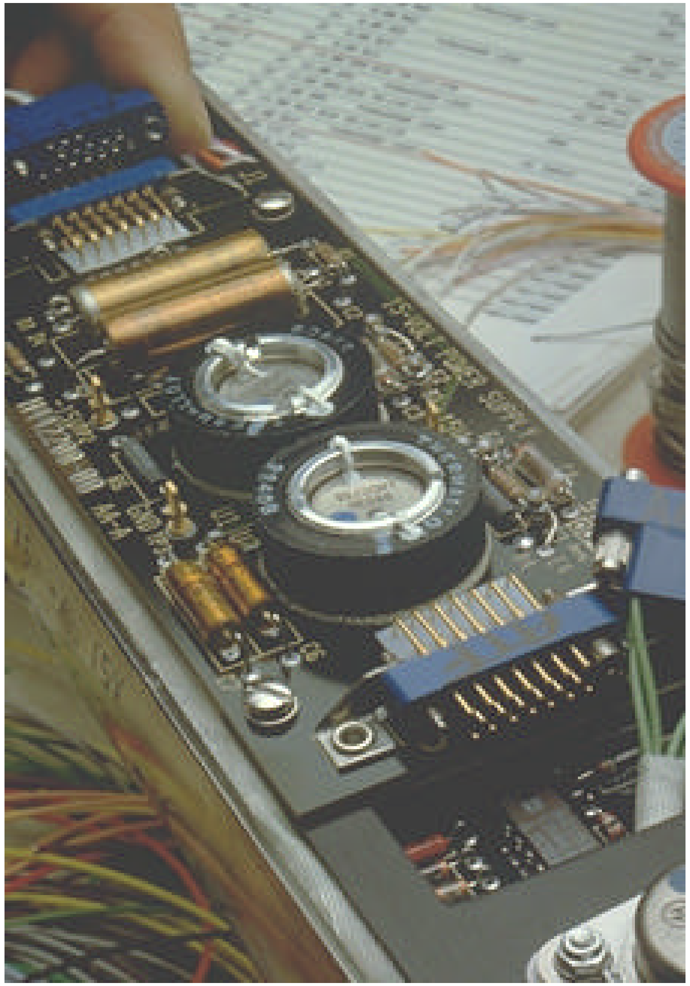
Tools

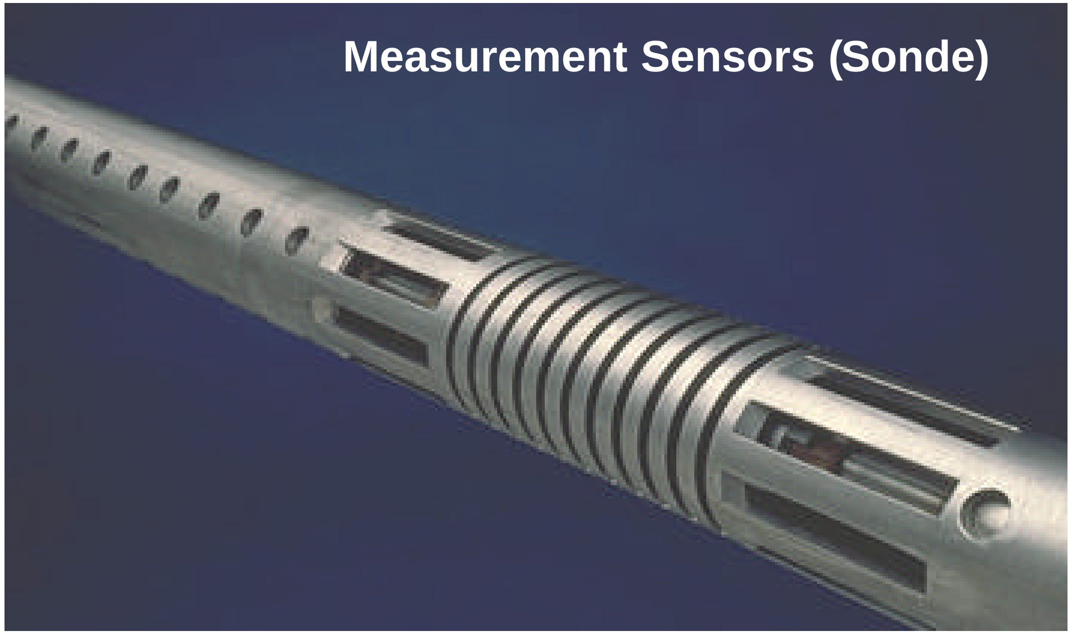
Source: Reeves Website

Logging Tools

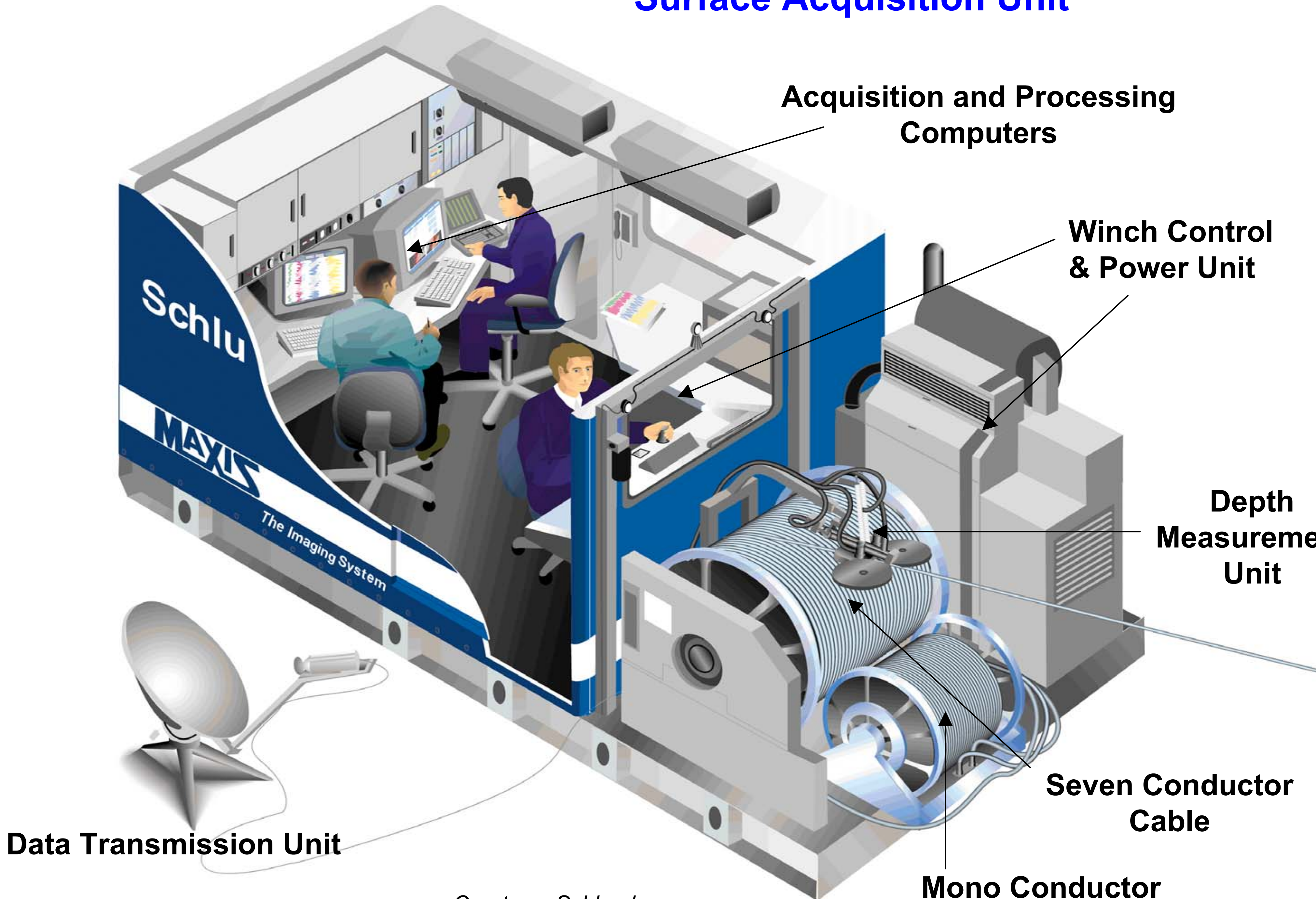


Logging tool Electronics



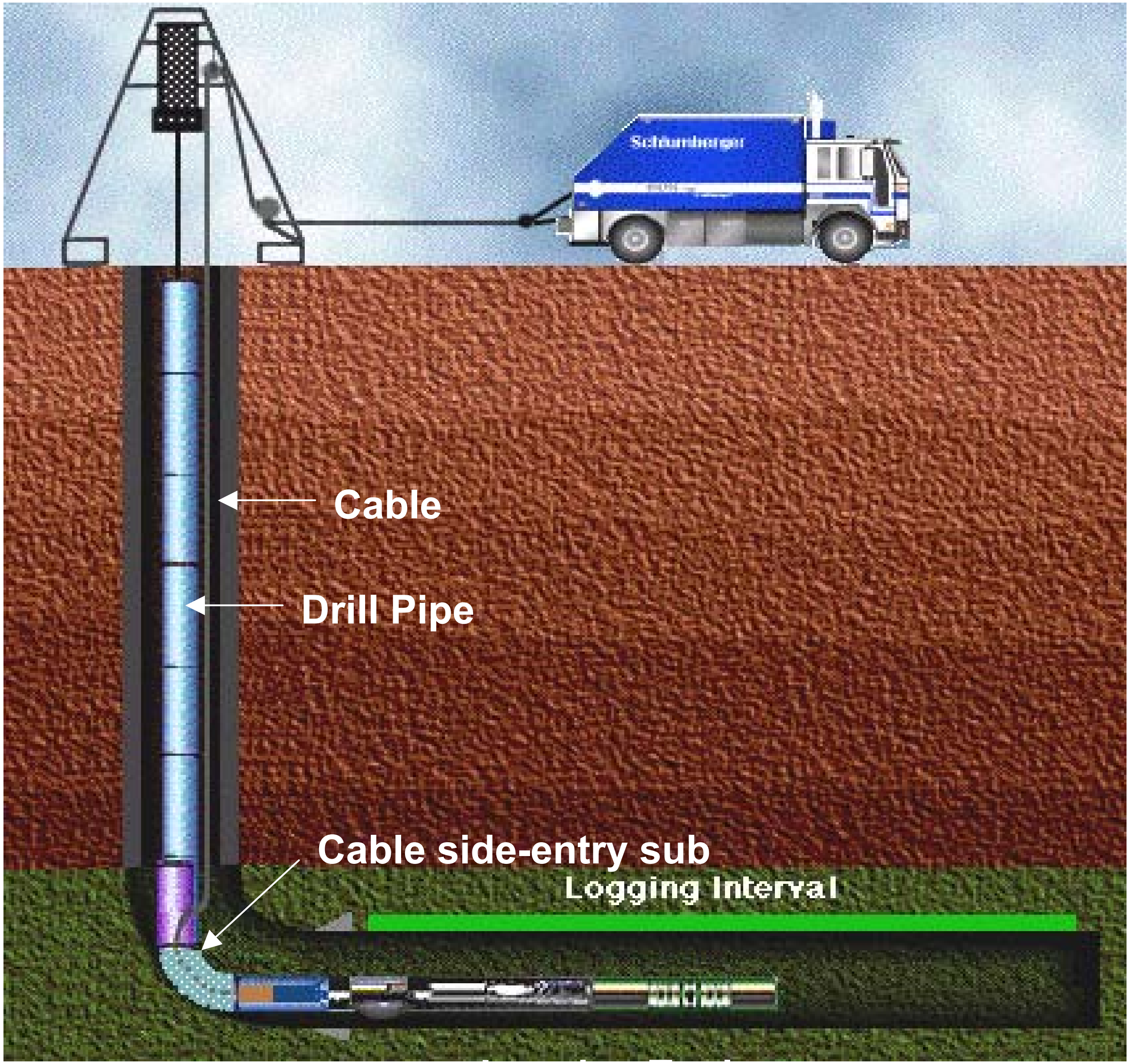

Measurement Sensors (Sonde)

Surface Acquisition Unit



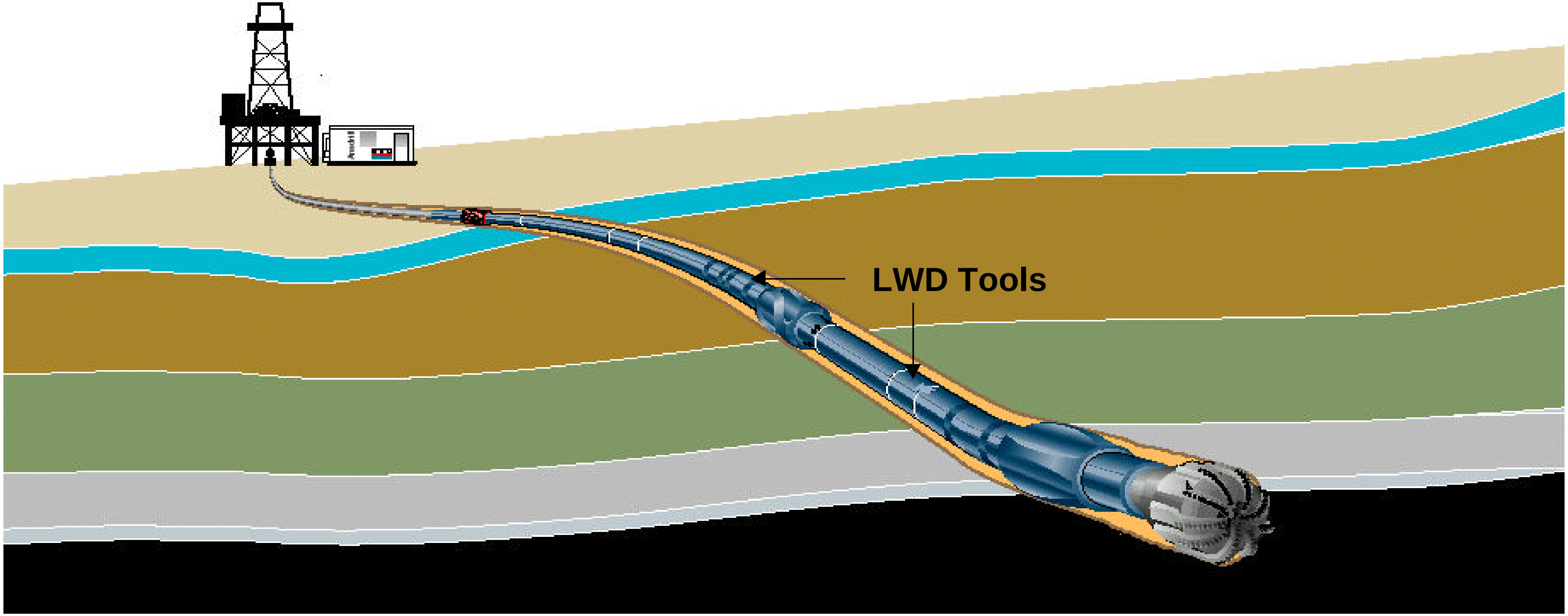
Courtesy: Schlumberger

Horizontal Well Logging



courtesy of Schlumberger

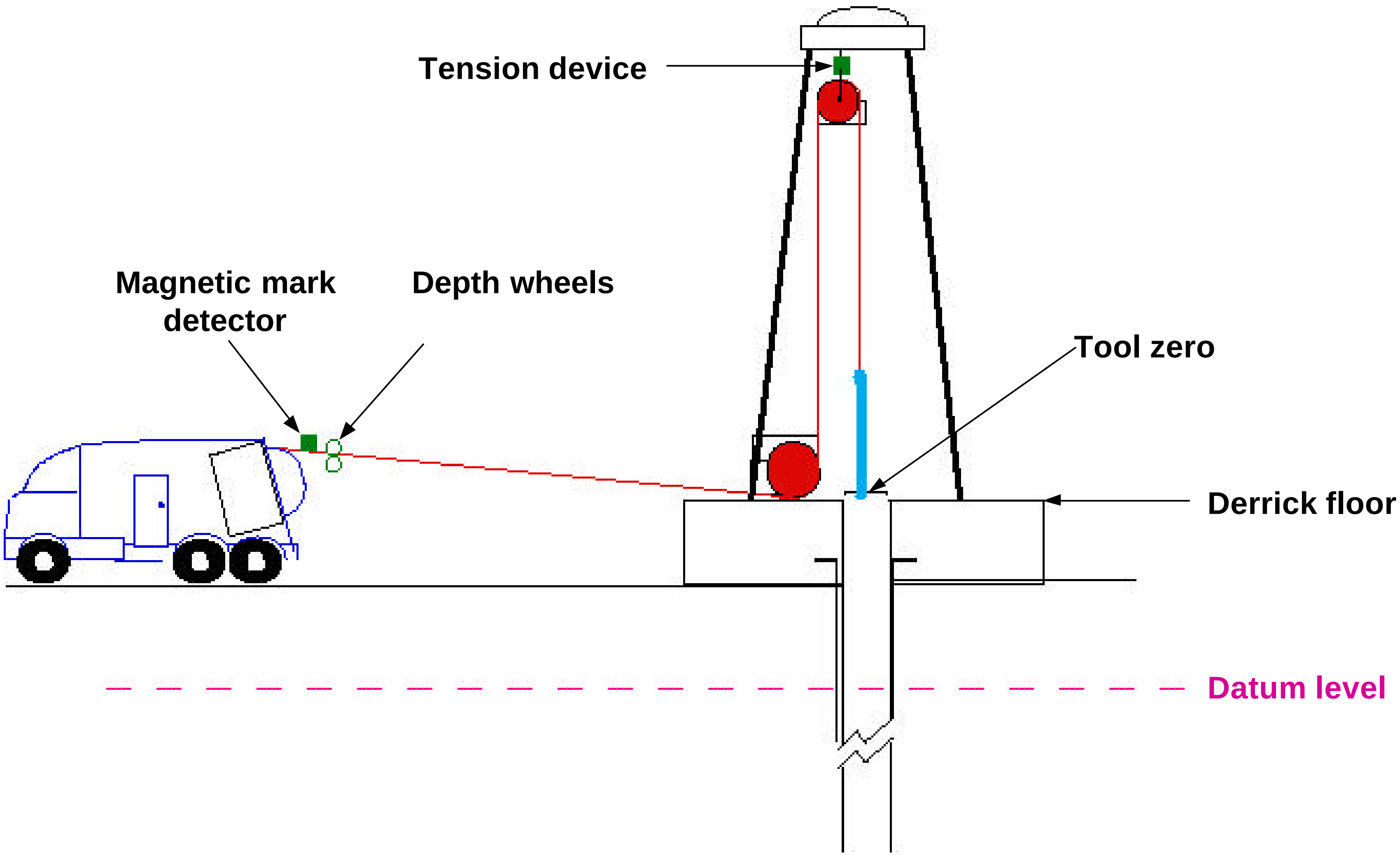
Logging while Drilling



Depth

- Loggers (wireline) depth
  - Depth determined from wireline measurement using a calibrated cable and calibrated wheel
  - Generally provides the most accurate depth
  - All log analysis is carried out using the loggers depth (sometimes referred to as "measured depth" or MD)
- Drillers depth
  - Depth determined by counting the number of stands of drill pipe
  - Generally provides less accurate depth than wireline
  - All core analysis is carried out using the drillers depth (sometimes referred to as "core measured depth" or CMD)
- A correction is generally required from drillers depth to loggers depth
- Well TD will be different for logger and driller
  - Wireline tools are not lowered into the very bottom of the hole (the "rat hole")

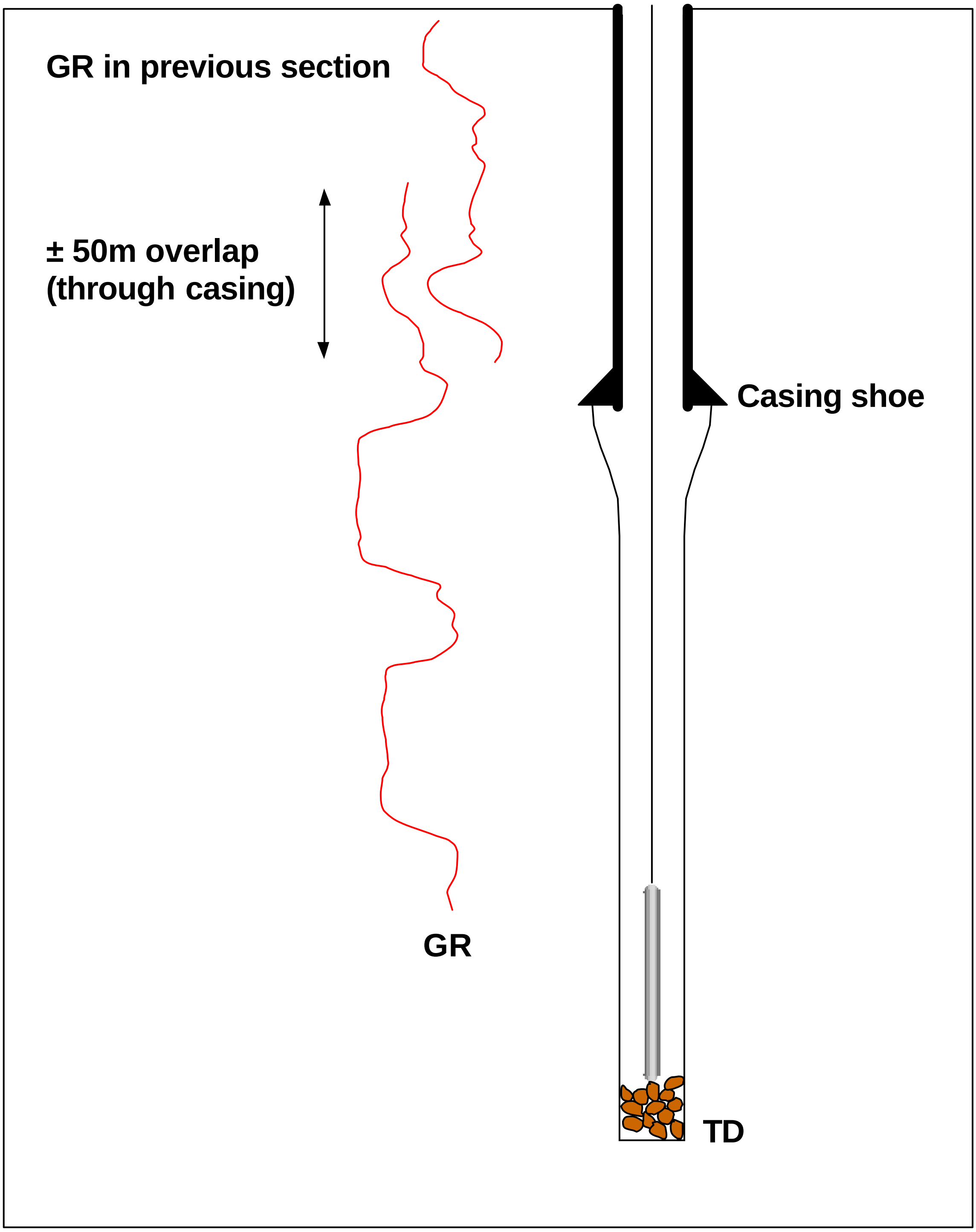
Depth measurement



Depth control

- First Survey in Well
  - Usually GR-Resistivity
  - Calibration using magnetic marks
- Subsequent Surveys (Same Section)
  - Correlate to first survey
  - Errors expected
    - tool weight differences
    - travelling block movements
- Subsequent Surveys (New Section)
  - First log must include GR
  - Calibration using magnetic marks
  - Overlap of >50m on previous GR
  - Correlate if error < 0.5 m
- Stretch Corrections
  - Only applied above 3000 m

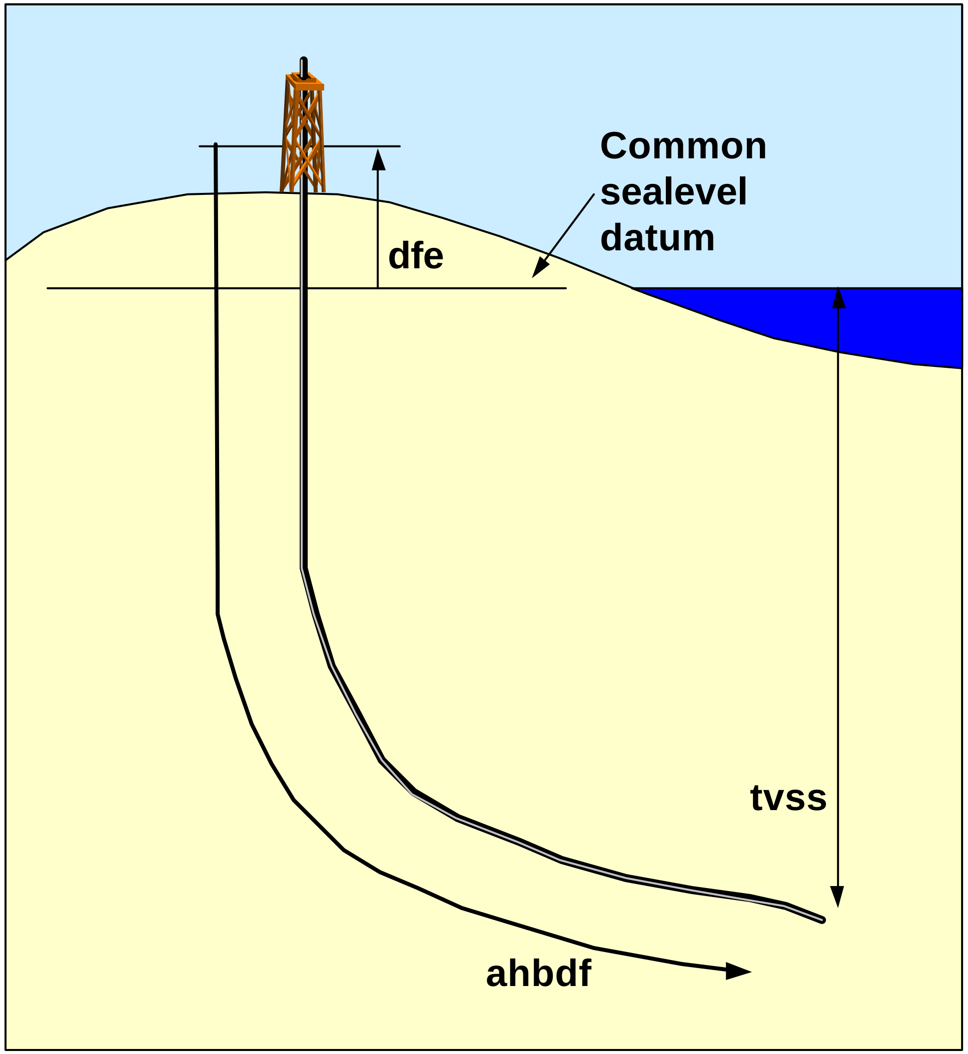
Depth checks



Casing shoe: Depth logger = Depth driller ± 0.1%

TD: Depth logger £ Depth driller

Depth measurements



- **Raw wireline logs** *(ahbdf)*
  - **along hole**
  - **below drill floor**
- **Geological logs** *(tvss)*
  - **true vertical sub sea**
- **Drill Floor Elevation** *(dfe)*

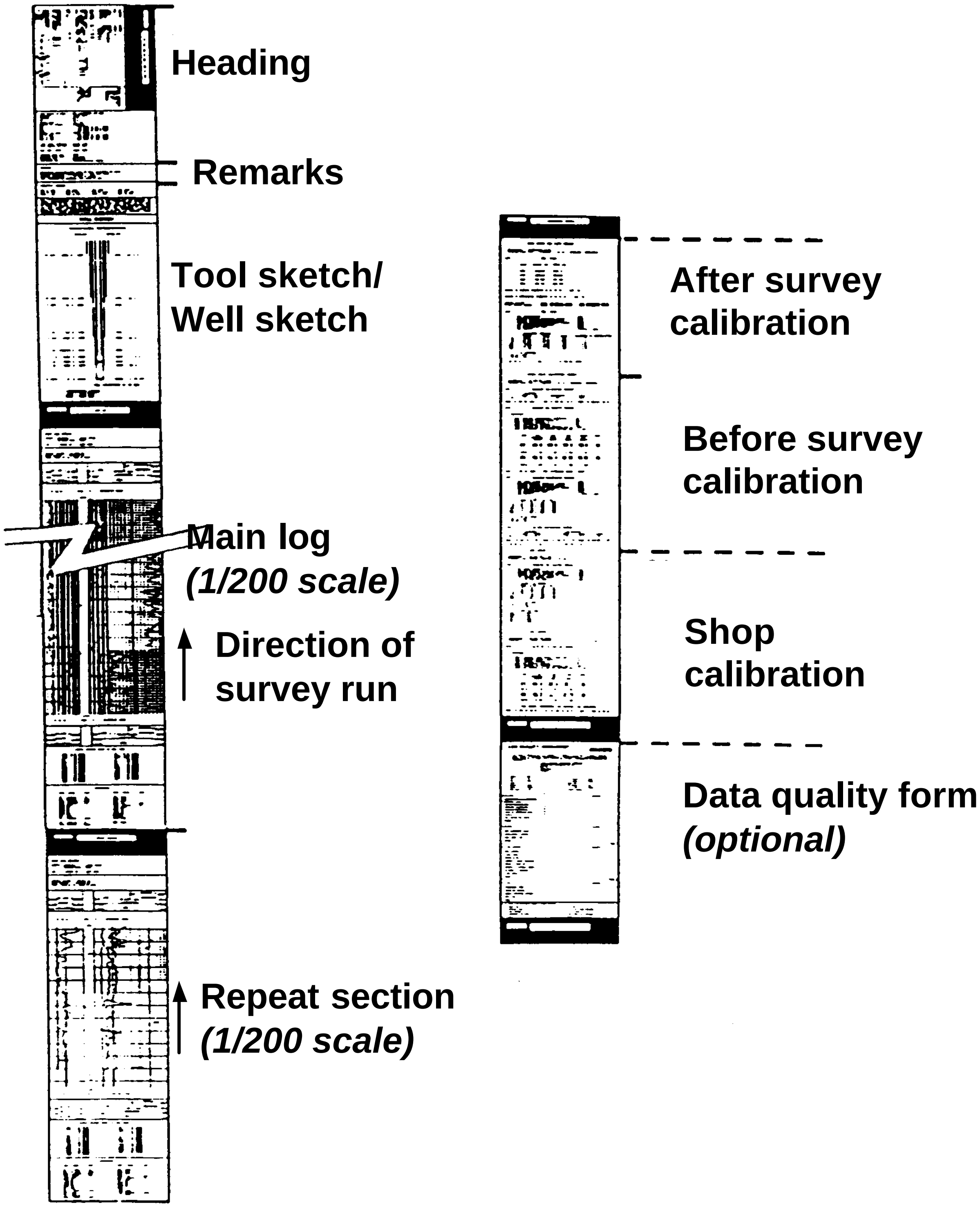
Conversion required for:
correlation, pressures, collision risk

Methods:
*** single shot (vertical wells)**
*** gyro (accelerometer)**
*** magnetic (correct for earth field)**

The LOG

Figure 76. Developing film in "Maggie's Drawers".

The LOG



Heading
Remarks
Tool sketch/
Well sketch
Main log
(1/200 scale)
Direction of
survey run
Repeat section
(1/200 scale)
After survey
calibration
Before survey
calibration
Shop
calibration
Data quality form
(optional)

Example of Log Header

COMPANY: PetroSkills

WELL: BPP-1

FIELD: BPP

RIG: Floating-124

Schlumberger

PEx(HALS)-DSI-NGS
SUITE - 1 , RUN - 1
SCALE: 1/200

RIG: Field: Location: Well: Company:

LOCATION

WA-6-L
Eastings: **126789.3**
Northings **36784.7**

Elev.:		
	R.T.	25.9 M
	G.L.	-127.6 M
	D.F.	25.9 M

Permanent Datum:	L.A.T.	Elev.:	0 M
Log Measured From:	D.F.	25.9 M	above Perm. Datum
Drilling Measured From:	D.F.		

STATE: Alafun	Max. Well Deviation 2.7 DEG	Longitude	Latitude

Logging Date		12-APR-1998					
Run Number		1					
Depth Driller		3495 M					
Schlumberger Depth		3480.5 M (HUD)					
Bottom Log Interval		3477.5 M					
Top Log Interval		153.5 M					
Casing Driller Size @ Depth		9.625 IN	@	1566.84 M		@	
Casing Schlumberger		1568.5 M					
Bit Size		8.500 IN					
Type Fluid In Hole		KCl / PHPA					
MUD Density	Viscosity	1.22 G/C3	70 S				
Fluid Loss	PH	3.4 C3	9.5				
Source Of Sample		Pits					
RM @ Measured Temperature		0.099 OHMM	@	29 DEGC		@	
RMF @ Measured Temperature		0.078 OHMM	@	29 DEGC		@	
RMC @ Measured Temperature		0.186 OHMM	@	28 DEGC		@	
Source RMF	RMC	Sample Pressed	Sample Pressed				
RM @ MRT	RMF @ MRT	0.038 @ 111	0.030 @ 111		@		@
Maximum Recorded Temperatures		111 DEGC	111	109			
Circulation Stopped	Time	12-APR-1998		12:00			
Logger On Bottom	Time	13-APR-1998		5:20			
Unit Number	Location	242	MWA				
Recorded By		D.Pastor/B.Charbit/A.McMillan					
Witnessed By		R. Blake/M. Bilek/S. Western					

Example of Remarks Section

ALL INTERPRETATIONS ARE OPINIONS BASED ON INFERENCES FROM ELECTRICAL OR OTHER MEASUREMENTS AND WE CANNOT, AND DO NOT GUARANTEE THE ACCURACY OR CORRECTNESS OF ANY INTERPRETATIONS, AND WE SHALL NOT, EXCEPT IN THE CASE OF GROSS OR WILLFUL NEGLIGENCE ON OUR PART, BE LIABLE OR RESPONSIBLE FOR ANY LOSS, COSTS, DAMAGES OR EXPENSES INCURRED OR SUSTAINED BY ANYONE RESULTING FROM ANY INTERPRETATION MADE BY ANY OF OUR OFFICERS, AGENTS OR EMPLOYEES. THESE INTERPRETATIONS ARE ALSO SUBJECT TO CLAUSE 4 OF OUR GENERAL TERMS AND CONDITIONS AS SET OUT IN OUR CURRENT PRICE SCHEDULE.

OTHER SERVICES1		OTHER SERVICES2
OS1:	FMI-DSIX-GR	OS1:
OS2:	CMR-GR	OS2:
OS3:	MDT-GR, MSCT-GR	OS3:
OS4:	VSP (CGG)	OS4:
OS5:	CST-GR	OS5:

REMARKS:

First run in hole. Tool string eccentred as per tool sketch.

3 x 1.0" standoffs used on DSI. 2 x 1.0" standoffs used on HALS.

GR and CNT eccentred by bowspring.

Additional mud data: KCl w/v% = 7%;
Barite w/v% = 3.9%;
KCl equivalant = 81,900 mg/L;
Total mud chlorides = 39,000 ppm;
Chemicals: KCl, caustic soda, flowspan, Drispac reg and SL, soltex, circal.

Tide correction = 1.4 m.

Circulation time = 1.5 hours (10:30 - 12:00).

DSI firings: Upper Dipole, Lower Dipole, P & S and DFMD.

GR, CNL, TLD and AIT environmentally corrected.

Neutron porosity corrections: borehole salinity, mud cake, hole size, mud weight, standoff, pressure/temperature.

Surface re-zero = 9.1 m.

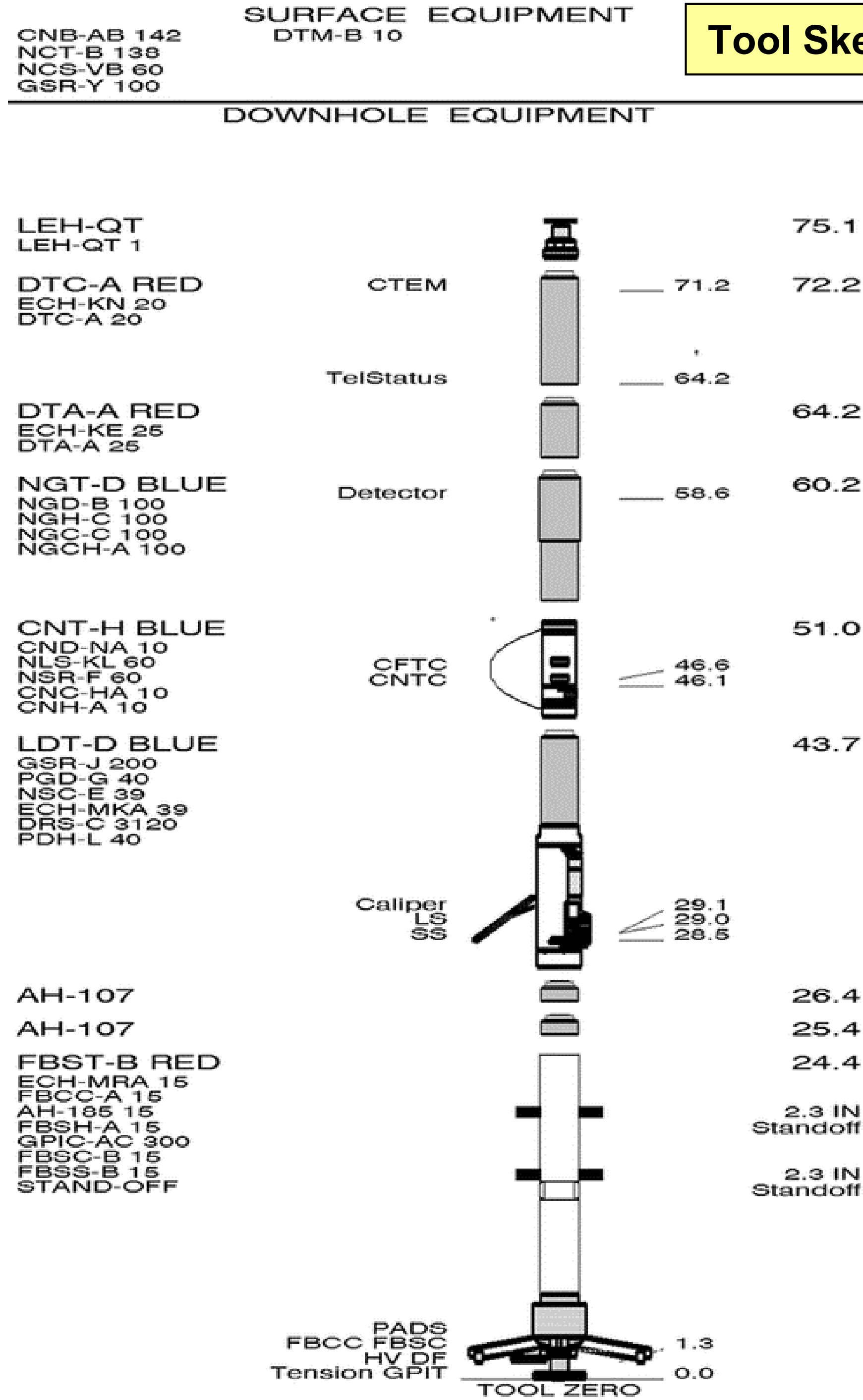
Logger did not tag TD. HUD at 3480.5m.

Log was spliced at 2770m due to software problems.

The NGS appears to be off depth in some places. This is due to the NGS data not being speed/tension corrected (PEx is corrected)

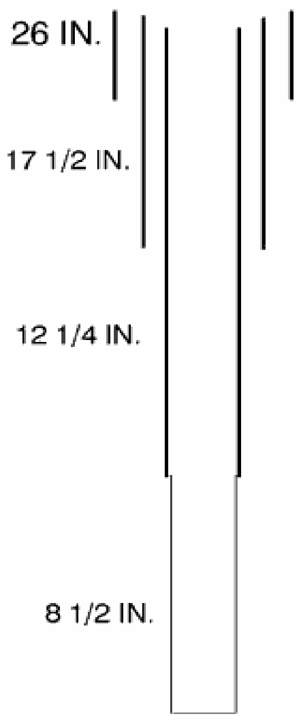
Well & Tool Sketch

Tool Sketch



WELL SKETCH

BIT SIZE

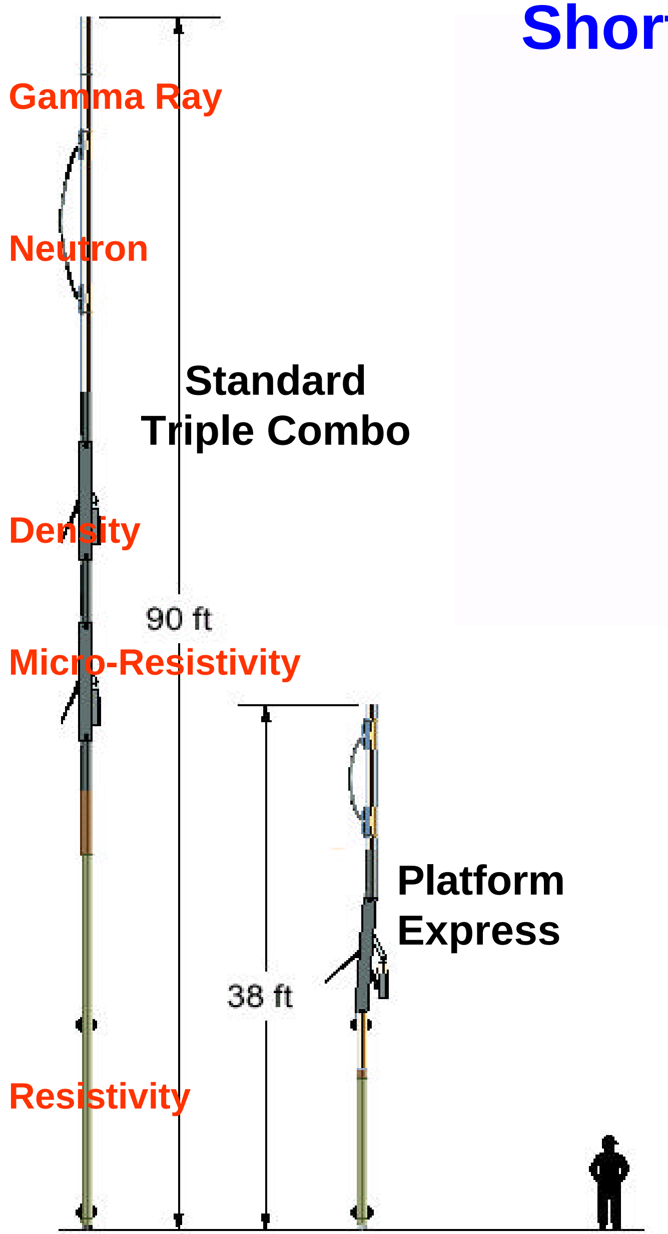


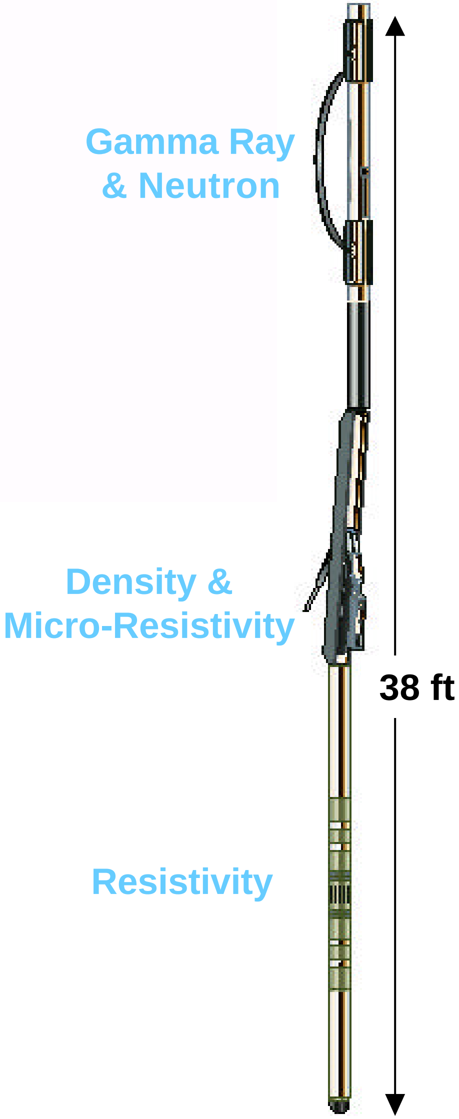
MAXIMUM DEVIATION = 35.3 DEG @ 11350 FT.

TYPE	WEIGHT	DRILLERS DEPTH	WIRELINE DEPTH	DRILLERS BIT SIZE DEPTH
20"CSG	94 lb/ft	---	1922 ft	1958 ft
13 3/8"CSG	68 lb/ft	---	4480 ft	4500 ft
9 5/8"CSG	47 lb/ft	9656 ft	9659 ft	9675 ft
OPEN HOLE	-----	11370 ft	11382 ft	11370 ft

courtesy of Schlumberger

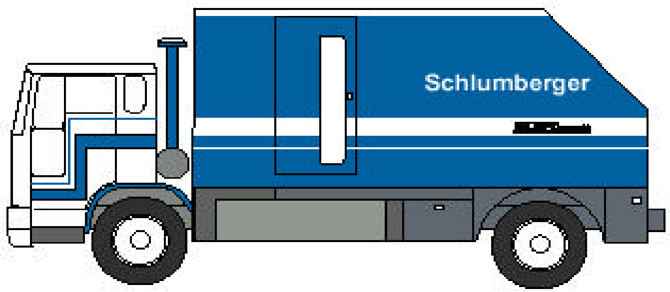
Short Tool Strings - The New Standard





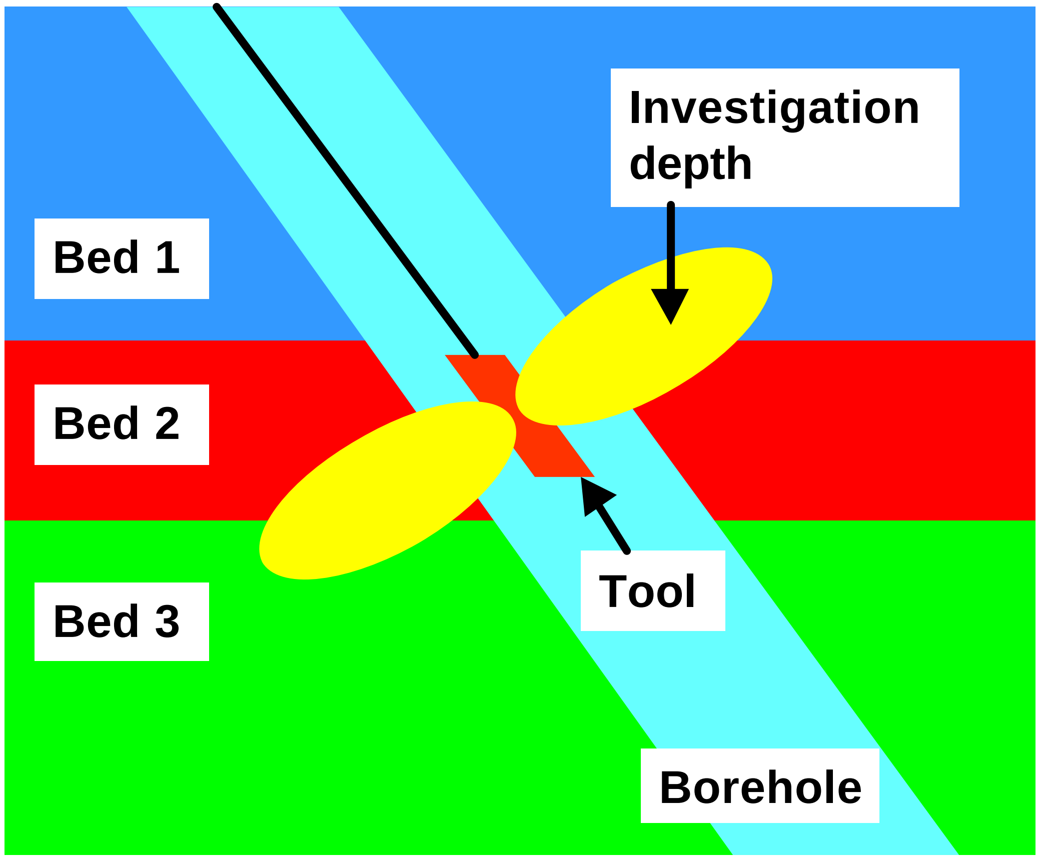
Platform Express Specifications

- 38 ft
- 690 lbm
- 3⅜-in. minimum OD
- 4⅝-in. maximum OD
- 260°F
- 10,000 psi
- 6- to 16-in. hole sizes
- 3600 ft/hr



courtesy of Schlumberger

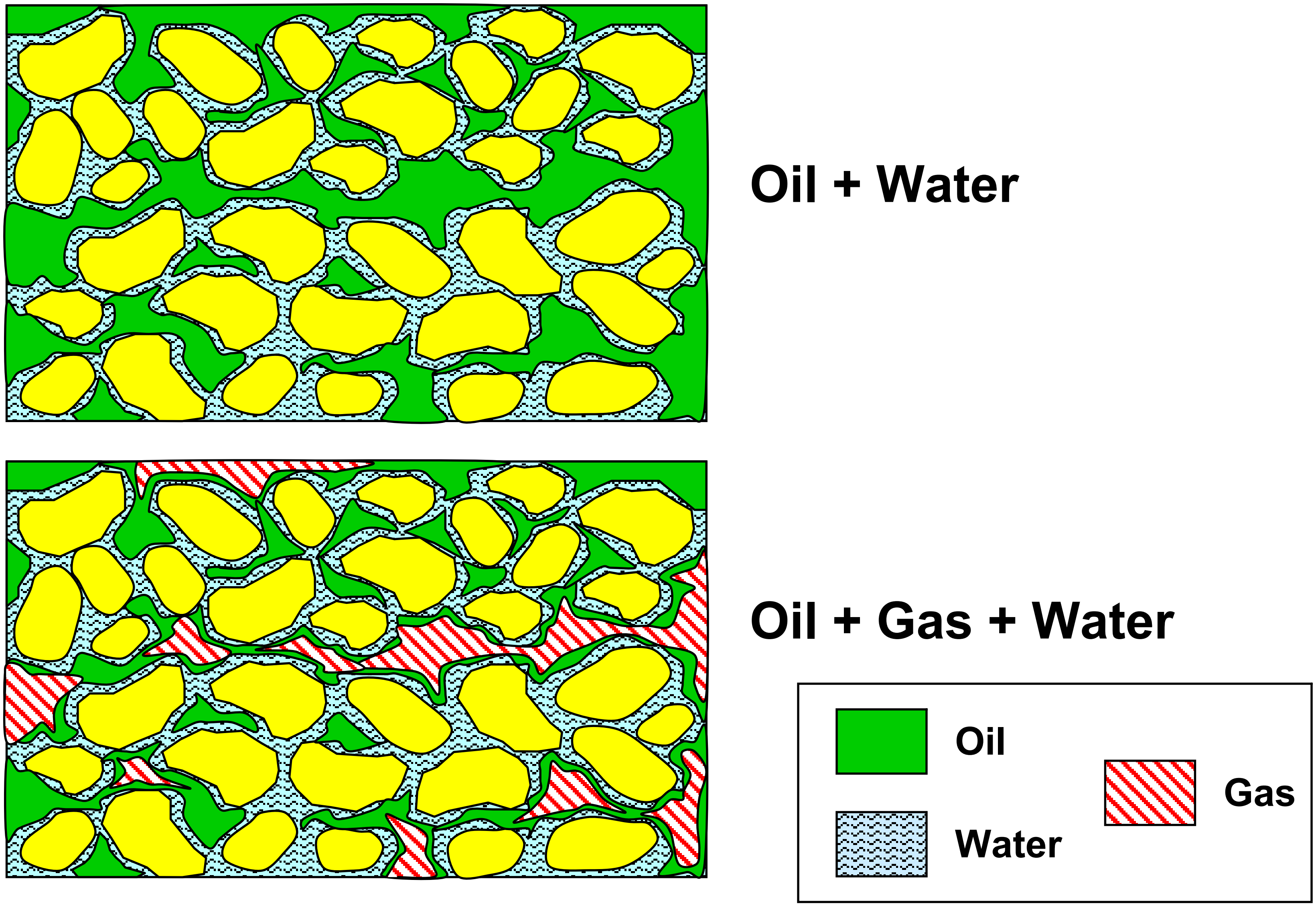
Factors influencing the resistivity measurement



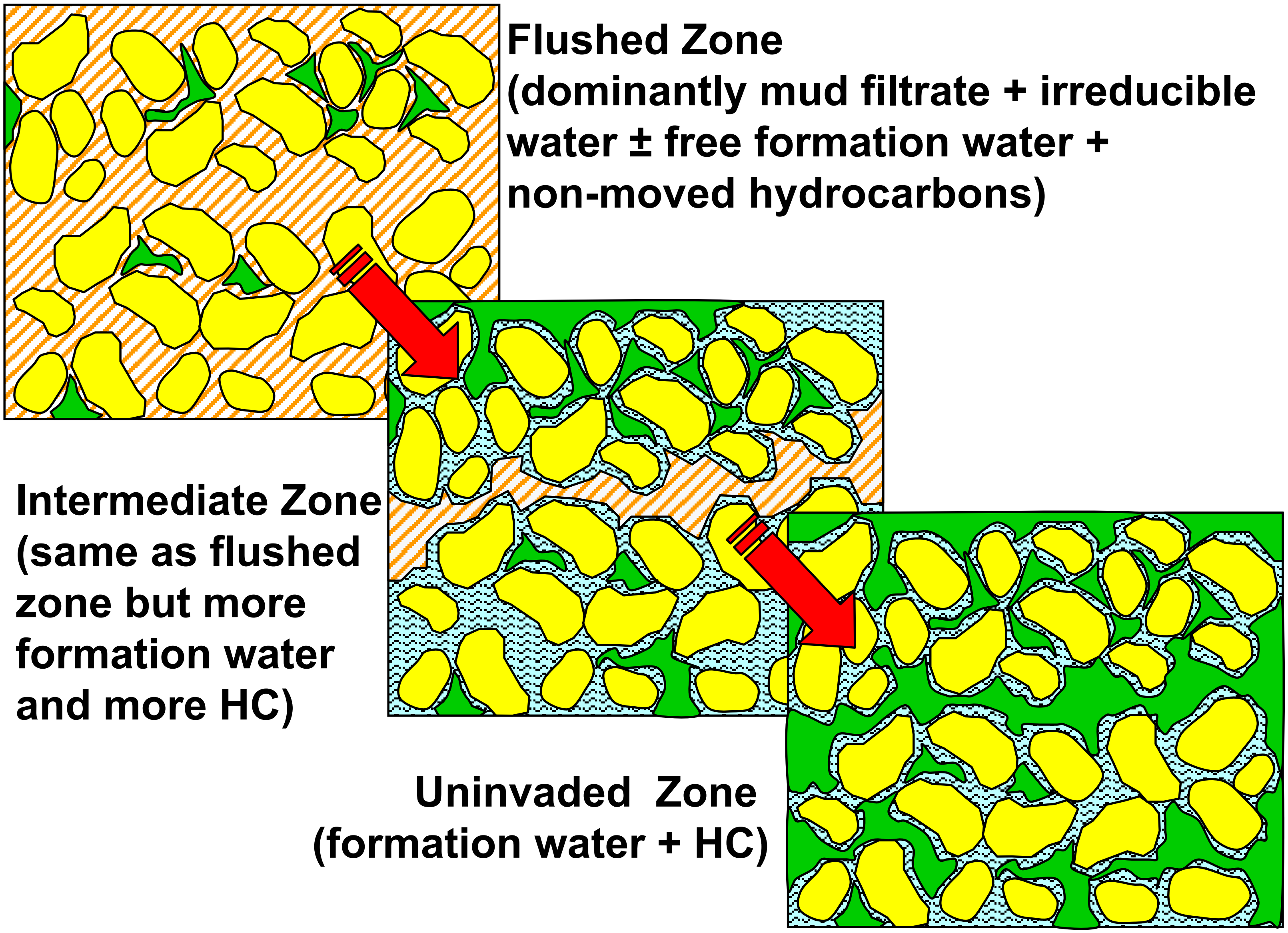
Tool response dependent on:

* borehole diameter
* borehole deviation
* mud salinity
* mud filtrate invasion
* formation layering:
  bed thicknesses
* bed resistivities
* type of tool (design)
* tool position in hole

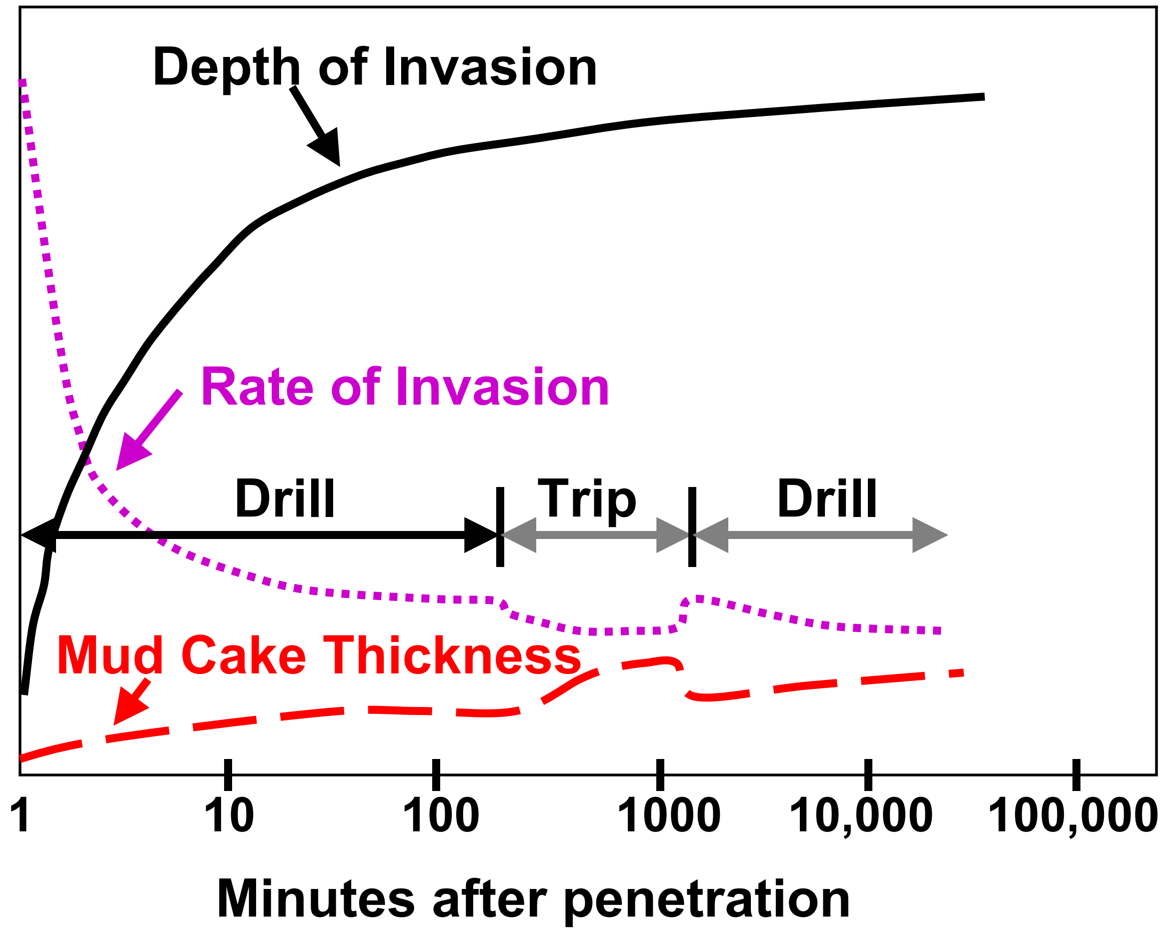
Saturation Profile: Hydrocarbon-Bearing Rock



Saturation Profile, Invaded Rock



Invasion Effects



Typical invasion depth, 1 to 2ft. Range 0.1 ft – 10 ft

After Dewan, 1983, Fig. 1-5, p. 11

Invasion

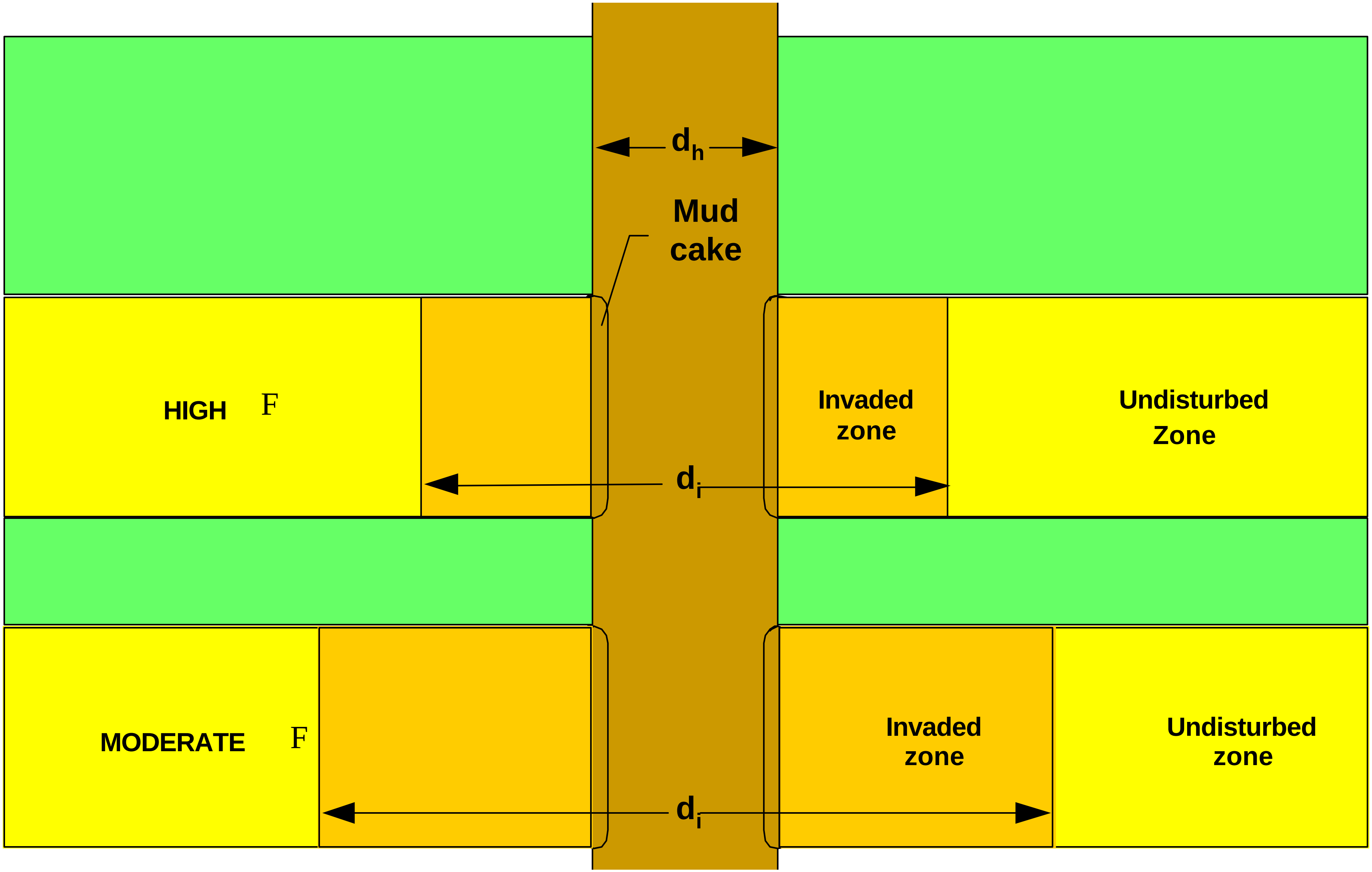
Controlled by:

* Water loss
* Time
* Porosity / permeability

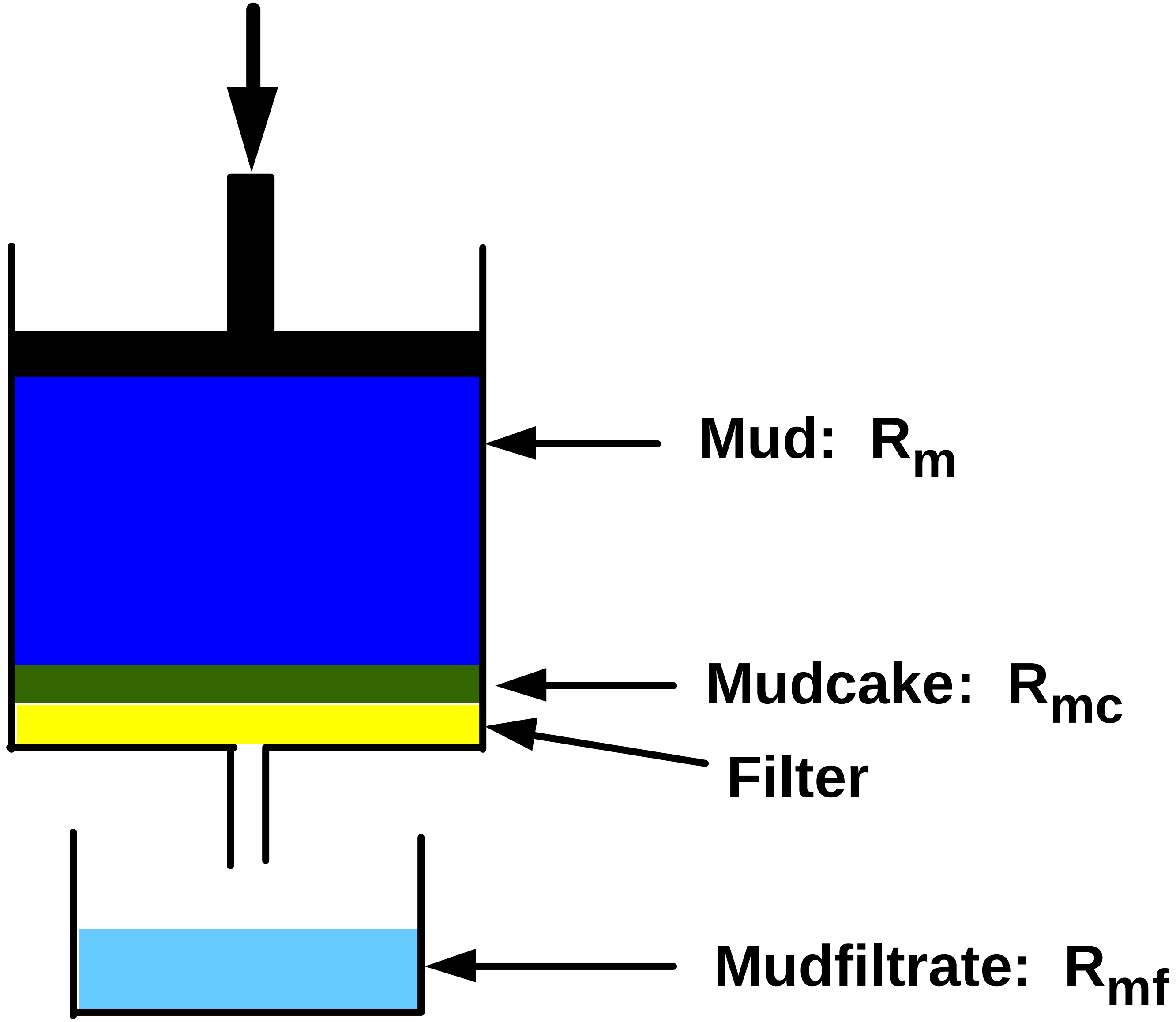
Tools affected:

* Resistivity
* Density: porosity calculation requires mud filtrate density
* Sonic: can be corrected using Gassmann equation

Mud filtrate invasion

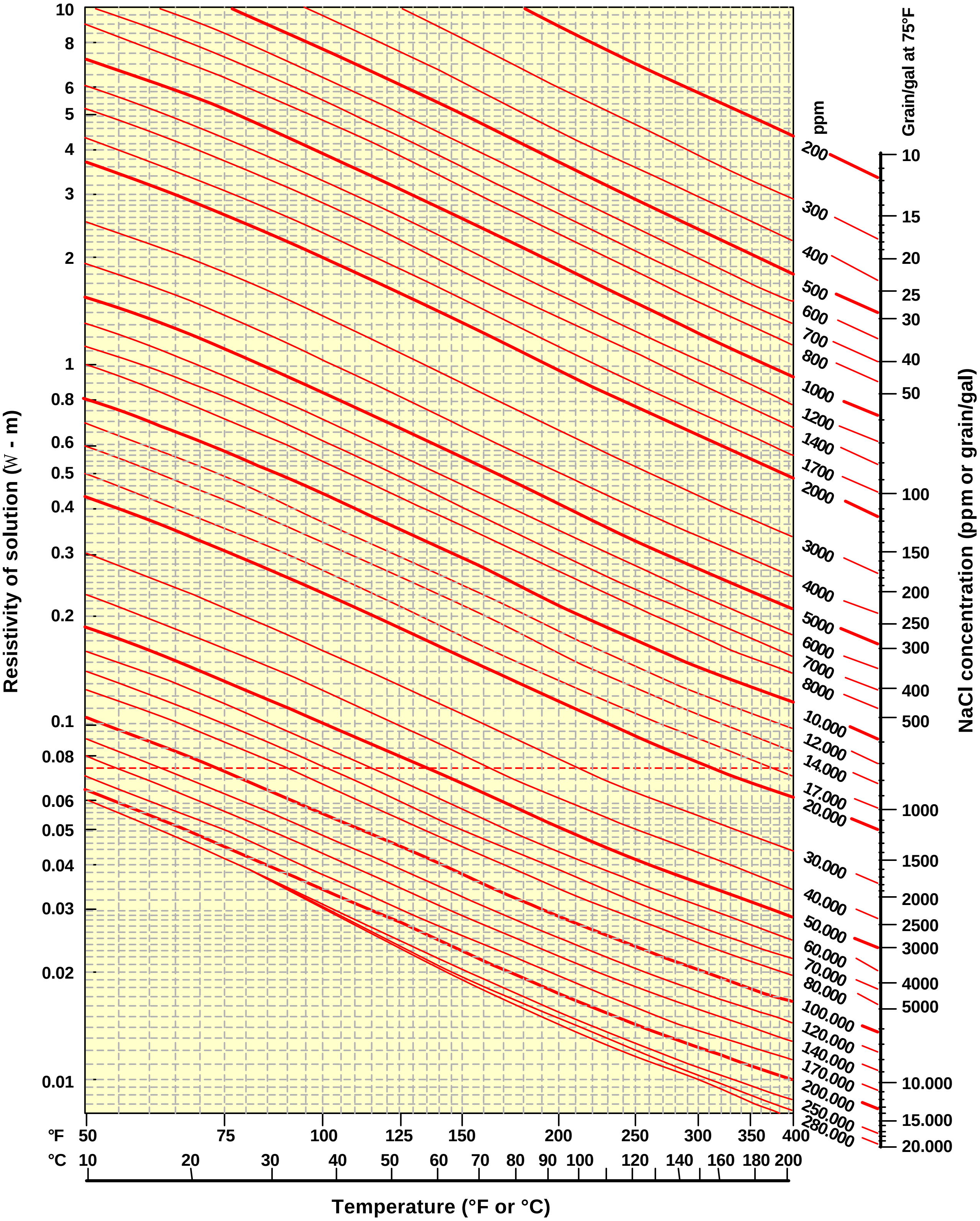


Wellsite measurement of R_{mf}

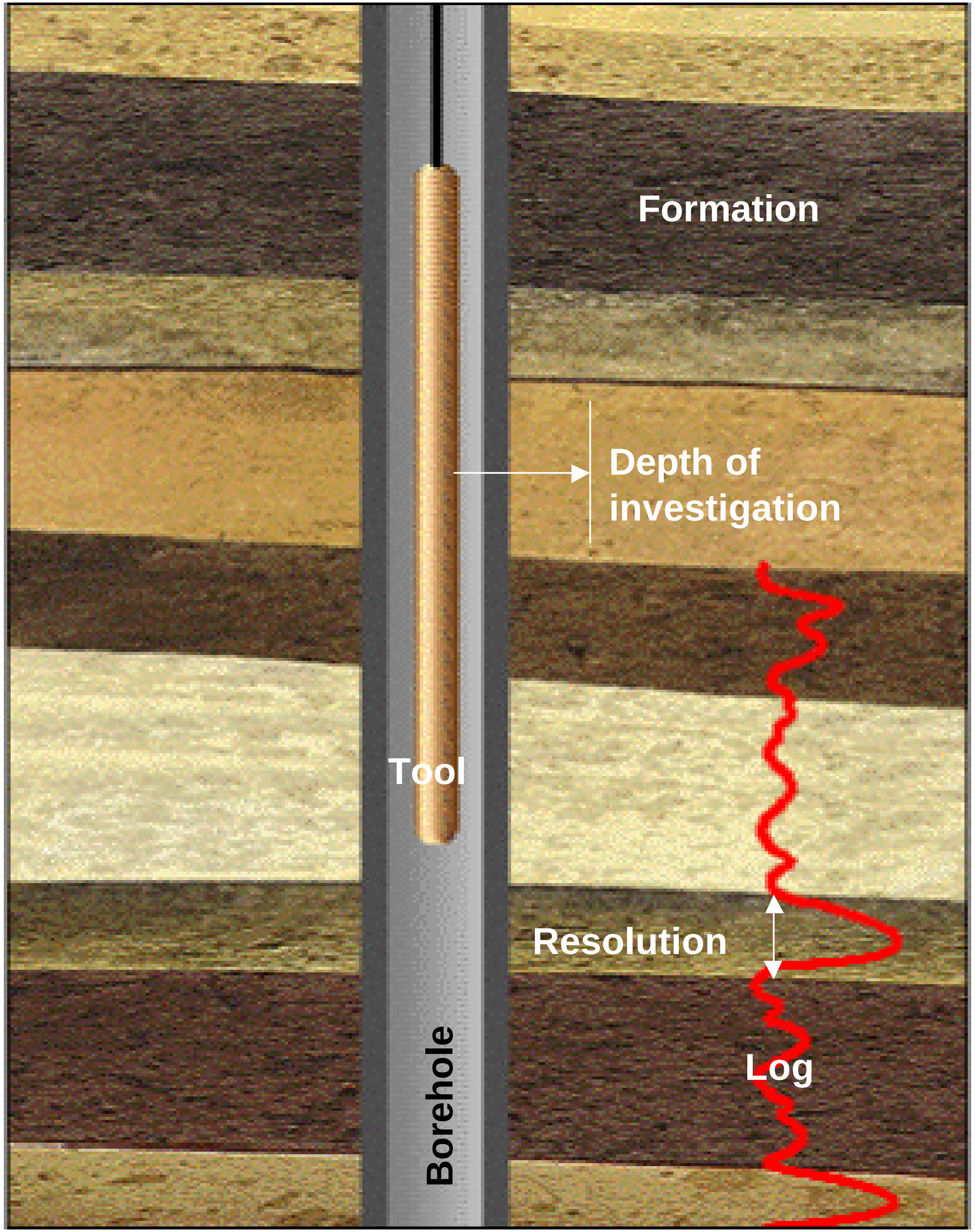


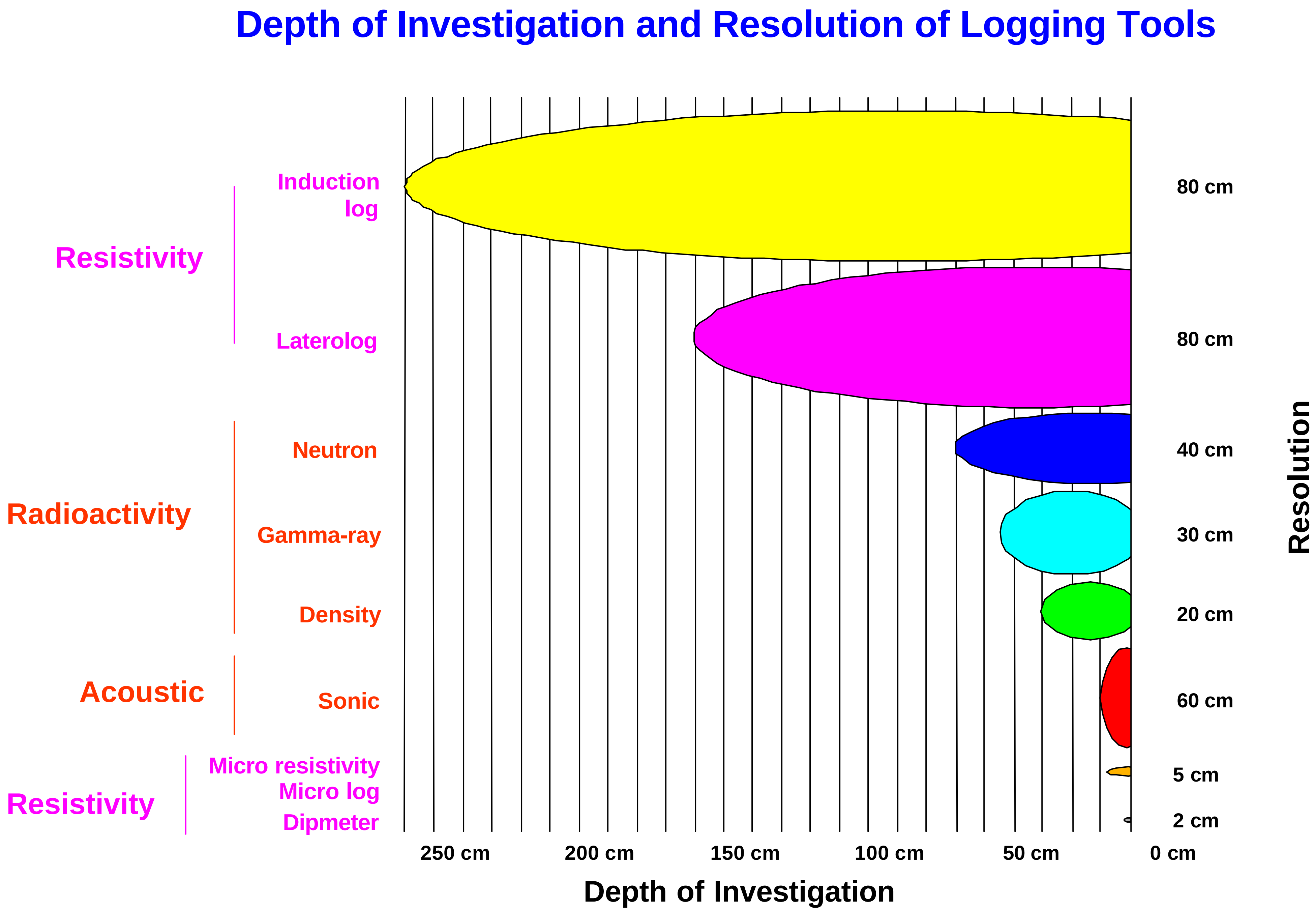
Resistivity of NaCl solutions

Conversion approximated by: $R_2=R_1[(T_1+6.77)/(T_2+6.77)]$ °F or $R_2=R_1\ [(T_1+21.5)/(T_2+21.5)]$°C



Depth of Investigation and Resolution




Depth of Investigation and Resolution of Logging Tools
Resistivity
Induction log
Laterolog
Radioactivity
Neutron
Gamma-ray
Density
Acoustic
Sonic
Resistivity
Micro resistivity
Micro log
Dipmeter
80 cm
80 cm
40 cm
30 cm
20 cm
60 cm
5 cm
2 cm
Resolution
250 cm
200 cm
150 cm
100 cm
50 cm
0 cm
Depth of Investigation

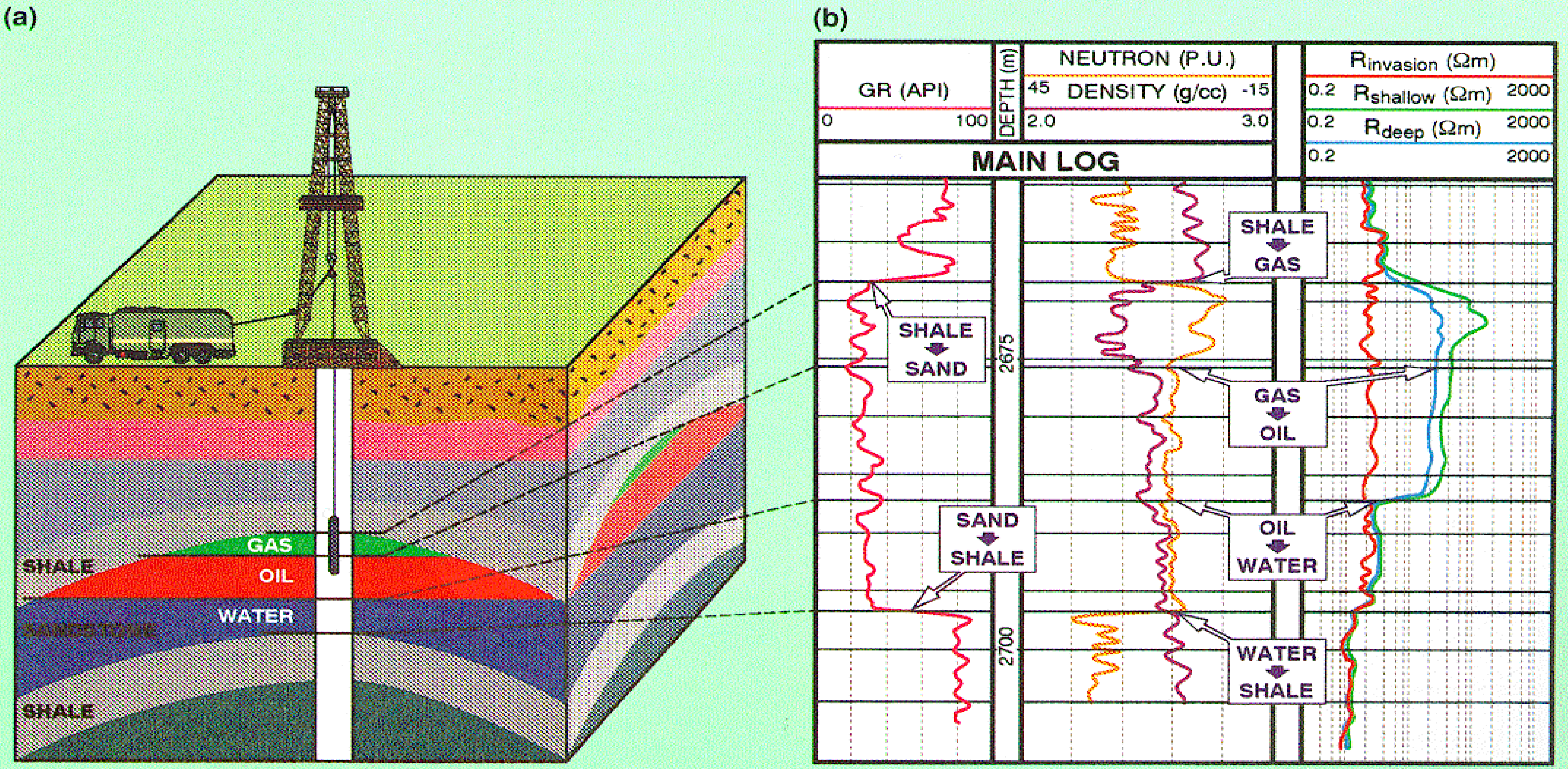
Principle of log interpretation

- Rock
  - Reservoir
    - Hydrocarbon bearing
      - Gas bearing → Evaluate
      - Oil bearing → Evaluate
    - Water bearing → Evaluate
  - Non-reservoir

1. Locate reservoirs
2. Detect hydrocarbons
3. Distinguish oil and gas
4. Evaluate: S_{hc}, ϕ, h, k

Principle of log interpretation

Well logging tools are lowered into the wellbore and data are recorded at the surface where analysis reveals subsurface properties



In (b): Gamma ray log (magenta in track 1). Density and neutron logs (purple and gold respectively, track 2). Resistivity logs (red, green and blue, track 3).

Hydrocarbon Volume

$$HCVOL = A * h * (N/G) * \phi * (1 - S_w)$$

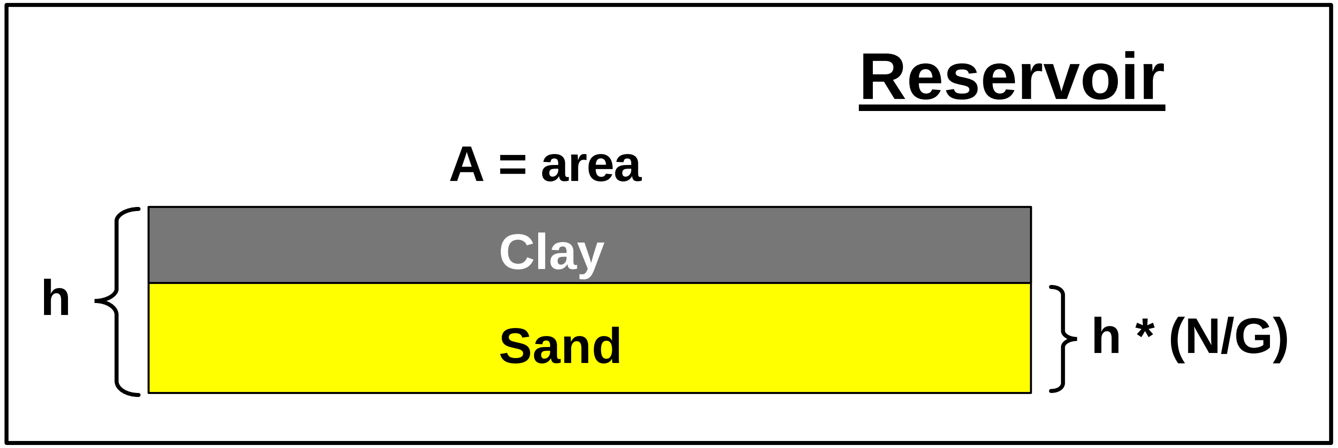
Hydrocarbon volume

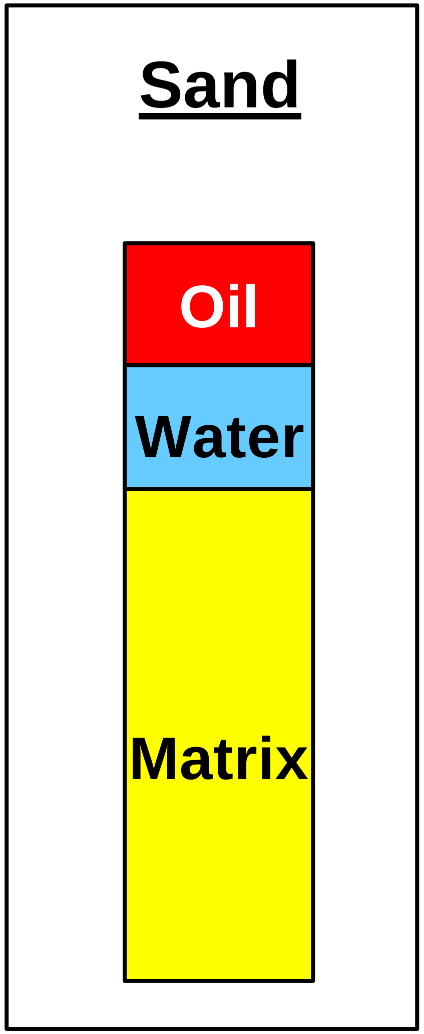
Reservoir volume

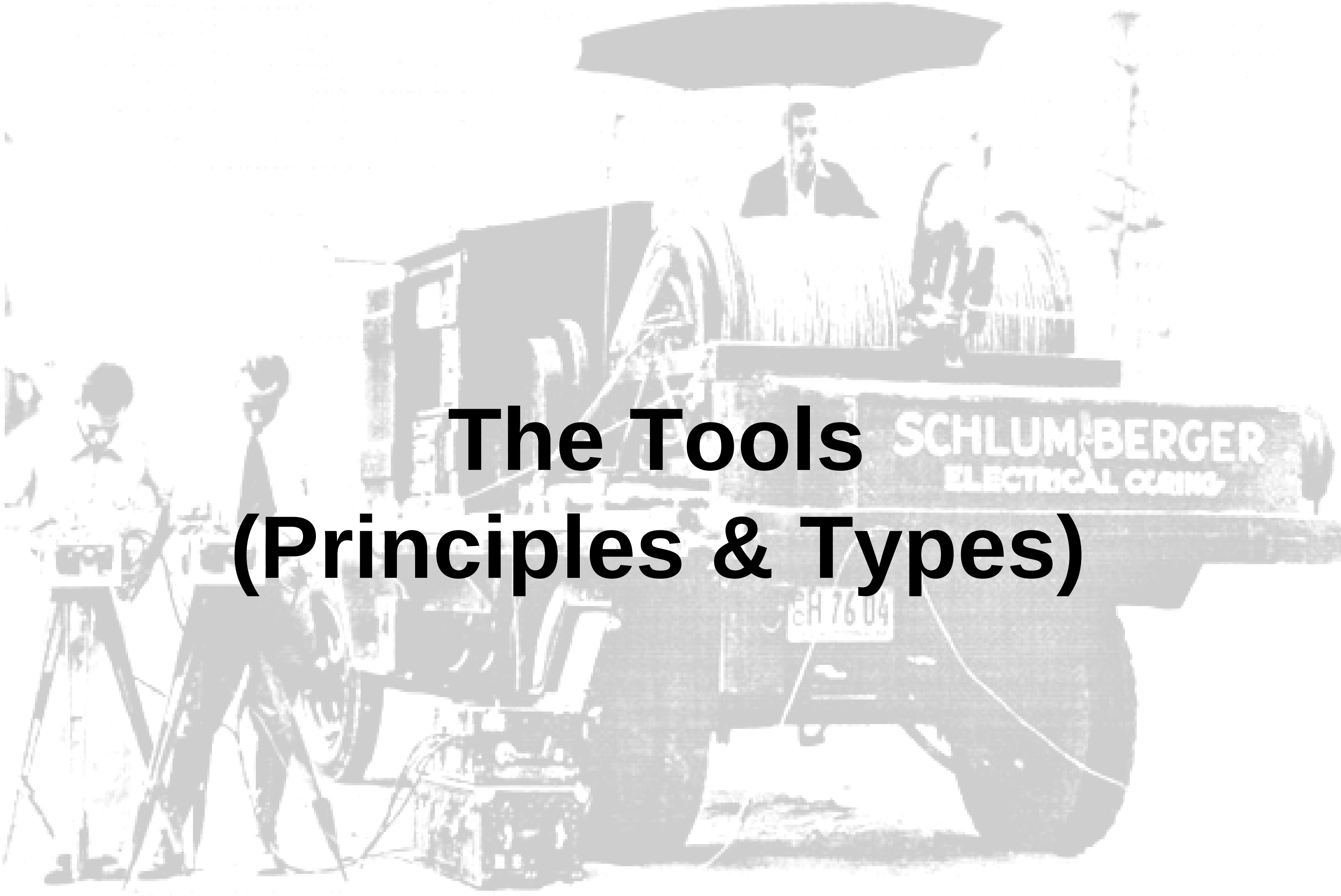
Net over gross

Porosity

Water saturation

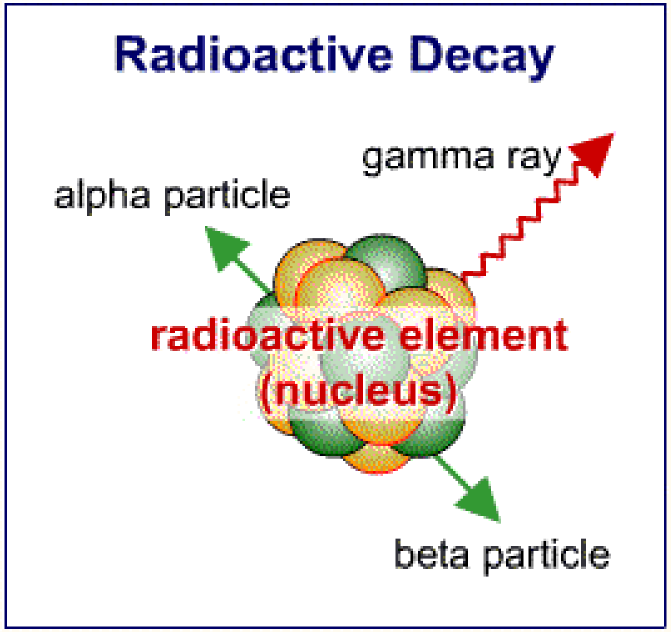






The Tools
(Principles & Types)

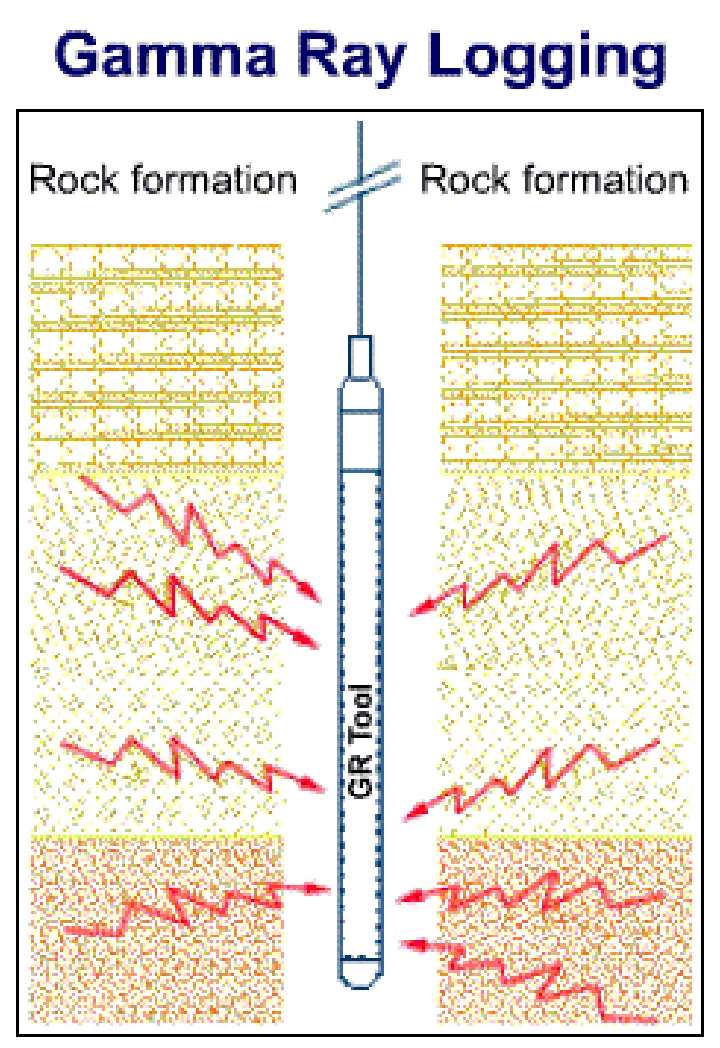
Net/Gross - Gamma Ray



During the same period it was also discovered that, as the atomic nuclei of some elements disintegrated, they spontaneously emitted :

1. Alpha particles : positively charged particles that are made up of two neutrons and two protons, making it identical to the nucleus of a helium atom. Alpha particles are easily stopped by a thick cloth.
2. Beta particles : either negatively or positively charged particles with the same mass and charge as an electron. Beta particles are easily stopped by a thin sheet of metal.
3. Gamma rays : electromagnetic waves traveling at the speed of light having discrete energy levels. Gamma rays penetrate farther than most particles, mainly because they lack charge.

Net/Gross - Gamma Ray



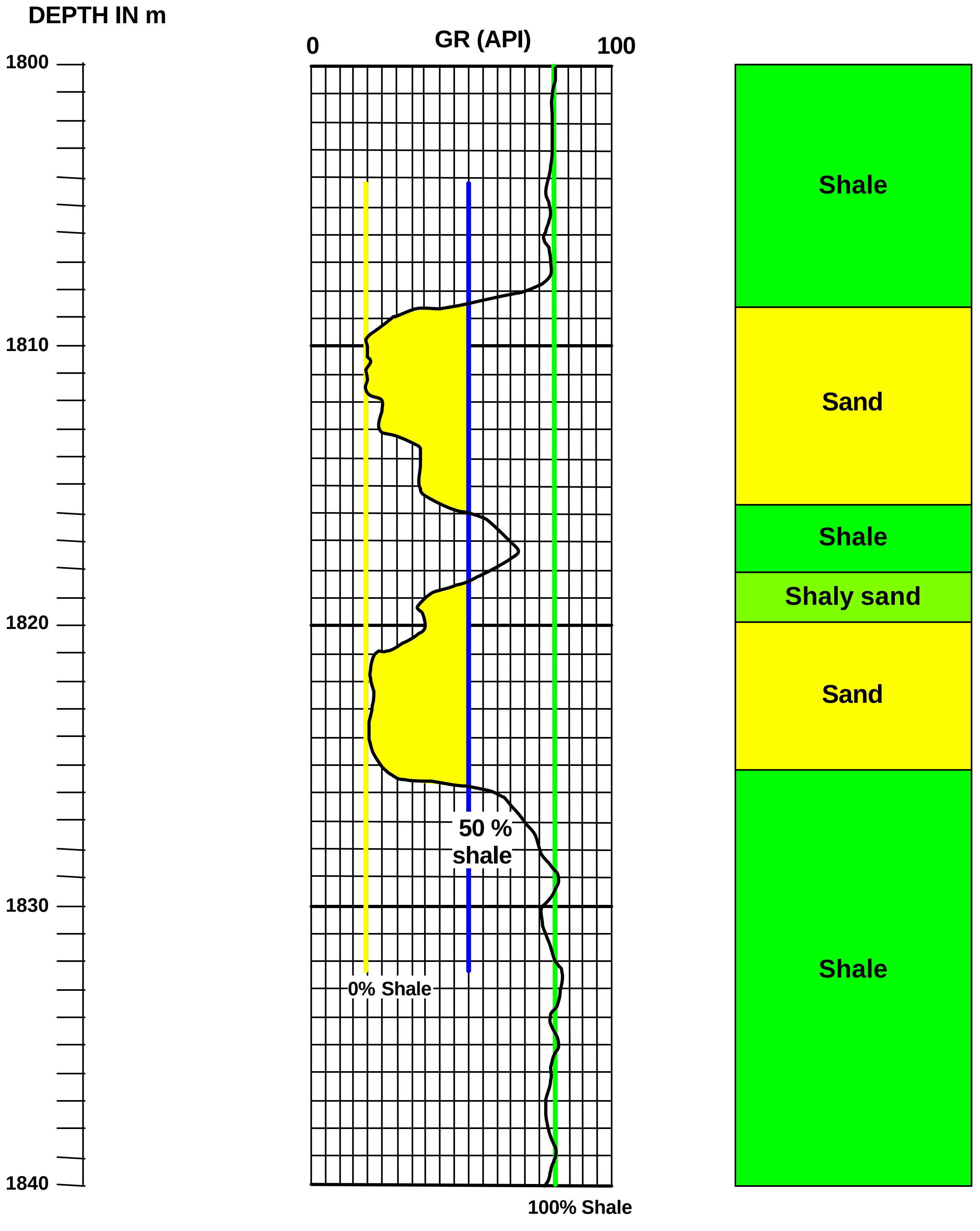
To measure the natural Gamma rays emitted from the formation, the Gamma ray (GR) tool is lowered in the borehole. The GR tool consists of a detector and associated electronics to measure the gamma radiation originating in the volume of formation near the tool.

GR Response to Lithology

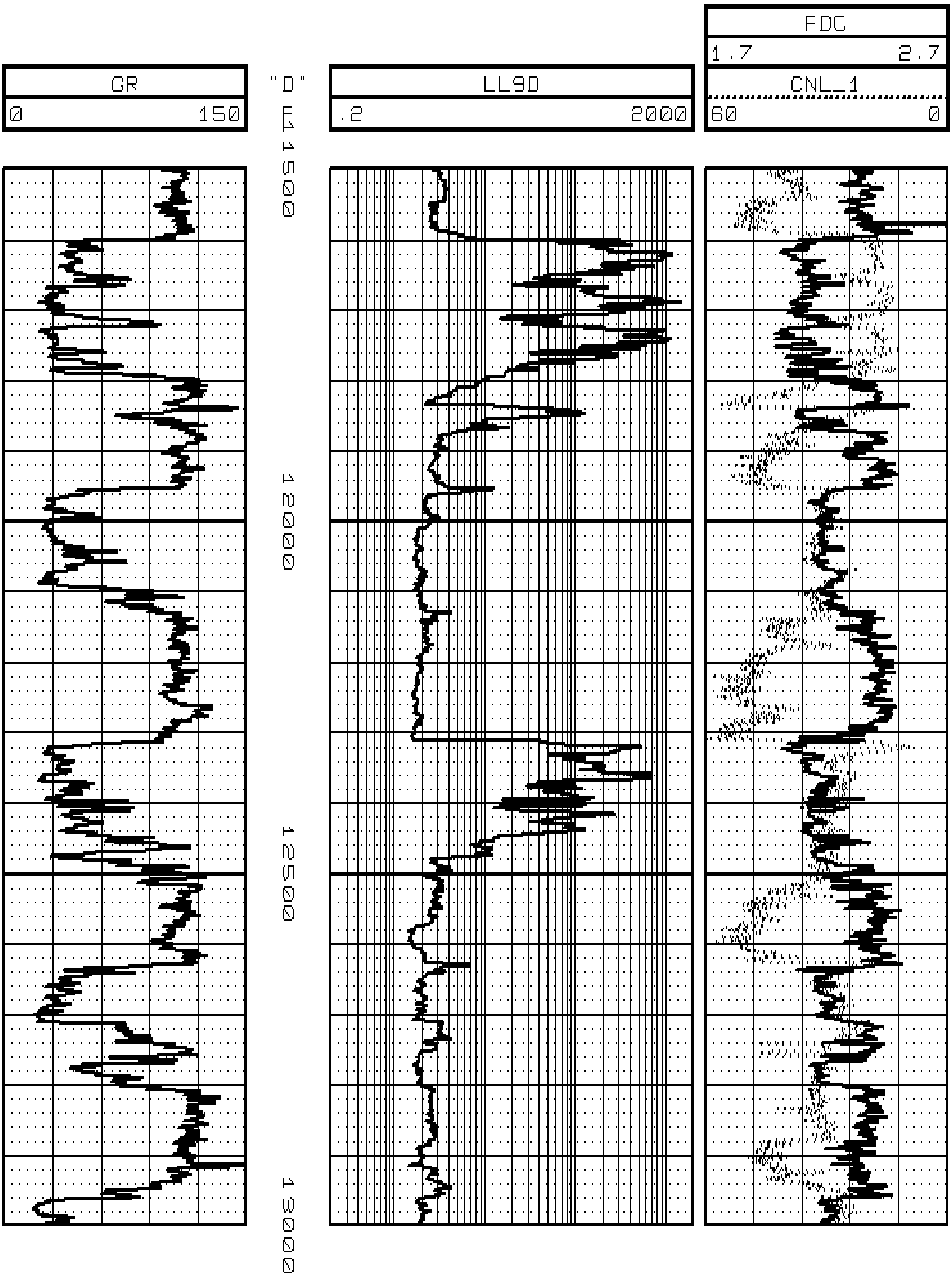
- The GR log records the abundance of the radioactive isotopes of K, Th and U
- K, Th and U are usually concentrated in shales and less concentrated in sandstones and carbonates (owing to differences in mineralogy)
- Common GR readings, in API units*, are:
  - Limestones and anhydrites, 15-20 API
  - Dolomites and “clean” (shale-free) sandstones, 20-30 API
  - Shales, average 100 API, but can vary from 75 to 300 API
  - Other lithologies: coal, salt (halite, NaCl) and gypsum usually give low readings while volcanic ash and beds of potash salts (sylvite, KCl) give high readings
- Therefore, the GR log is a good “first-pass” indicator of lithology

*1 API unit = 1/200th of the response generated by a calculated standard that has 2x the average radioactivity of shale with 6ppm U, 12ppm Th and 2% K

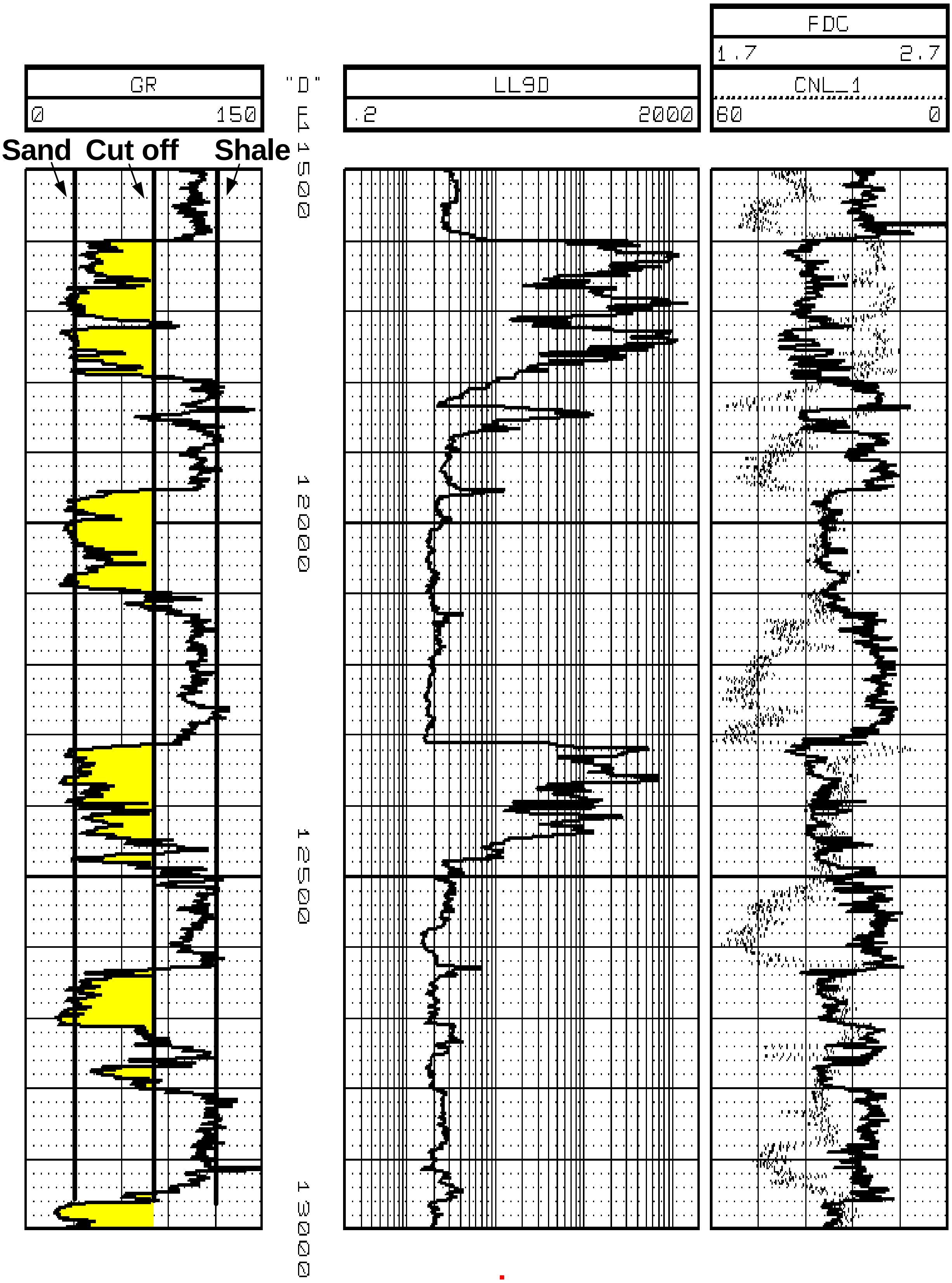
Net/Gross - GR interpretation in a sand-shale sequence



Identify the Sands



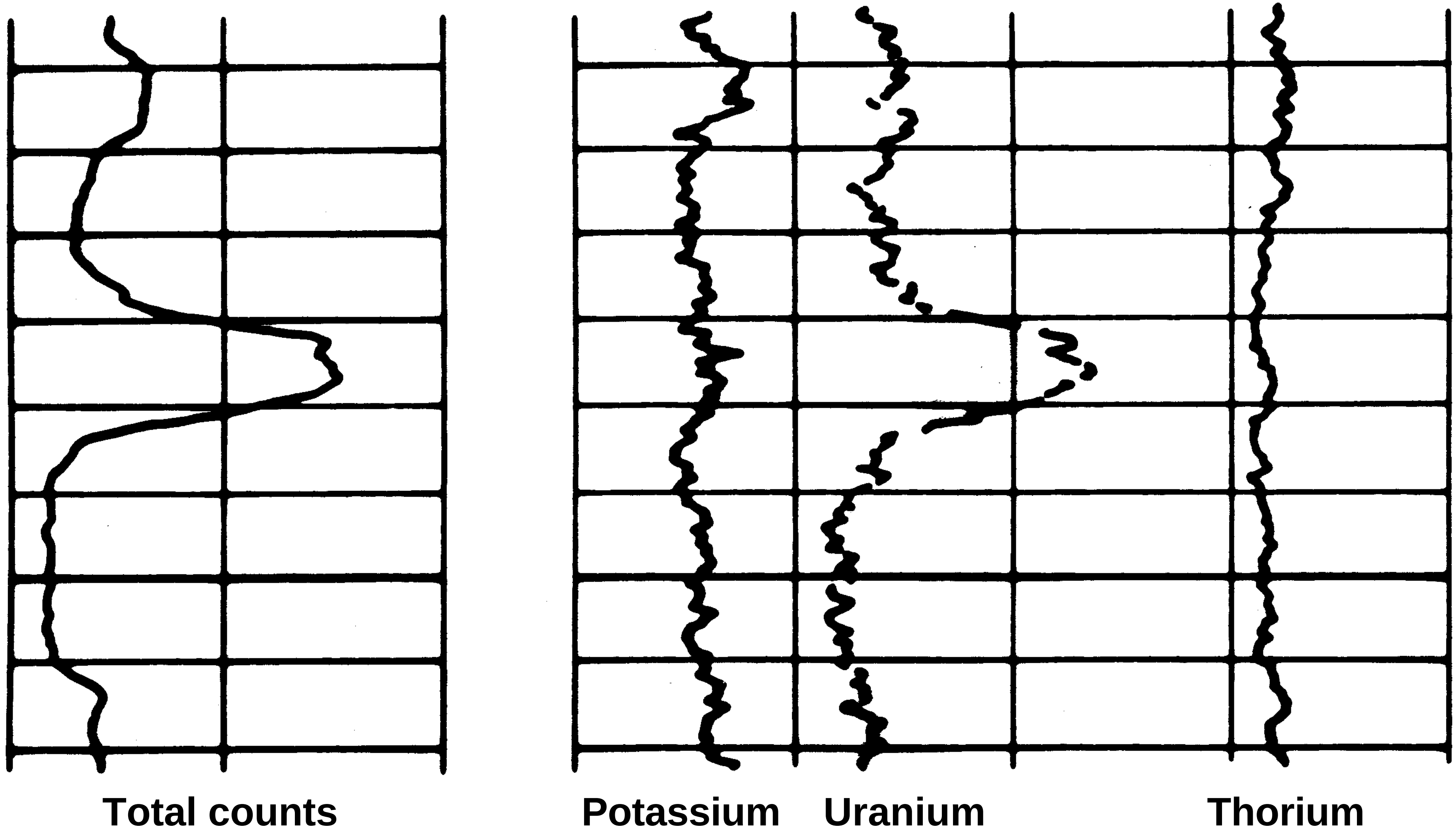
Net/Gross - Sands from Gamma-Ray



exercise

Net/Gross - Gamma Ray

Apparent shale caused by high uranium streak in Northern California well

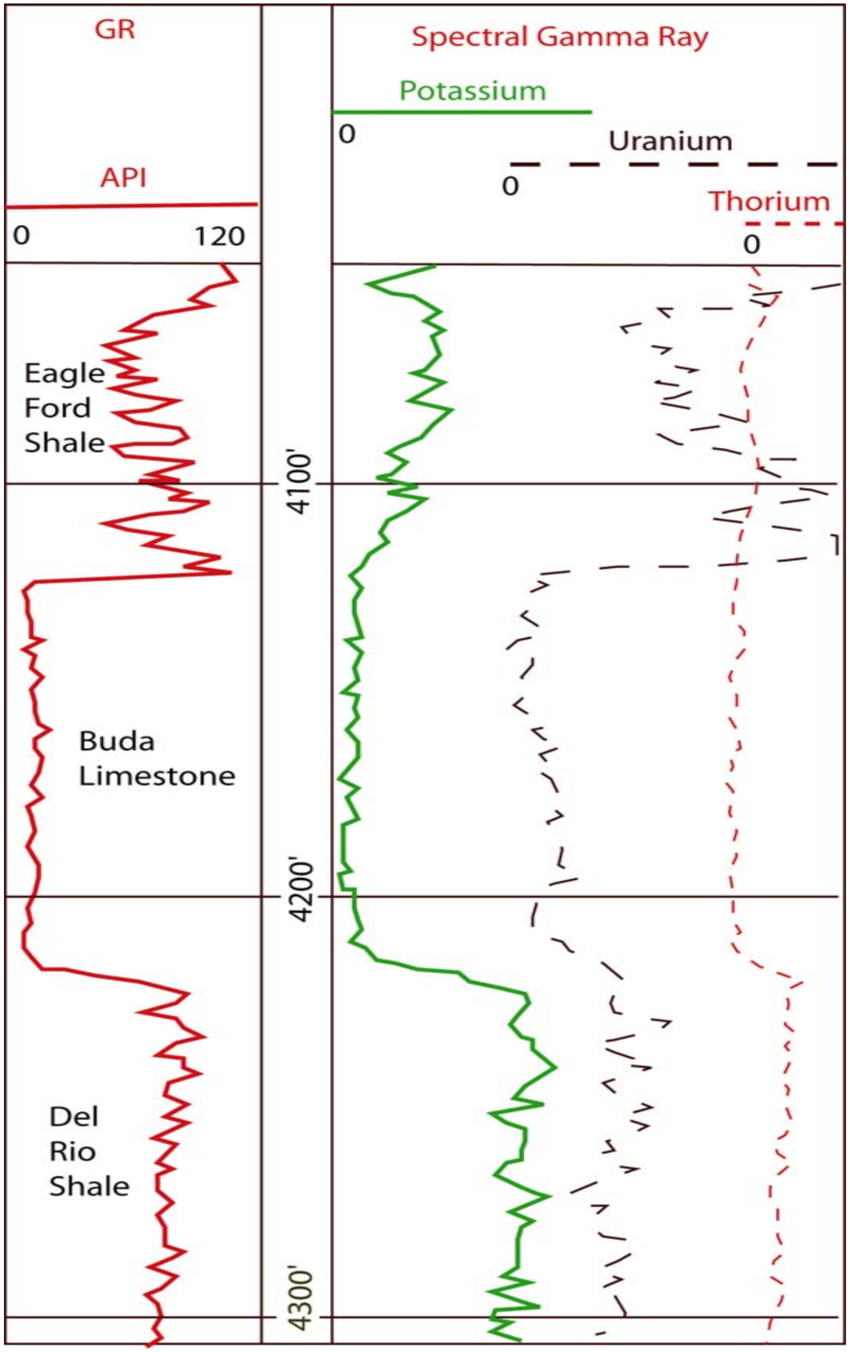


Spectral GR, Texas

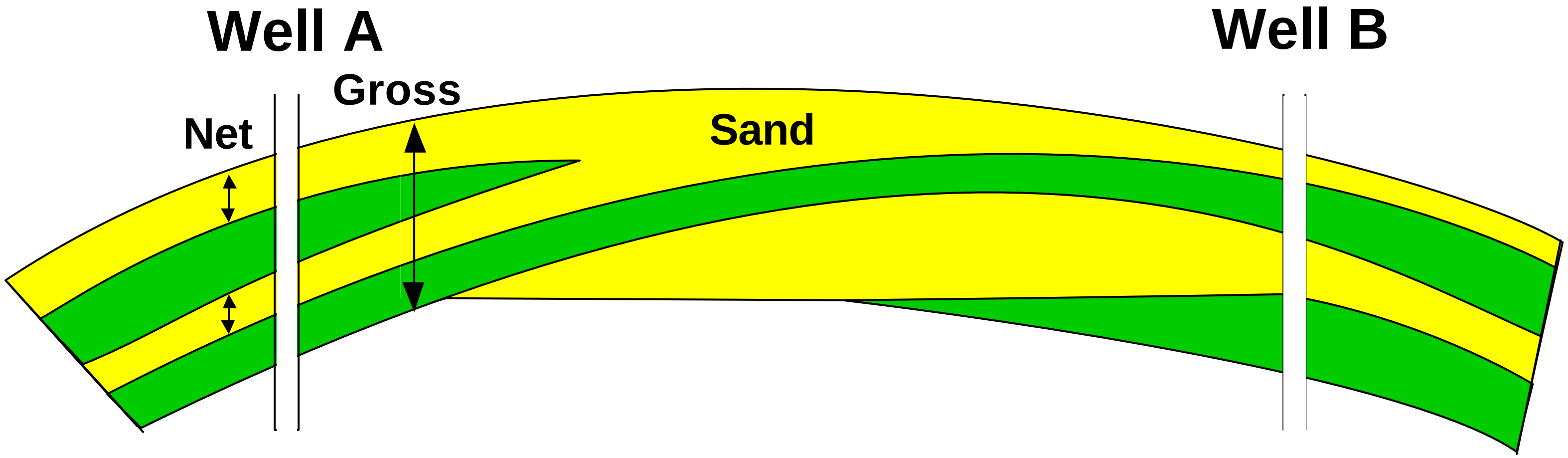
Eagleford Fm: Shale and source rock. High U content associated with high TOC (organics)

Buda Fm: Limestone. Very low radioactivity (<20 API)

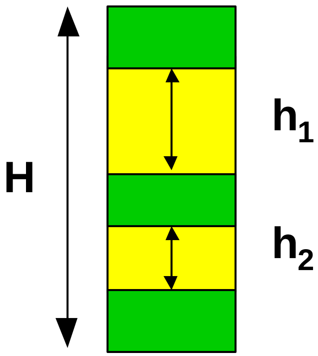
Del Rio Fm: Typical shale. High K content associated with illite



Net/Gross, net reservoir



N/G = 0.5 N/G = ? N/G = 0.3



$$N/G = \frac{h_1 + h_2}{H}$$

$$\text{Net reservoir} = h_1 + h_2$$

$$\overline{F} = \frac{S\, h_n F_n}{S h_n}$$

$$\overline{S_w} = \frac{S\, h_n S_w}{S h_n}$$

Shale Determination from the GR

- The GR log is the most frequently used log for the estimation of the fraction of shale by volume in the sand (Vsh)
  - ♦ Advantage: the GR is not affected by water salinity or hydrocarbon saturation
- GR technique for shale determination:

$$Vsh_{gr} = (GR - GR_{clean}) / (GR_{sh} - Gr_{clean})$$

Where: GR = reading at a specific depth or in an interval of interest

GR_{clean} = average reading in nearby clean sands

GR_{sh} = average reading in nearby 100% shale intervals

- Do not take the GR_{sh} reading from very thin, highly radioactive streaks. These are enriched in radioactive minerals owing to unusual geological conditions

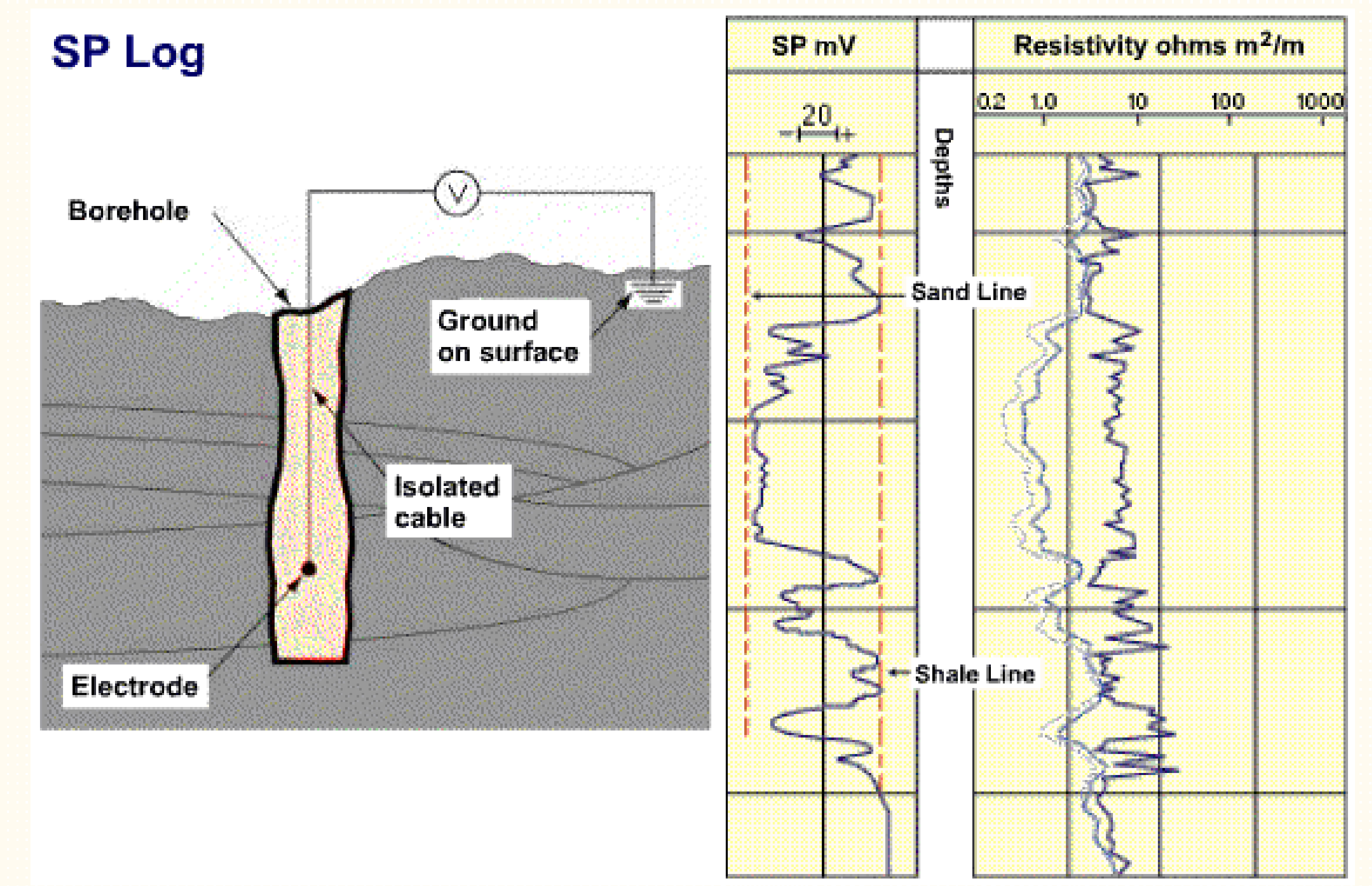
Net/Gross - Gamma Ray

Gamma Ray Applications

- Correlation
  - Well to Well correlation.
  - Depth matching between separate trips in the well.
  - Positioning of open-hole sampling tools.
  - Providing the depth control needed for cased hole perforation.
- General lithology indicator
  - Discriminate between reservoir & non-reservoir (Net/Gross)
- Quantitative shaliness evaluation of the reservoir rock

Net/Gross - SP

Spontaneous Potential …….. What in earth is that ????? (1)



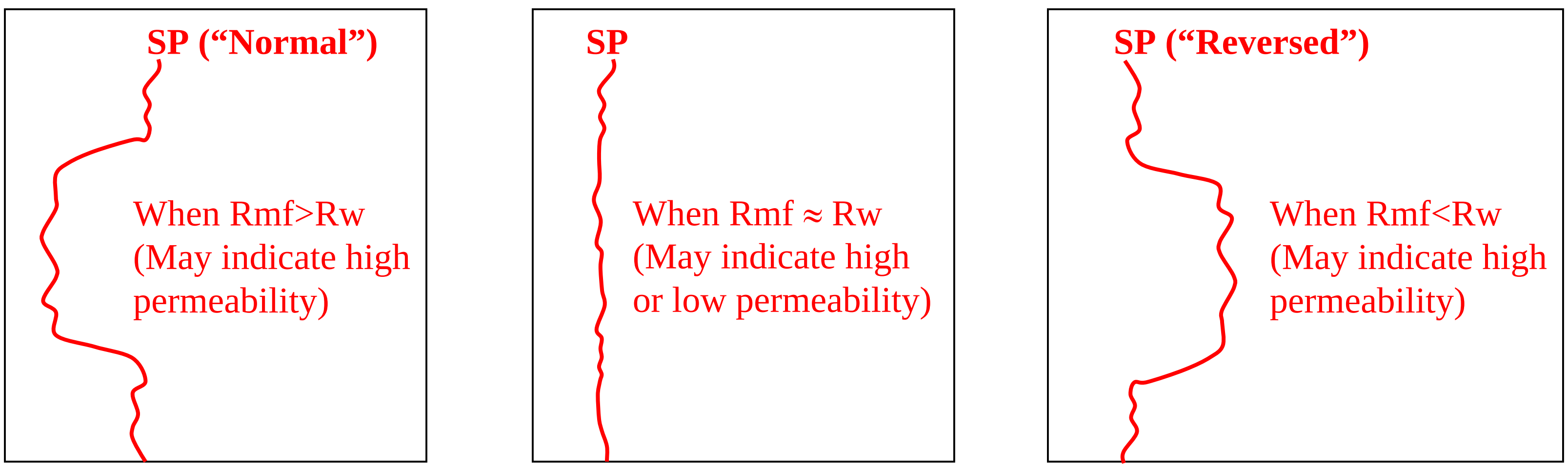
The SP log is recorded by placing a movable electrode in the borehole and measuring the difference between the electrical potential of this movable electrode and the electrical potential of a fixed surface electrode.

Spontaneous Potential Log

- The SP log measures the difference in electrical potential between a fixed electrode at the surface and a movable electrode in the borehole
  - The hole must be filled with conductive mud
  - No SP can be measured in oil based mud, empty holes or cased holes
  - The scale of the SP in in millivolts (MV). There is no absolute zero: only changes in potential are recorded
  - Vertical resolution $\approx 1/\Phi$ or $\sqrt{R_{inv\ zone}/R_{mud}}$
    - At 30% porosity, resolution = 3 ft
    - At 3% porosity, resolution = 30 ft
  - Depth of investigation ?
- Evaluation objectives
  - Identify permeable zones
  - Provide Rw values
  - Estimate the degree of shaliness of the rock

Problems with the SP Log

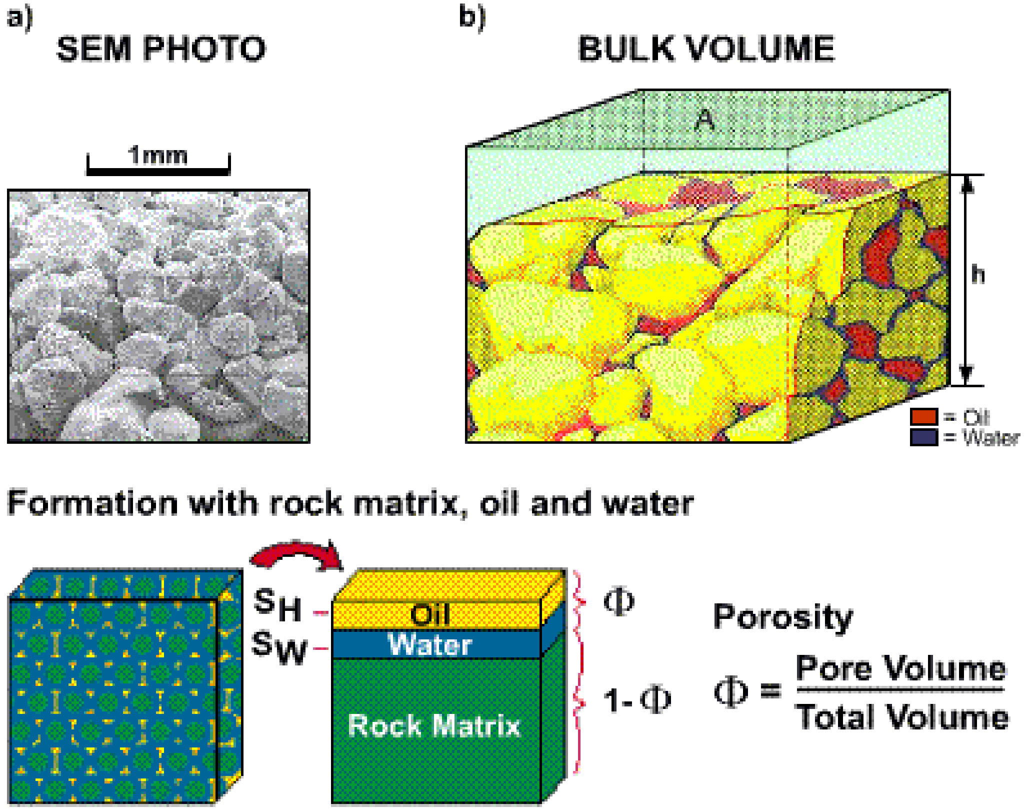
- SP logs delineate permeable beds well in relatively thick, porous sand and shale sequences but resolve beds poorly in thinly bedded and low permeability formations
- The SP log measures differences in the ionic activities (relative saltiness) of the drilling mud and the formation waters. In salt muds, the SP is often useless because the SP magnitudes at depths of interest are small ($R_{mf} \approx R_w$) and because boundary definition with low resistivity mud and high resistivity formations is very poor
- The SP curve can reverse under certain circumstances



What is Porosity ? (1)

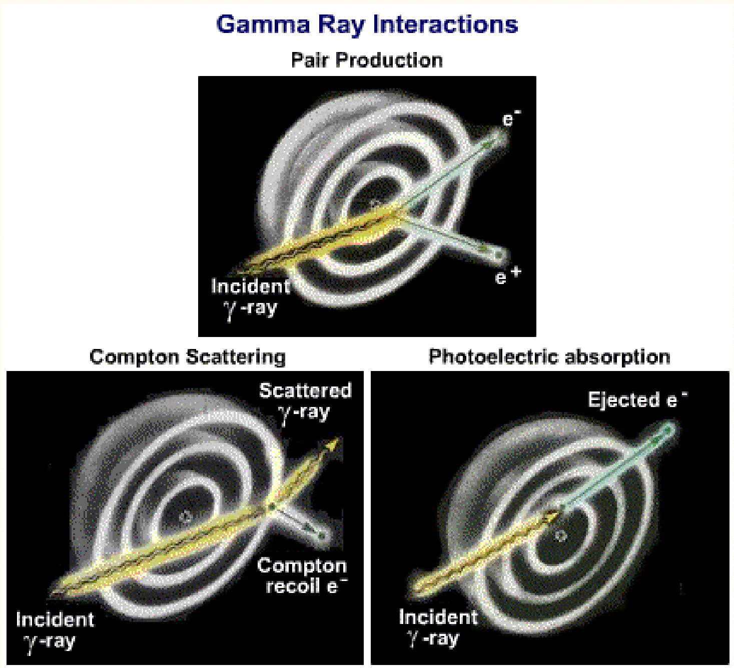
Porosity - Definition and Computation

Scanning Electron Microscopy (SEM) photograph of quartz sand. The total bulk volume (v) is comprised of grains and fluid fillled pores (v = A x h)



Porosity is the pore volume per unit volume of the formation. Porosity indicates how much fluid a rock can hold. Almost all oil and gas produced today comes from the accumulations in the pore spaces of reservoir rocks.

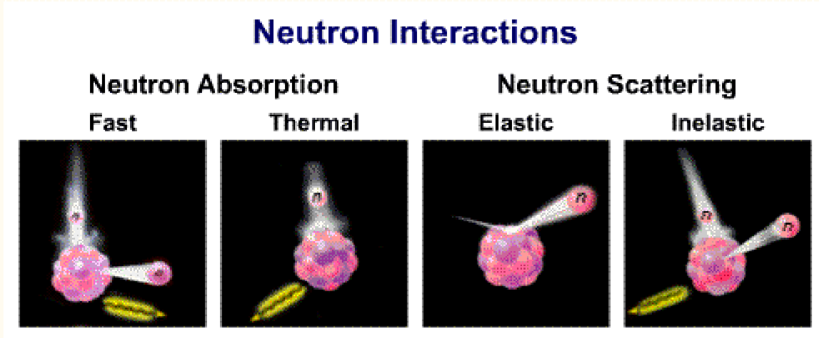
Porosity Determination



When the Gamma (γ) Rays pass through matter, they experience a loss of energy due to collisions with other atomic particles which can be divided into three basic categories :

- Pair production
- Compton scattering
- Photoelectric absorption.

For the determination of lithology the photoelectric absorption is the interaction of interest to us.



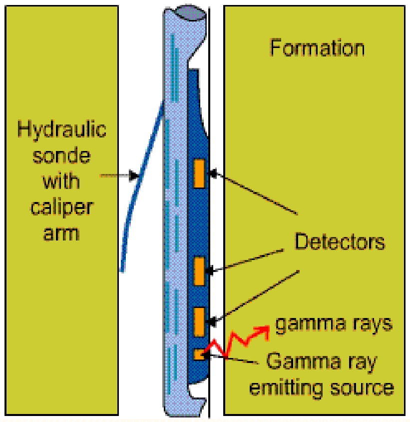
Neutrons have no electric charge and their mass is similar to that of the proton. This lack of charge allows the neutron to penetrate into the formation and makes it ideal for logging applications. Neutrons interact with matter in a wide variety of ways. There are four important interactions between a bombarding neutron and a target nucleus :

- Neutron absorption is said to occur when it strikes the nucleus and is absorbed. Depending on the energy of the incident neutron, the interaction can be described as thermal or fast.
- Neutron scattering is said to occur when it interacts with a nucleus, but both particles reappear after the interaction. In elastic scattering, the total kinetic energy of the two colliding particles is conserved but redistributed. In inelastic scattering, part of the kinetic energy from the neutron is transferred to the nucleus as excitation energy.

Gamma Rays…..

Neutrons…..

Porosity Determination



$$\rho_b = \phi\,[S_{xo}\rho_w + (1-S_{xo})\rho_h] + (1-\phi)\rho_{ma}$$

- ρ_b : formation bulk density
- ρ_{ma} : matrix density
- ρ_w : water density
- ρ_h : hydrocarbon density
- ϕ : formation porosity
- S_{xo} : invaded zone water saturation

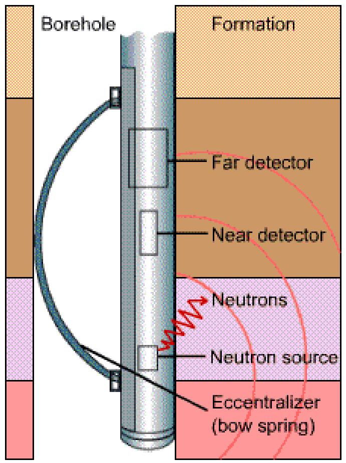
The Density tool responds to the electron density of the formation in front of the tool.

Density Log response is a combination of the matrix density and the density of fluids in the invaded zone in their relative proportions. For simplicity, we have considered $\rho_w = \rho_{mf}$.

The Density Tool

Porefill Determination with the Density/Neutron

The Neutron Tool



$$\phi_n = \phi\,[S_{xo}H_w + (1-S_{xo})\,H_h] + (1-\phi)\,H_{ma}$$

- ϕ_n : neutron porosity
- H_{ma} : matrix hydrogen index
- H_w : water hydrogen index
- H_h : hydrocarbon hydrogen index
- ϕ : formation porosity
- S_{xo} : invaded zone water saturation

The Neutron tool responds to the hydrogen index of the formation in front of the tool.

Neutron Log response is a combination of the matrix hydrogen index and the hydrogen index of the fluids in the invaded zone in their relative proportions. For simplicity, we have considered $H_w = H_{mf}$.

Density values in formation evaluation (g/cc)

Reservoir matrix

Quartz (sandstone)	2.65
Calcite (limestone)	2.71
Dolomite	2.87

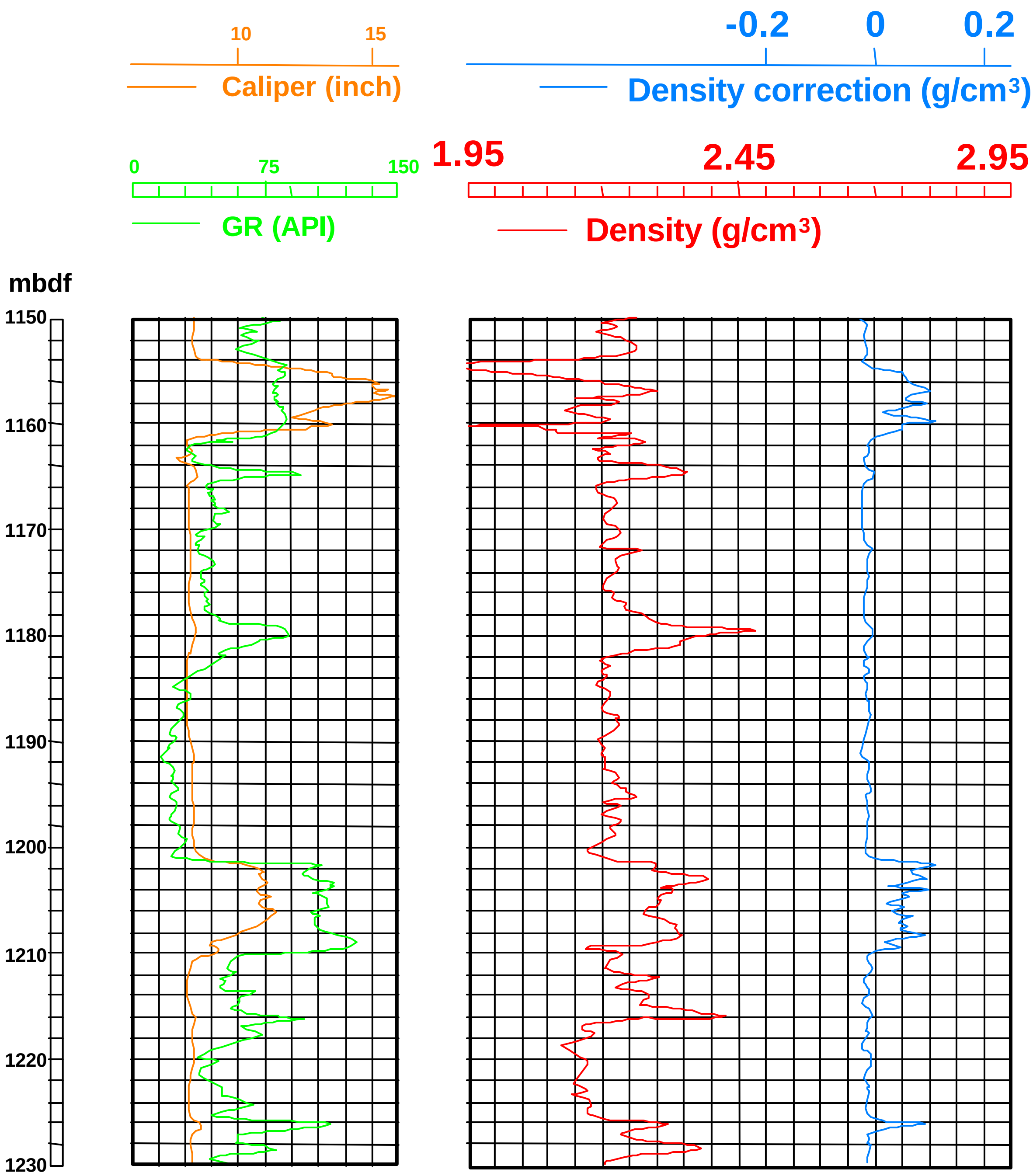
Pore fluids

Fresh water	1.00
Salt water (200 g/l)	1.13
Fresh water with 30 % residual oil	0.90 - 0.94
Fresh water with 30 % residual gas	0.73 - 0.74

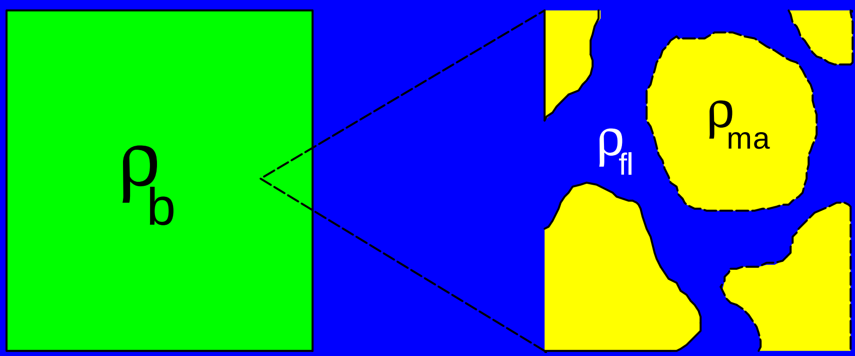
Other minerals

Halite (rock salt)	2.03
Anhydrite	2.98

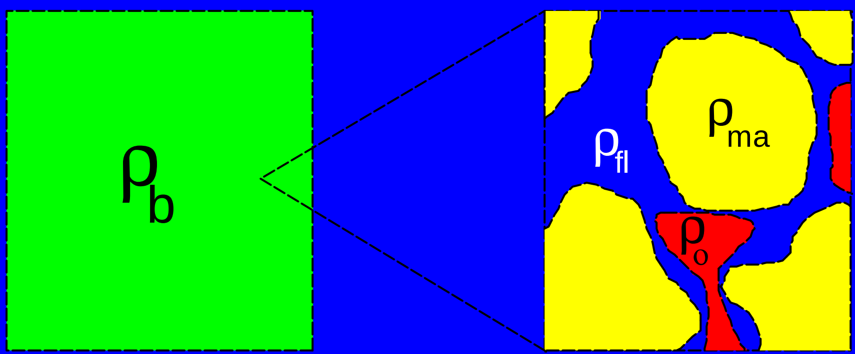
Example of a density log



Bulk Density

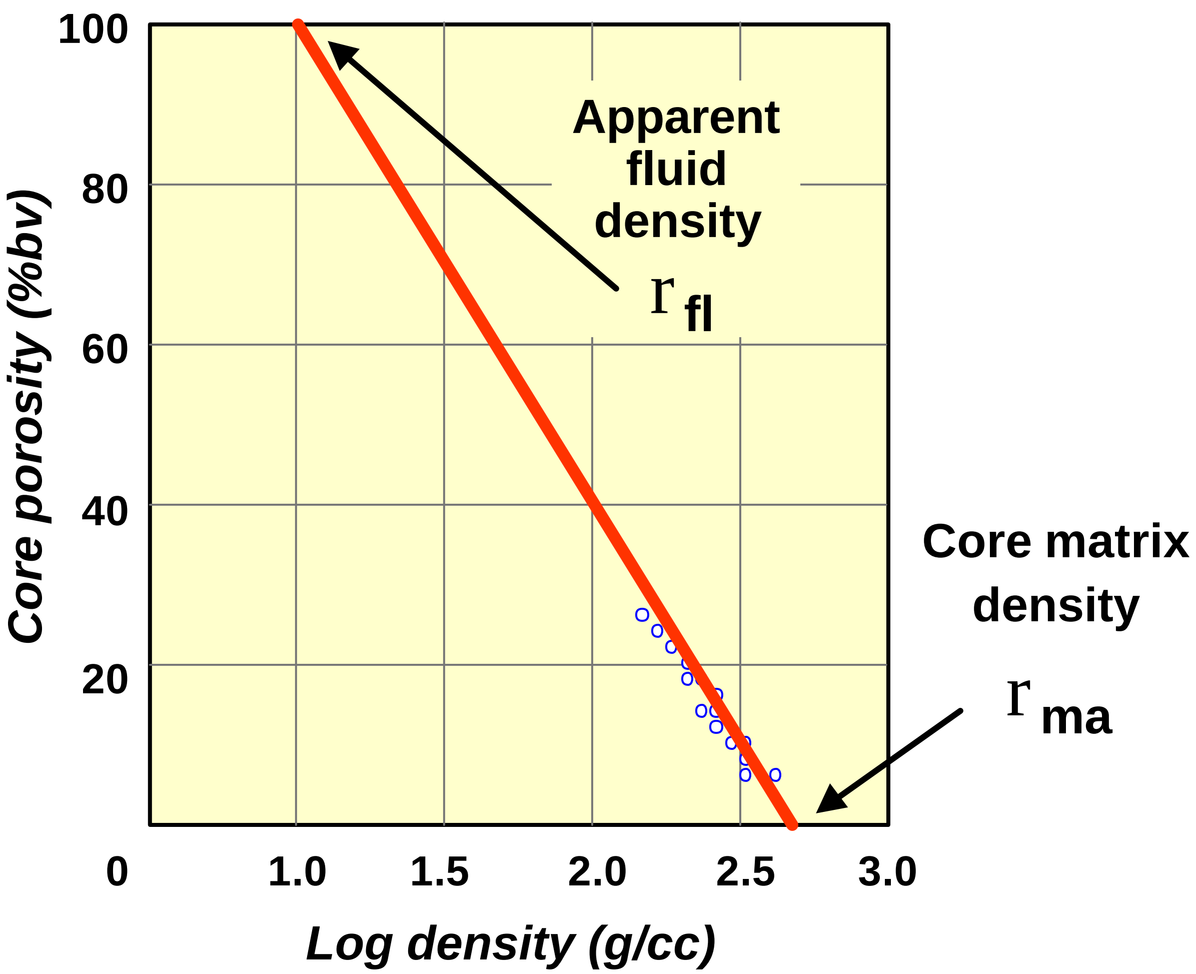


$$\rho_b = \Phi \, \rho_{fl} + (1-\Phi)\, \rho_{ma}$$

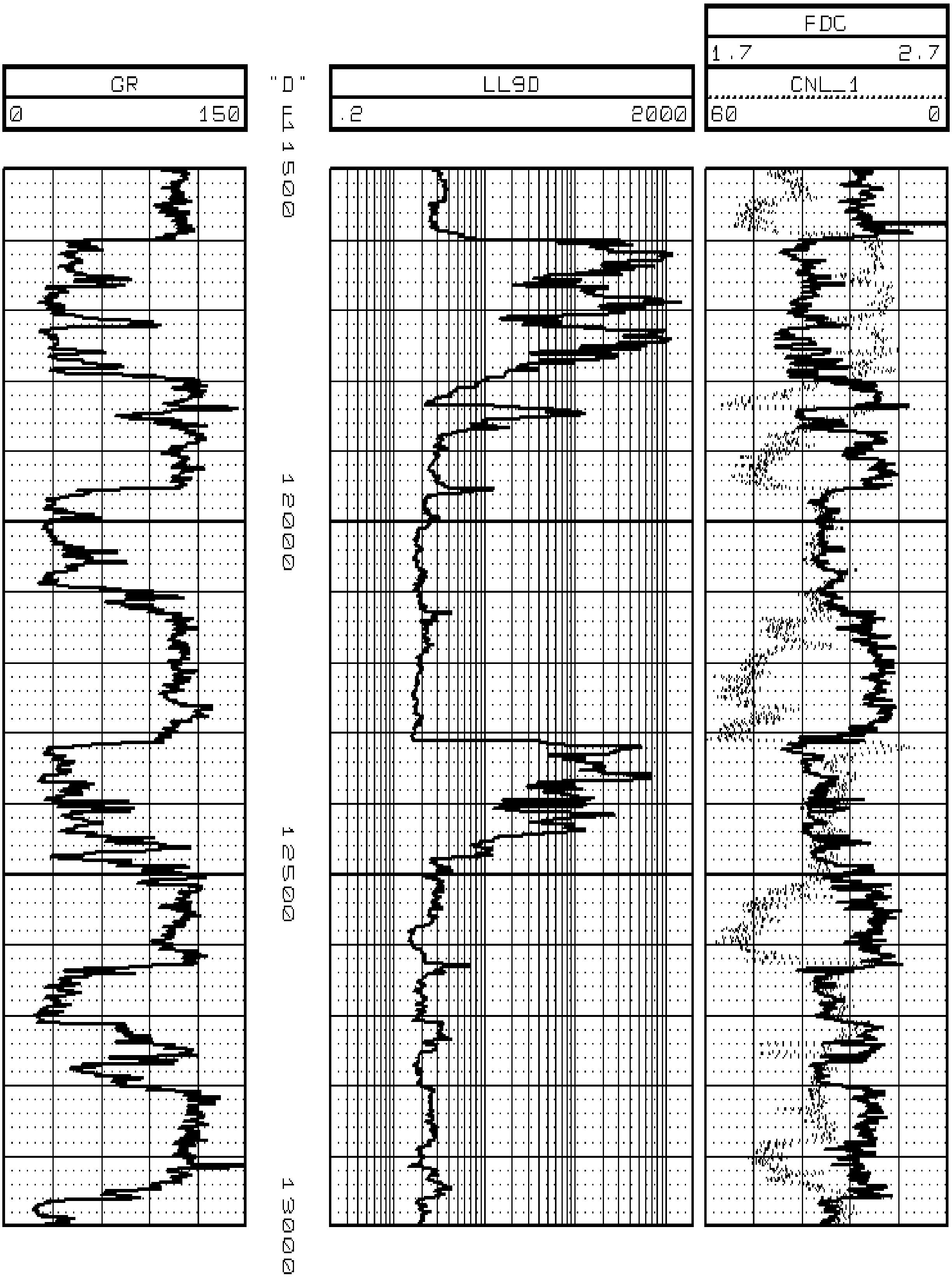


$$\rho_b = \Phi \{S_w \, \rho_{fl} + (1-S_w)\, \rho_o\} + (1-\Phi)\, \rho_{ma}$$

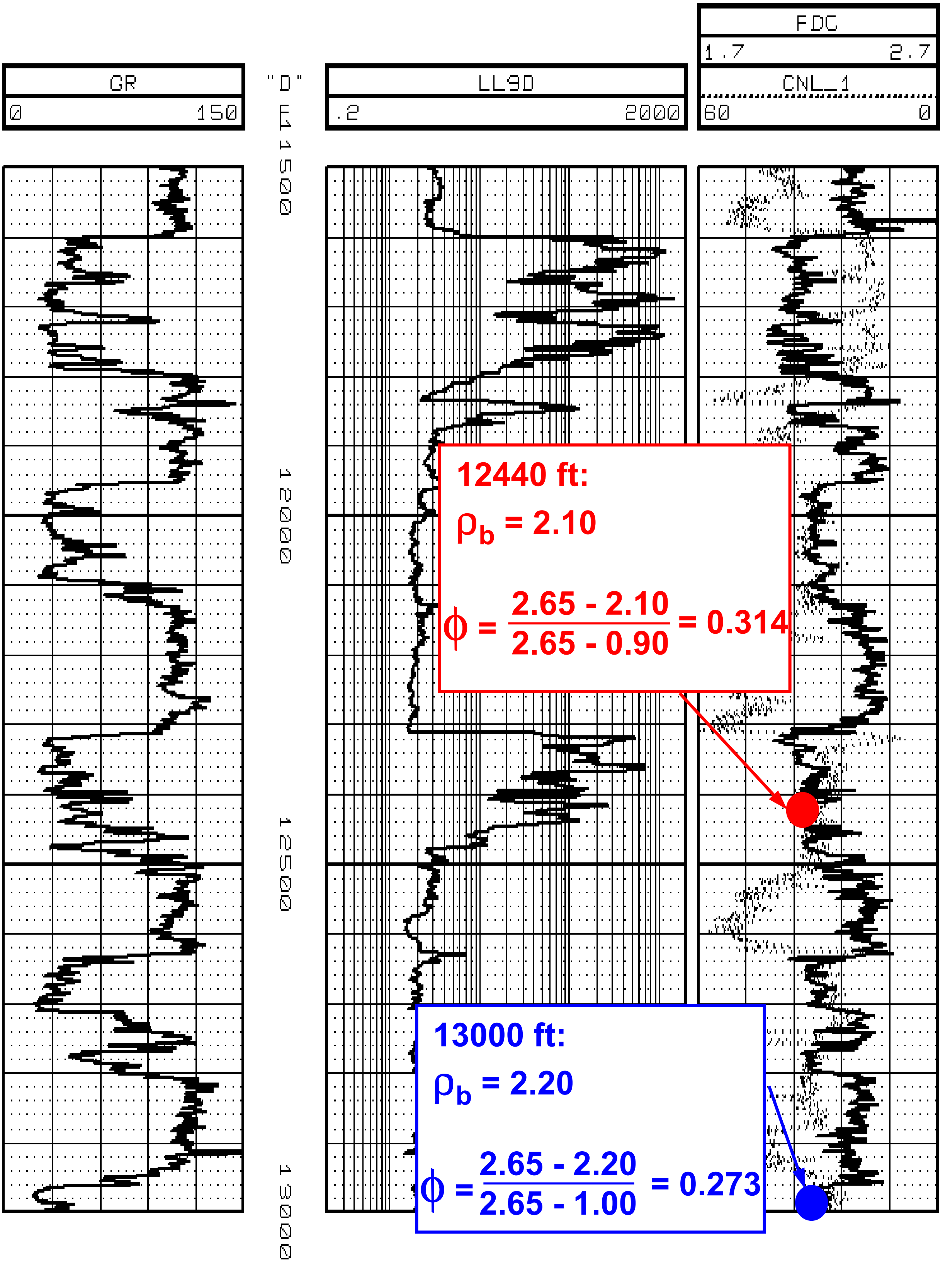
Core porosity calibration



Calculate the porosity @ 12440 ‘ and 13000’



Porosity in water sand: 13000 ft and oil sand: 12440 ft



12440 ft:

$\rho_b = 2.10$

$$\phi = \frac{2.65 - 2.10}{2.65 - 0.90} = 0.314$$

13000 ft:

$\rho_b = 2.20$

$$\phi = \frac{2.65 - 2.20}{2.65 - 1.00} = 0.273$$

Density and Neutron Tools

Density

LDT = Litho-Density Tool, Schlumberger

ZDEN = Litho-Density Tool, Baker Atlas

SDLT = Litho-Density Tool, Halliburton

Neutron (thermal)

CNL = Compensated Neutron Log, Schlumberger

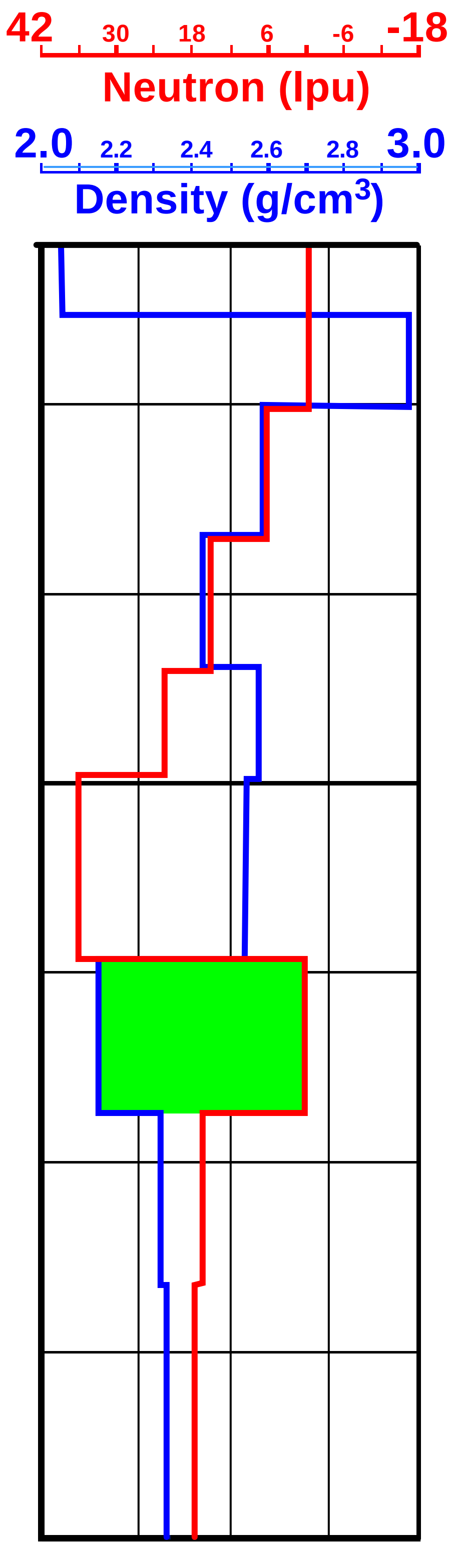
CN = Compensated Neutron Log, Baker Atlas

DSNT = Compensated Neutron Log, Halliburton

+

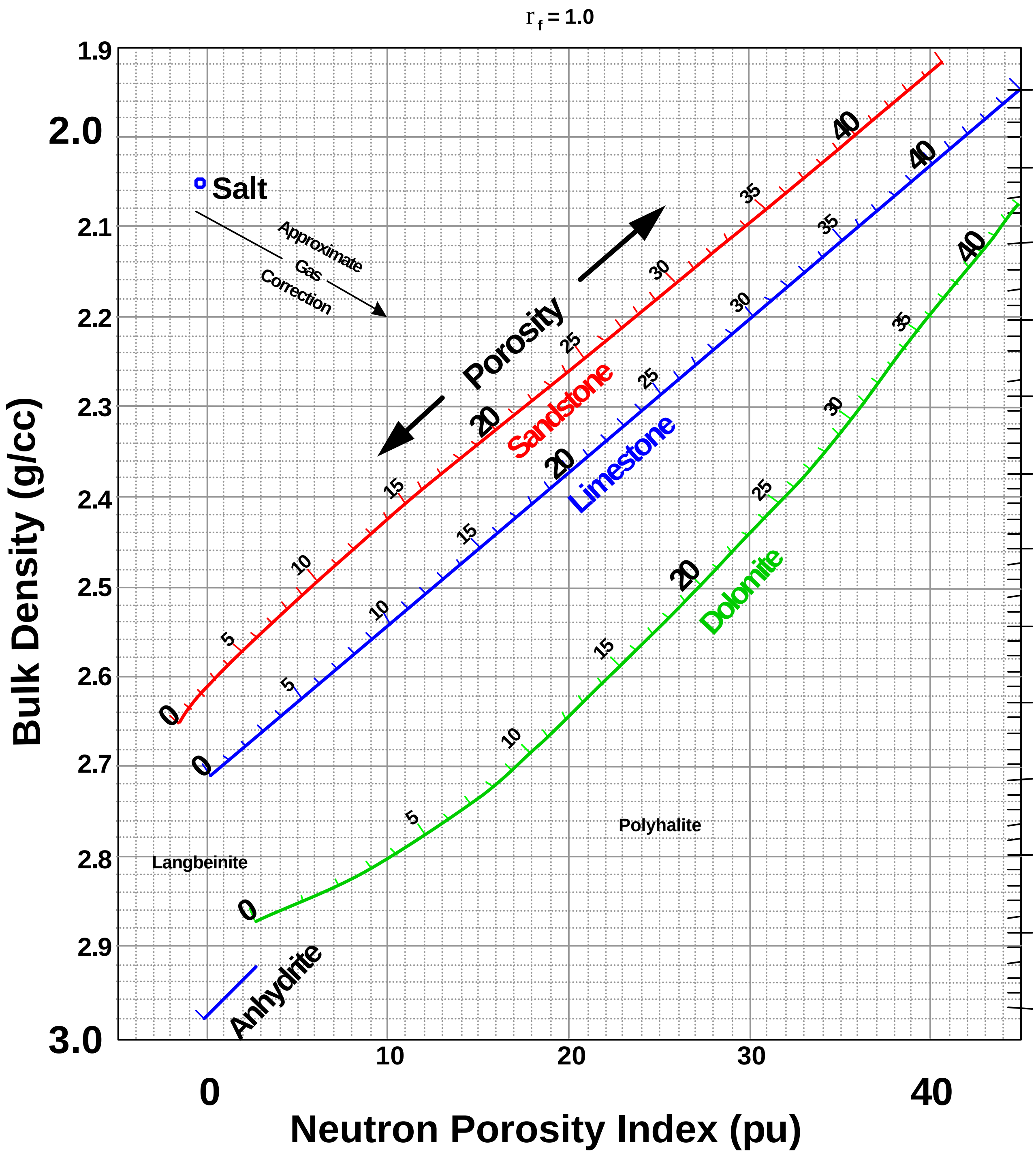
APS = Accelerator Porosity Sonde (epi-thermal)

Density / neutron Responses

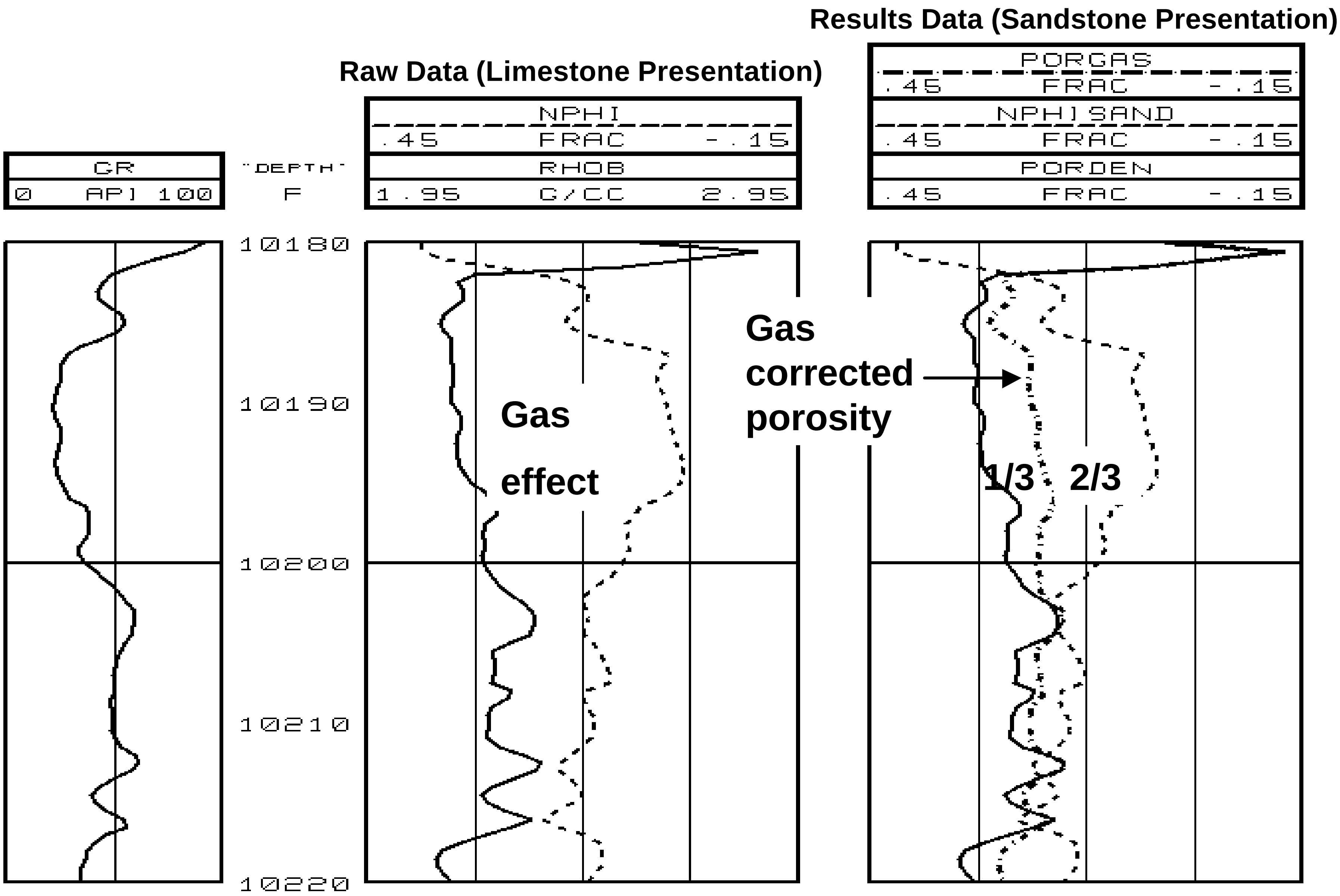


Lithology	Porosity	Fluid
Salt		
Anhydrite		
Limestone	5%	Water
Limestone	15%	Water
Dolomite	15%	Water
Shale		
Sandstone	20%	Gas
Sandstone	20%	Oil
Sandstone	20%	Water

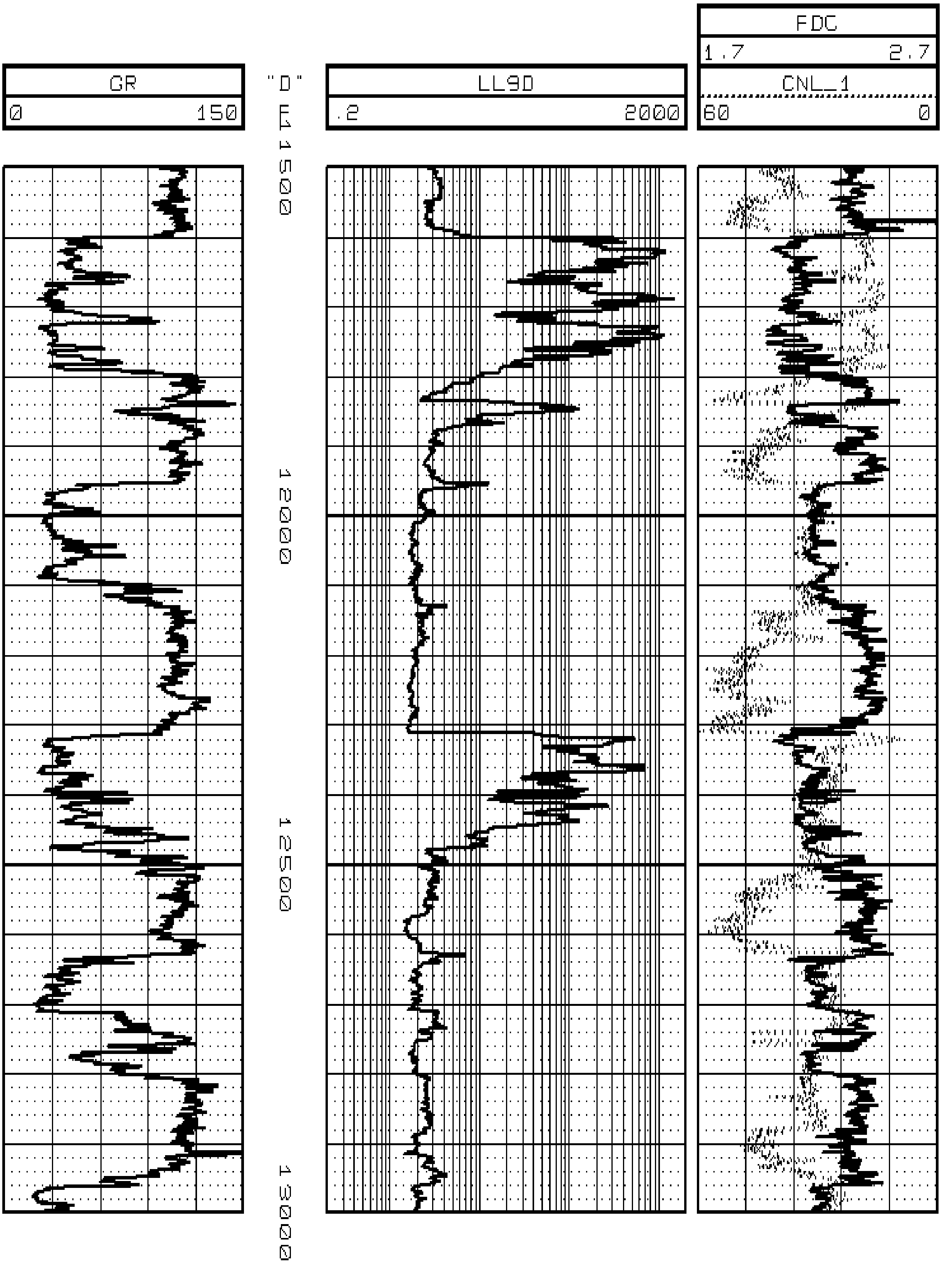
Neutron / density X-plot



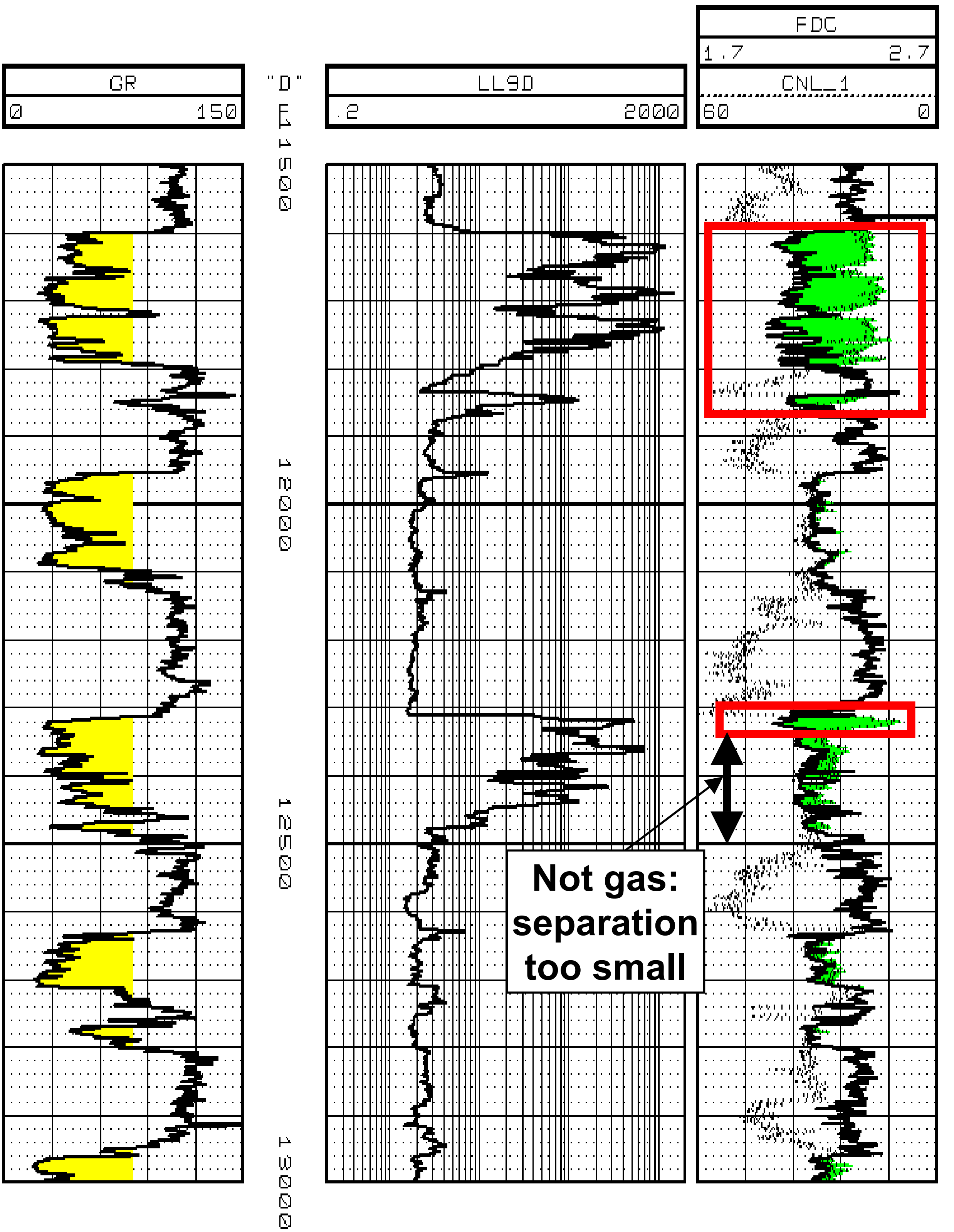
Quick look porosity determination in gas bearing zones



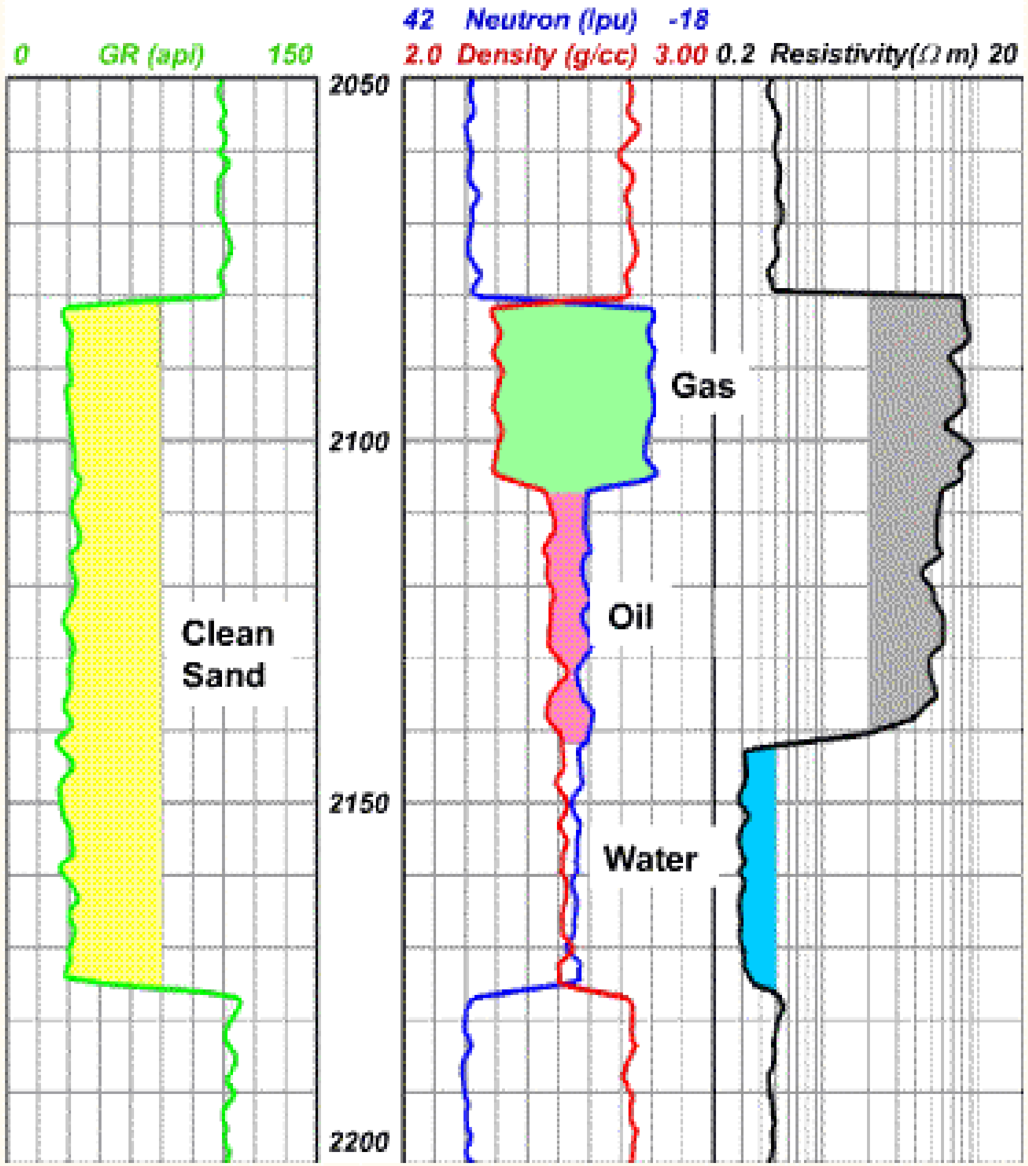
Identify the Gas



Recognition of gas



Porefill Determination with Density/Neutron

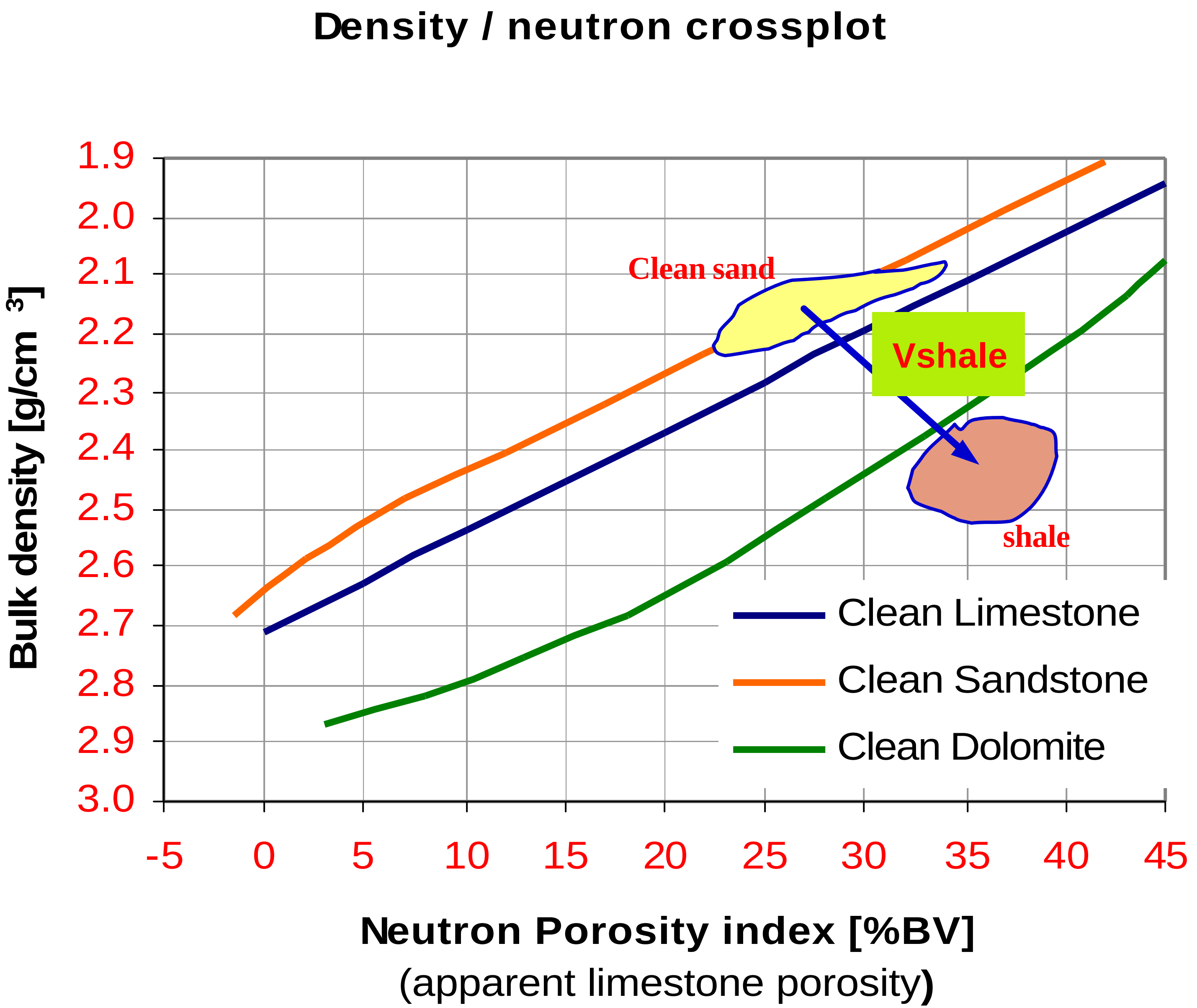


The hydrocarbons have density and hydrogen index less than that of water.

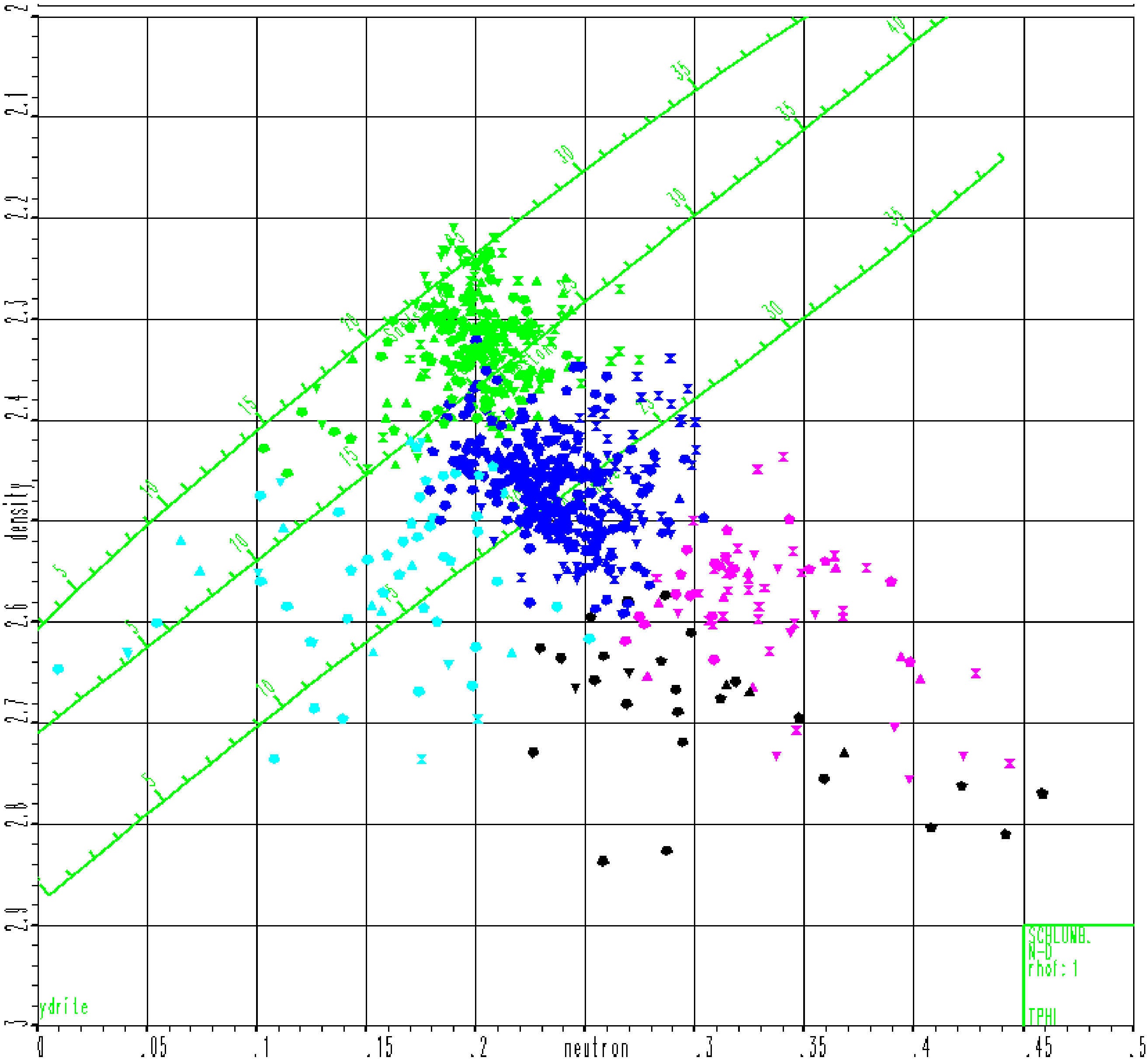
Thus the presence of hydrocarbons in the formation results in a decrease of density and neutron log responses, which results in the log separation.

Gas has very low density and hydrogen index compared to water or oil, resulting in a larger separation.

A few more words on Net Sand Selection



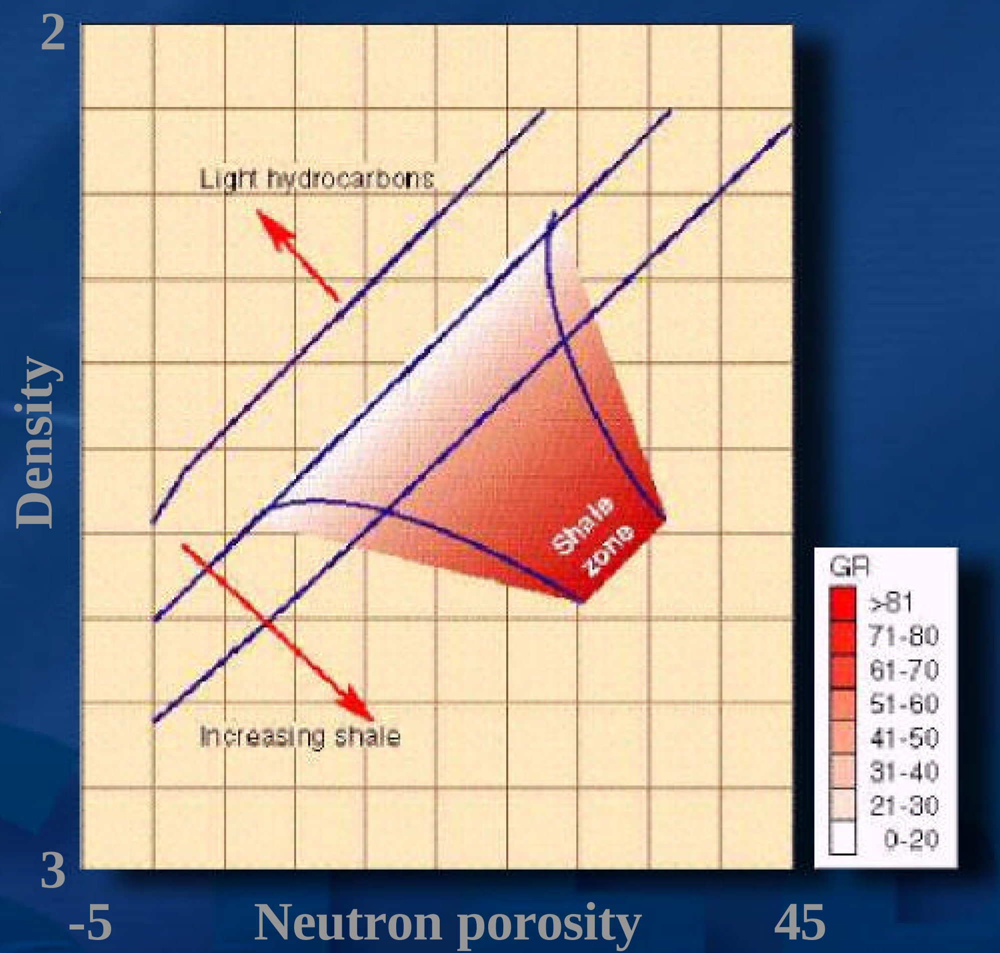
A few more words on Net Sand Selection



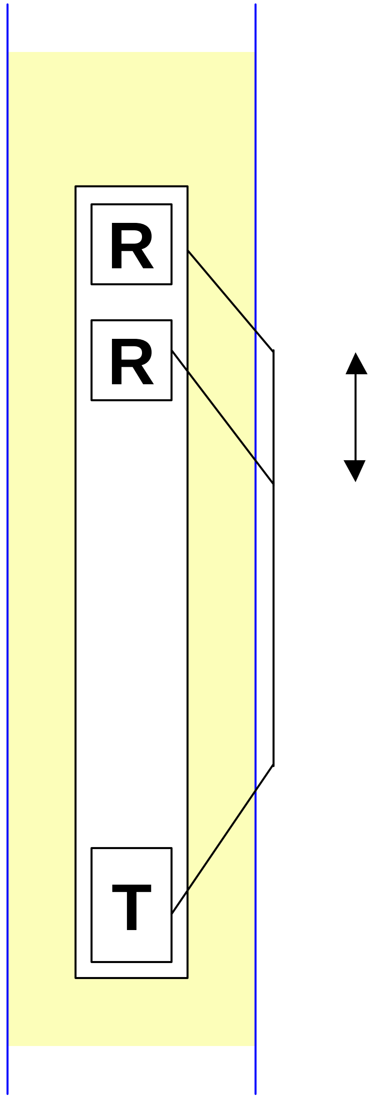
Example of Density Neutron Xplot: Clastic Reservoir

A few more words on Porosity

Gas and shale increase the matrix composition uncertainty and thus porosity uncertainty

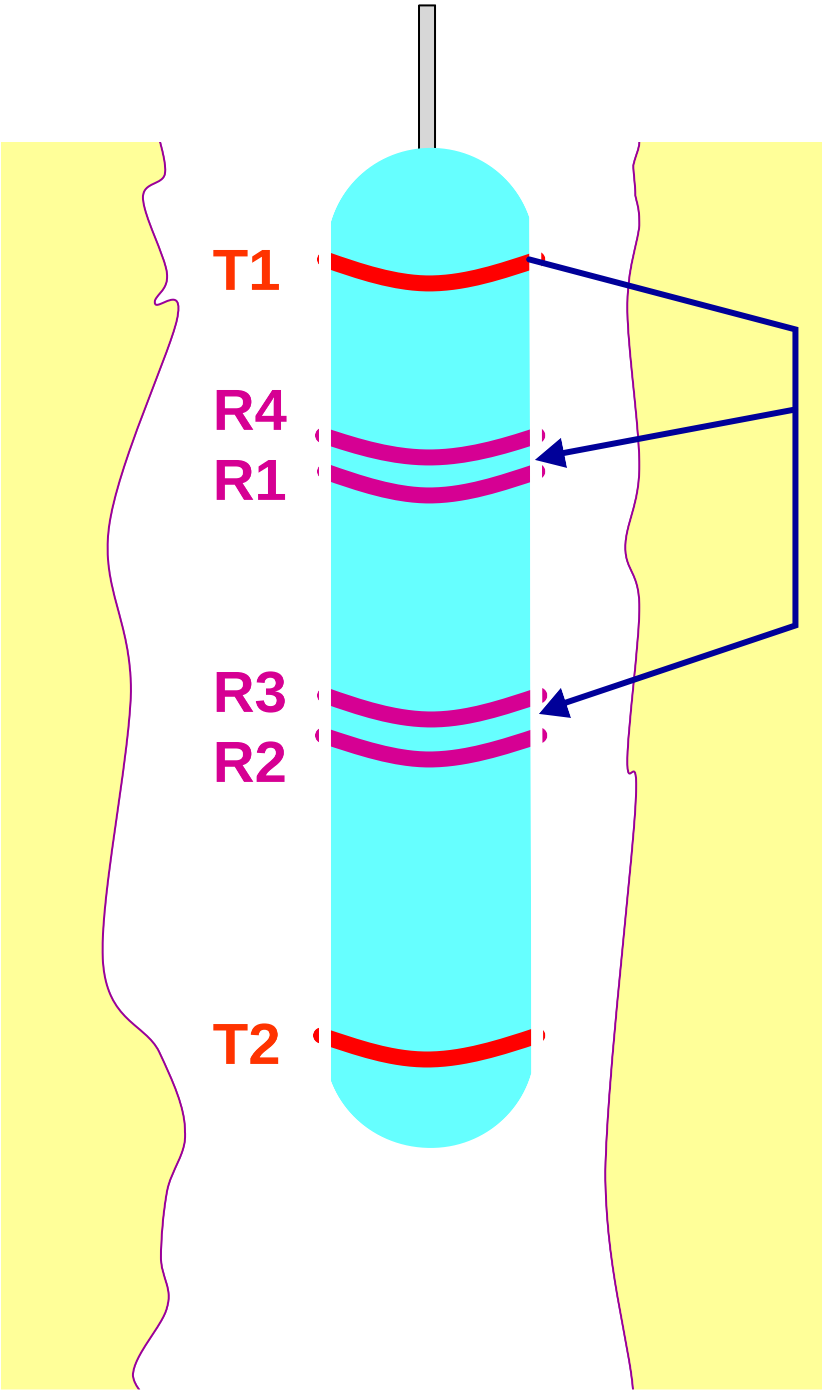


Sonic tool: principle

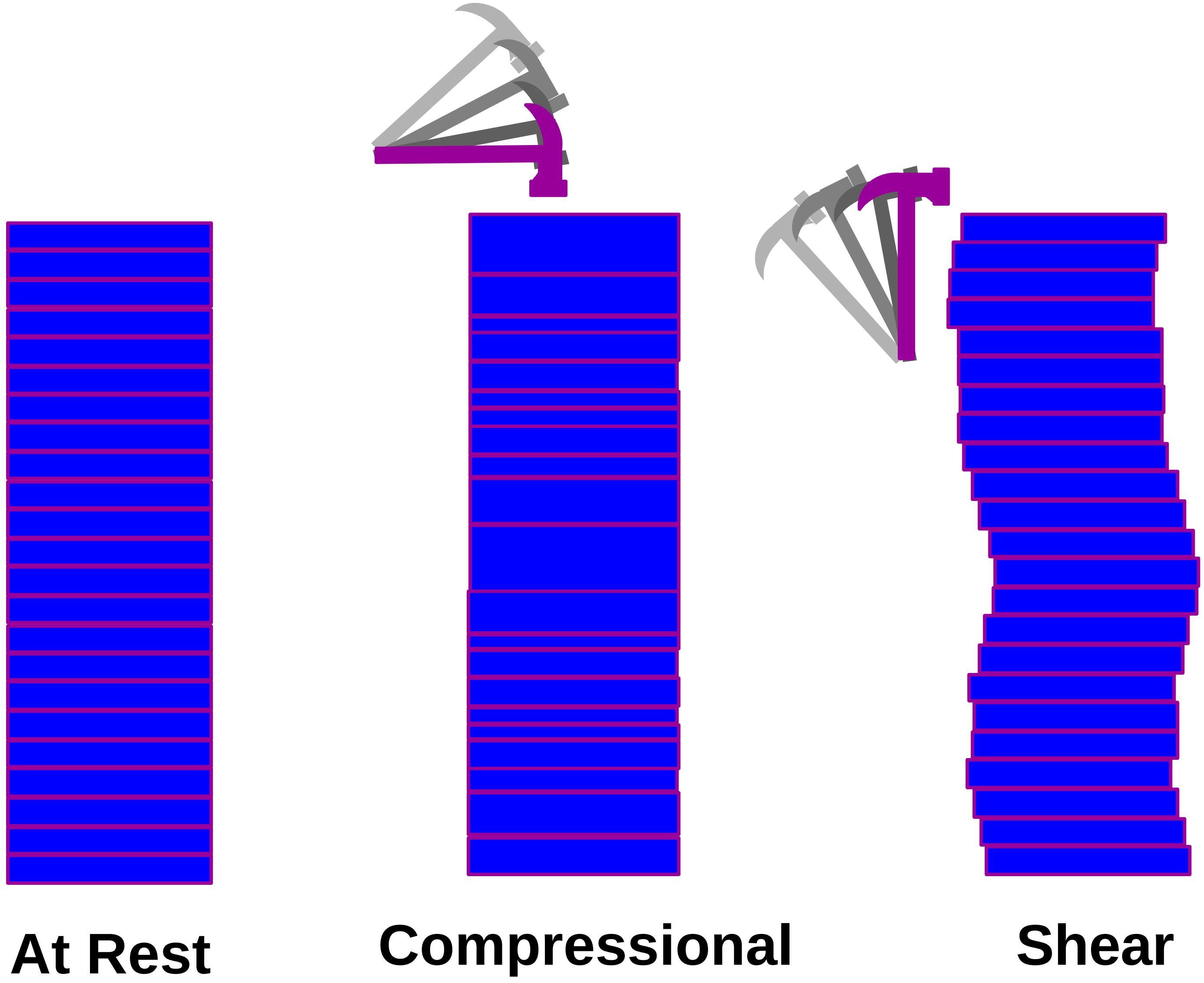


Travel time: Δt in $\mu s/ft$

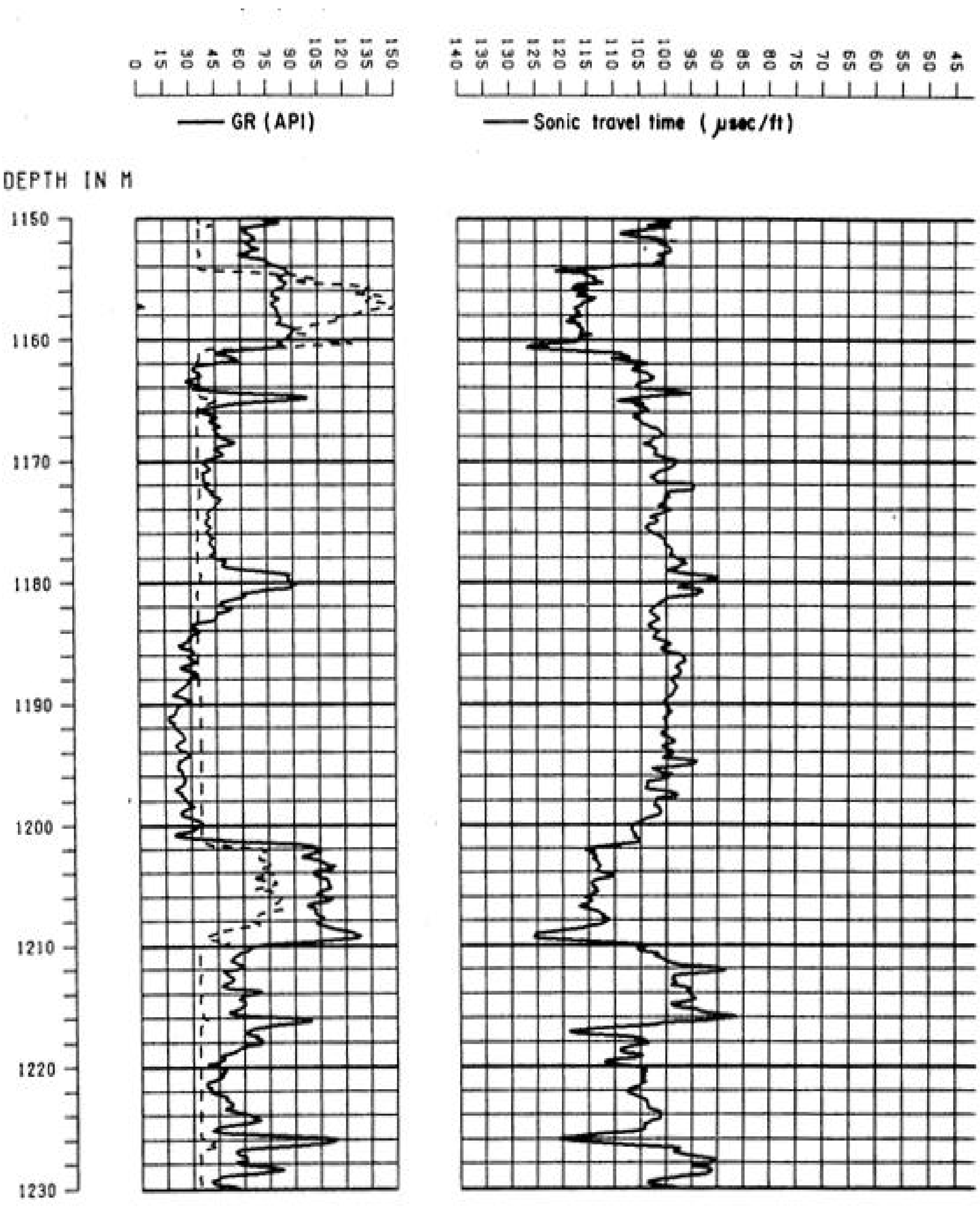
Sonic tool



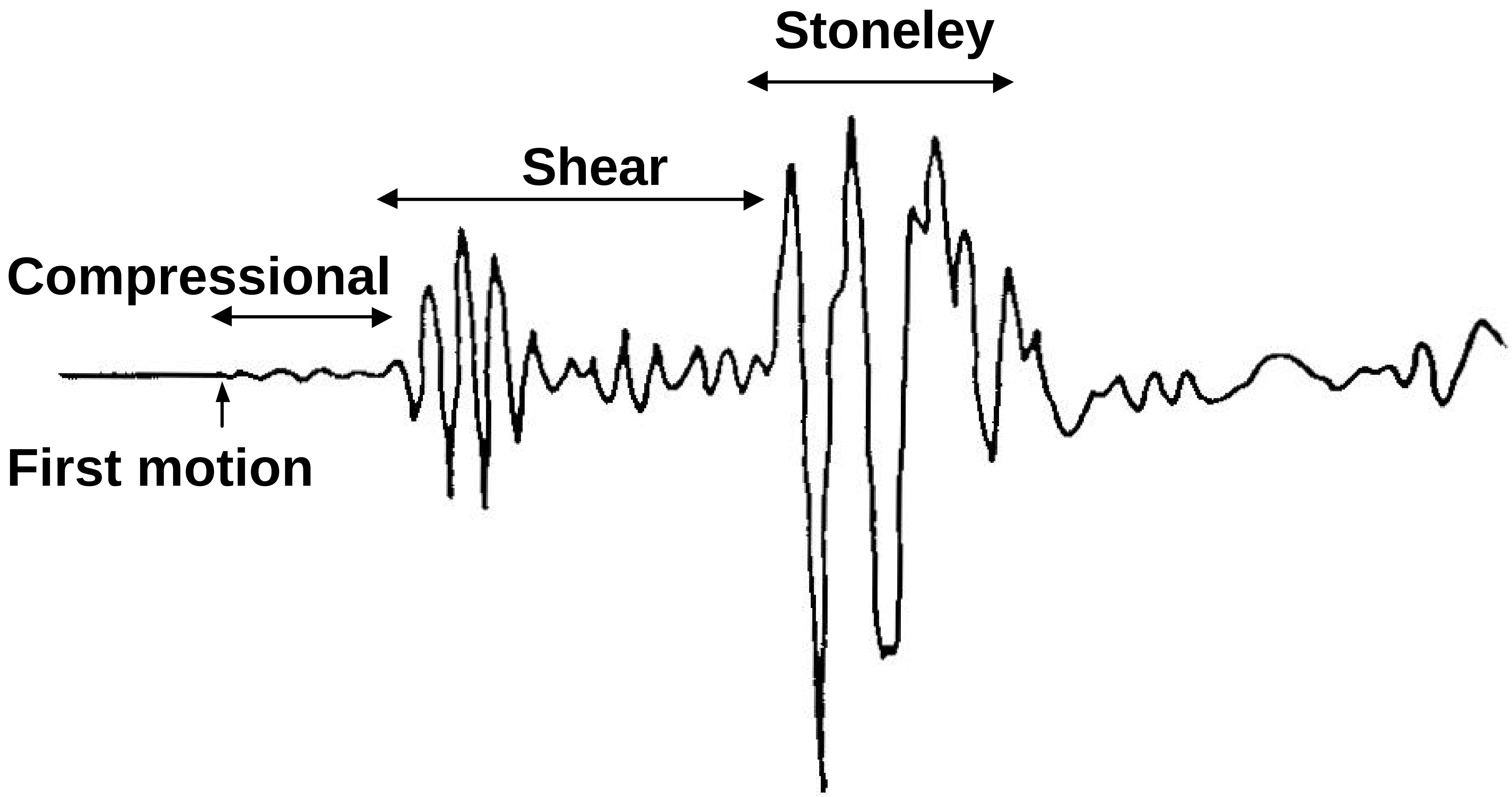
Sonic tool: principle



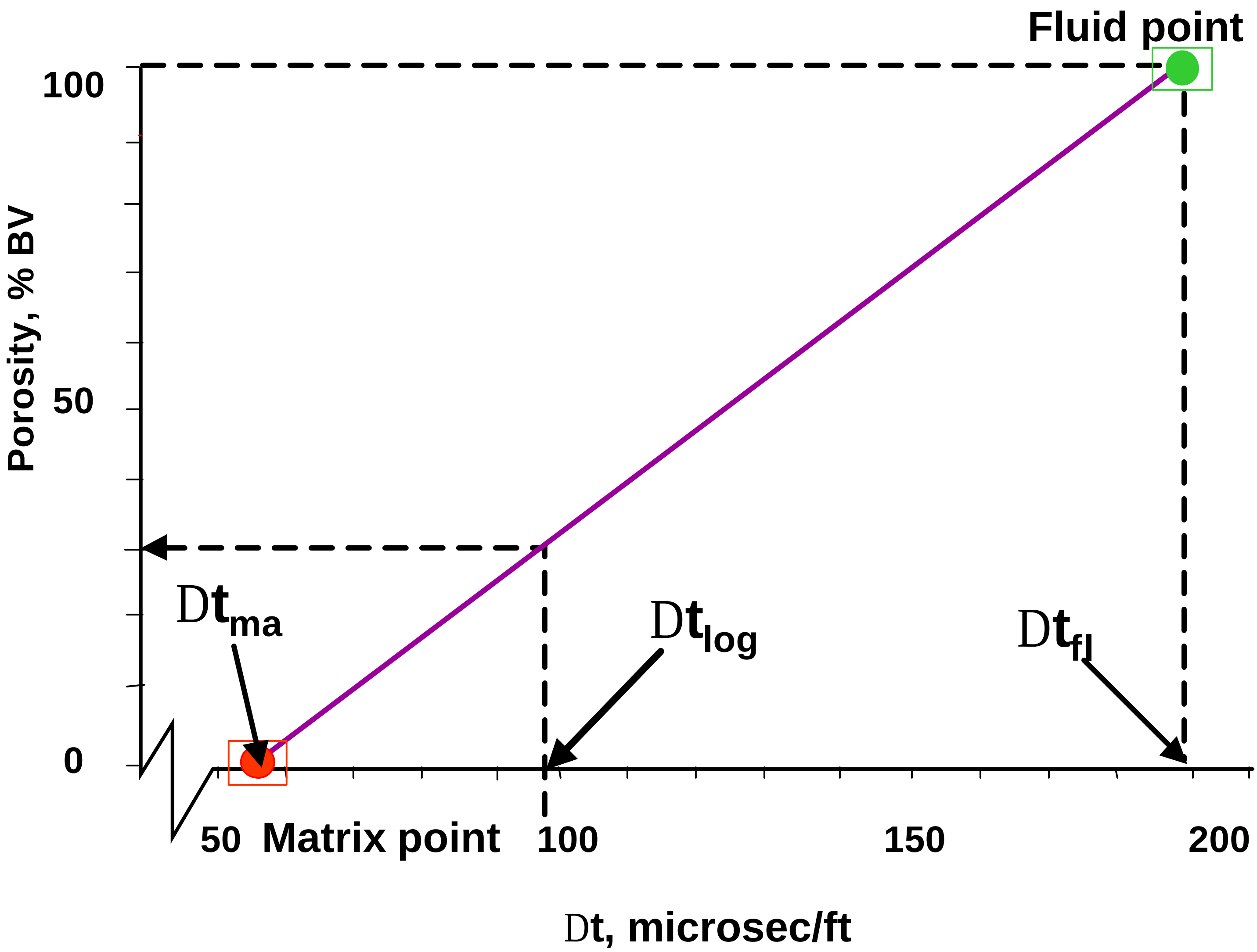
Example of a sonic log



Sonic tool: principle



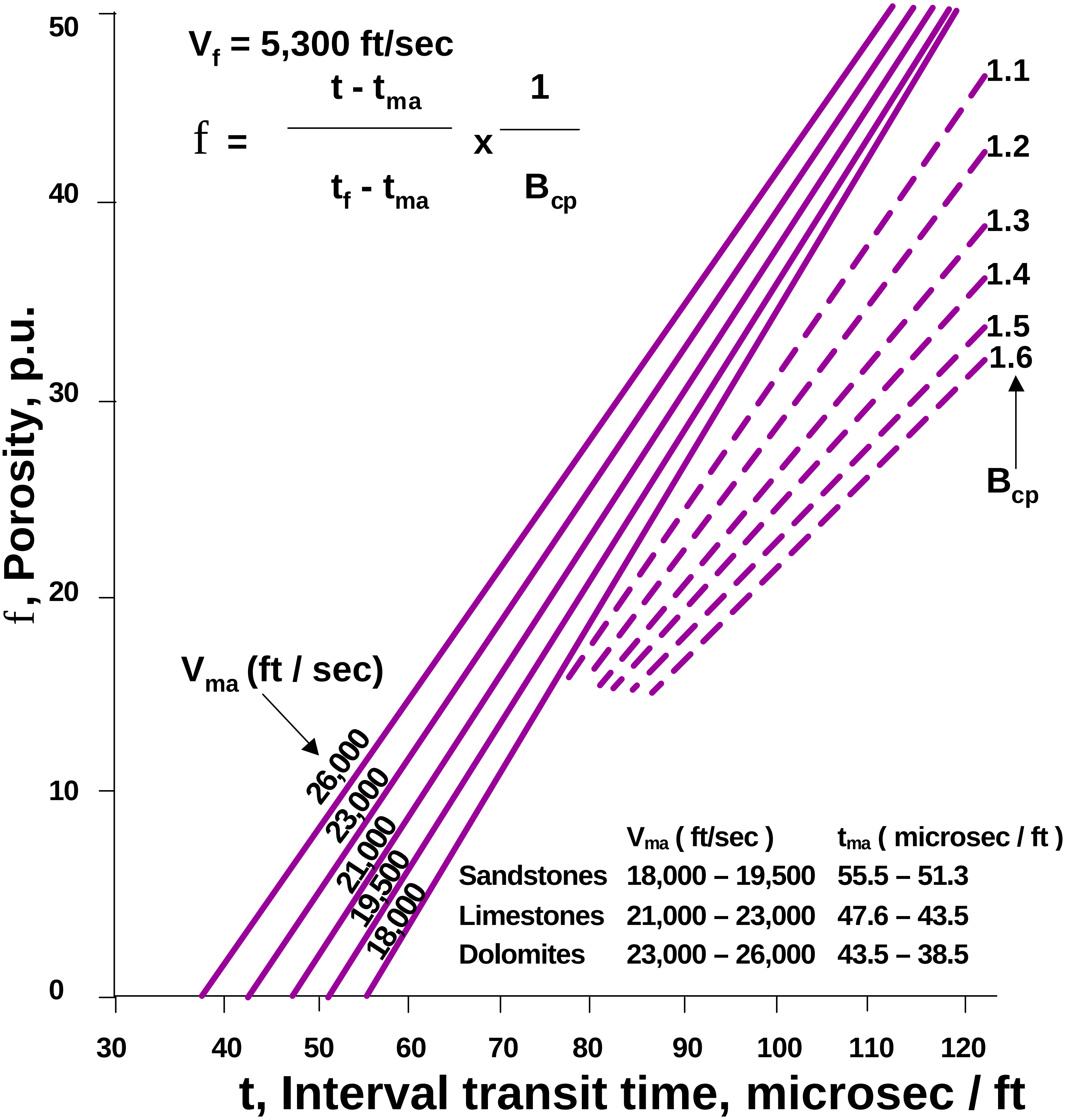
Time average equation sonic log



$$\phi = \frac{\Delta t_{log} - \Delta t_{ma}}{\Delta t_{fl} - \Delta t_{ma}}$$

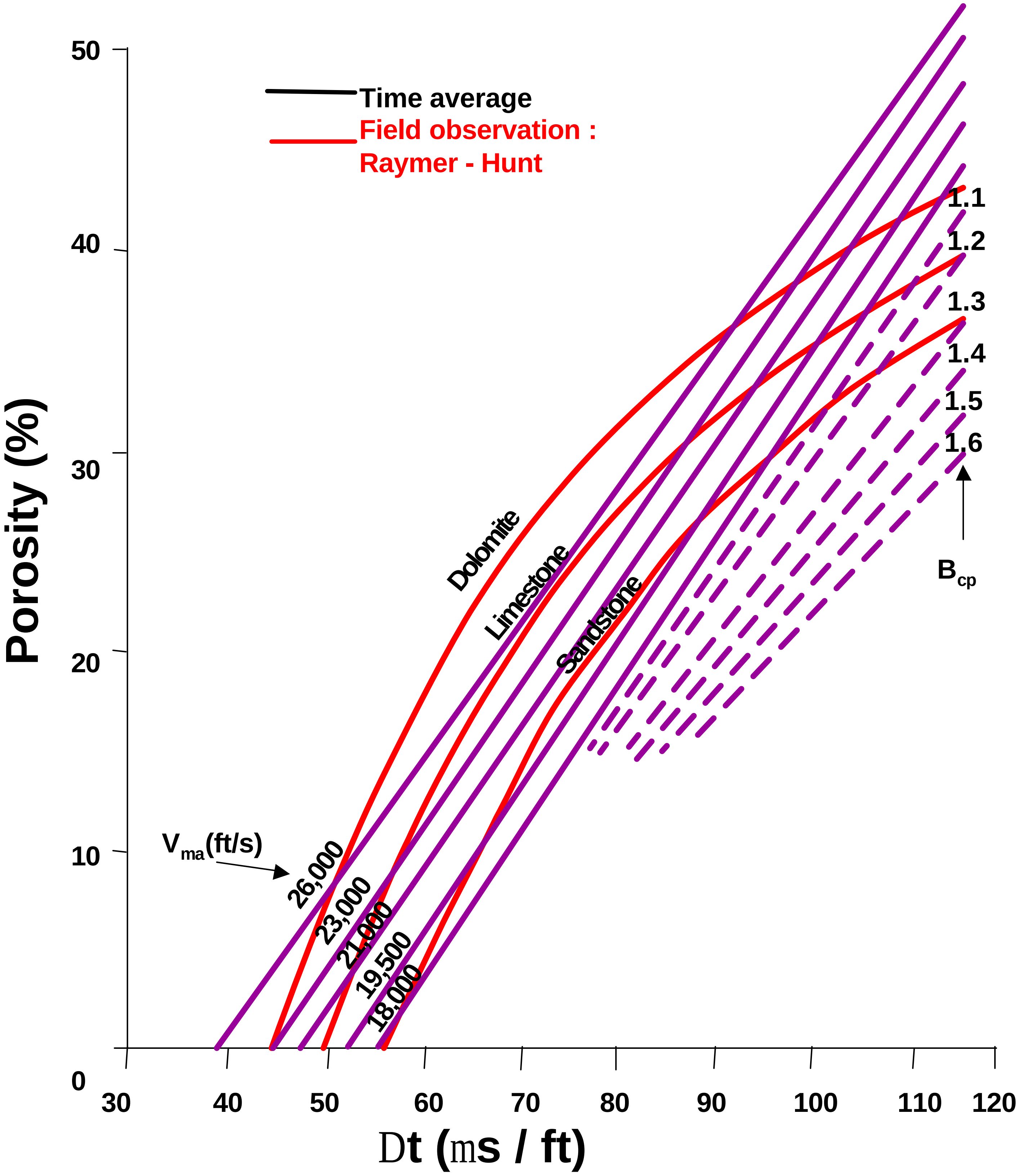
$$\Delta t_{log} = \phi \, \Delta t_{fl} + (1 - \phi) \, \Delta t_{ma}$$

Porosity evaluation from sonic

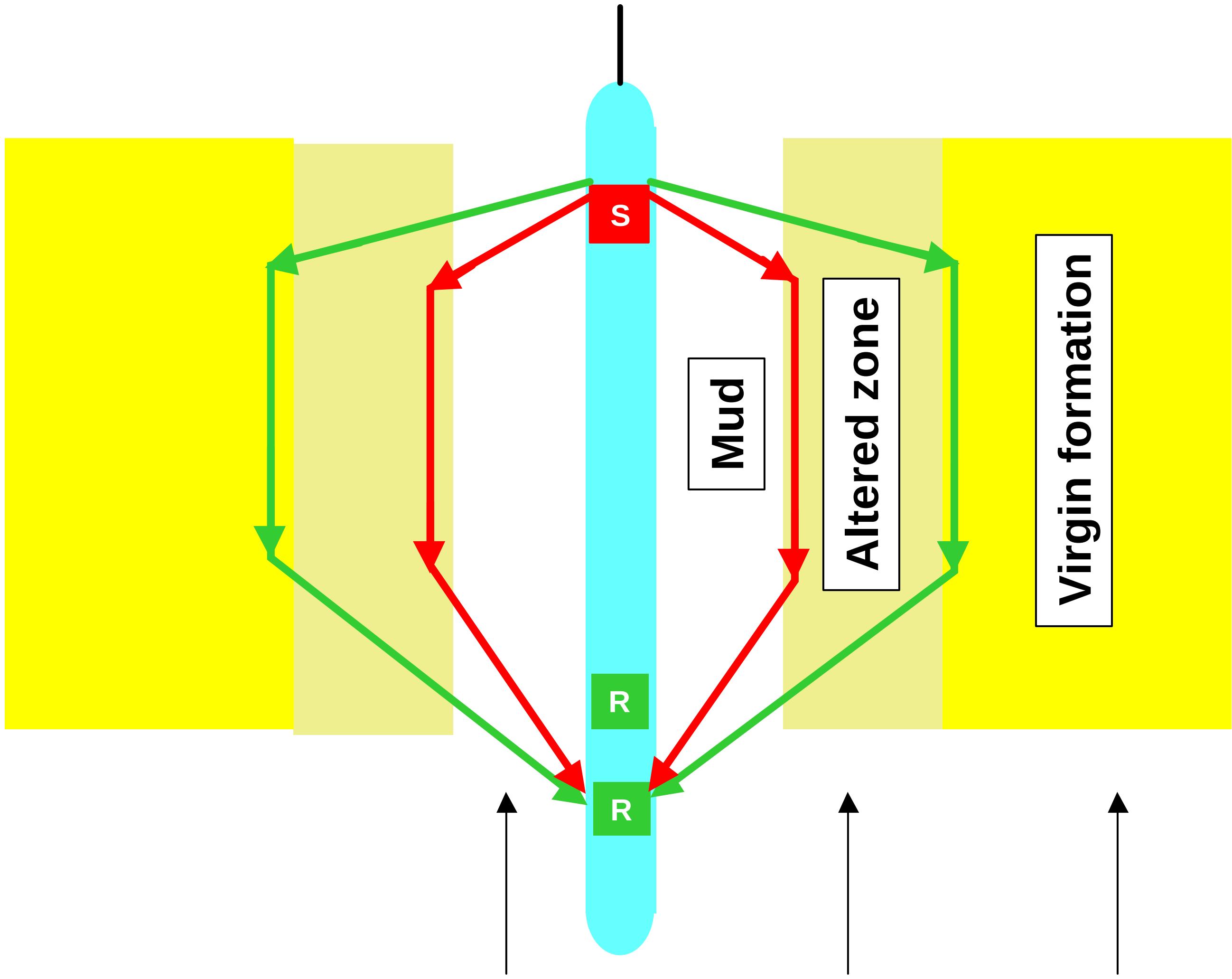


	V_{ma} (ft/sec)	t_{ma} (microsec / ft)
Sandstones	18,000 – 19,500	55.5 – 51.3
Limestones	21,000 – 23,000	47.6 – 43.5
Dolomites	23,000 – 26,000	43.5 – 38.5

Porosity evaluation from sonic: Raymer-Hunt

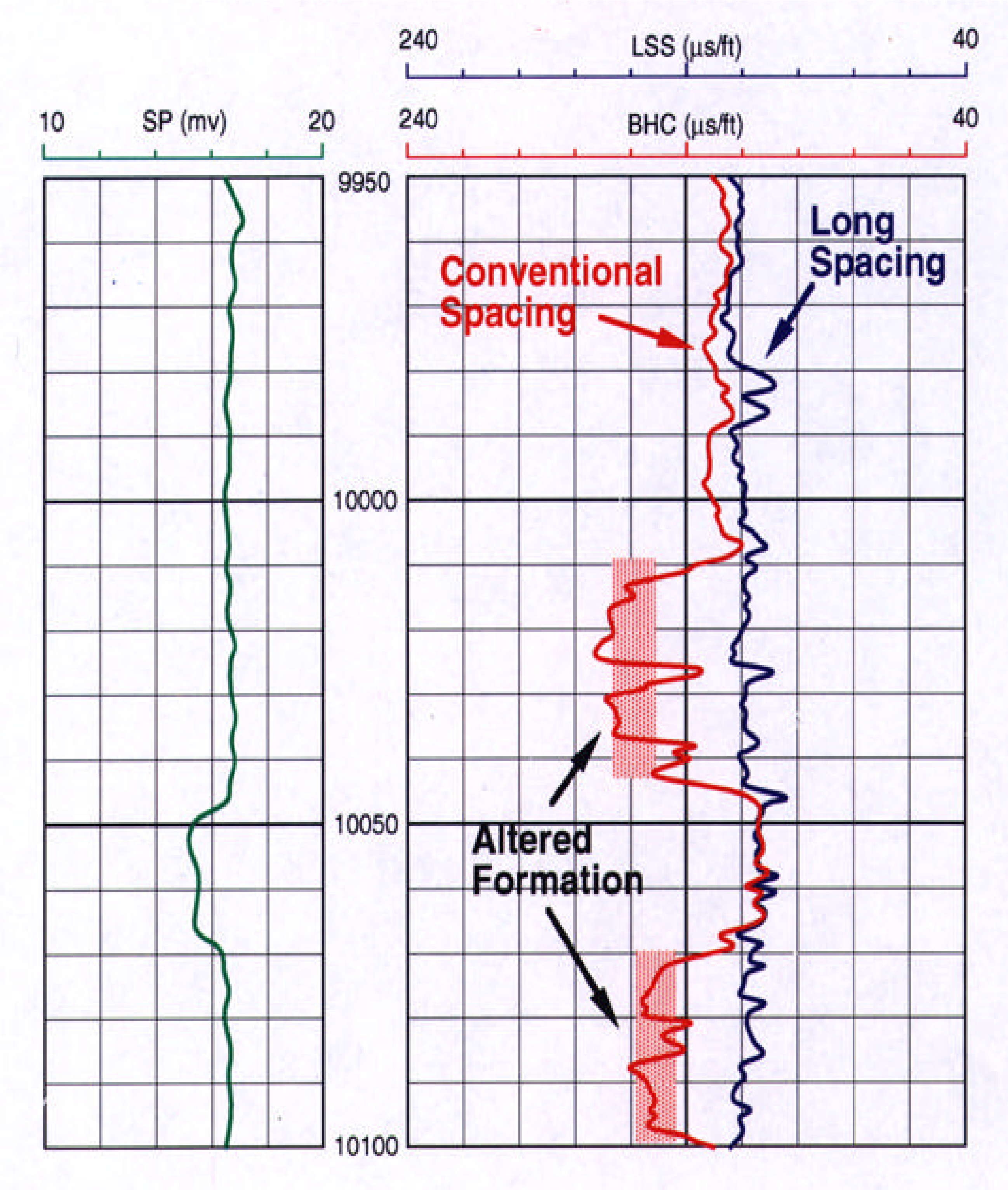


Altered formation



Sonic velocity: Low Intermediate High

Altered formation on sonic logs



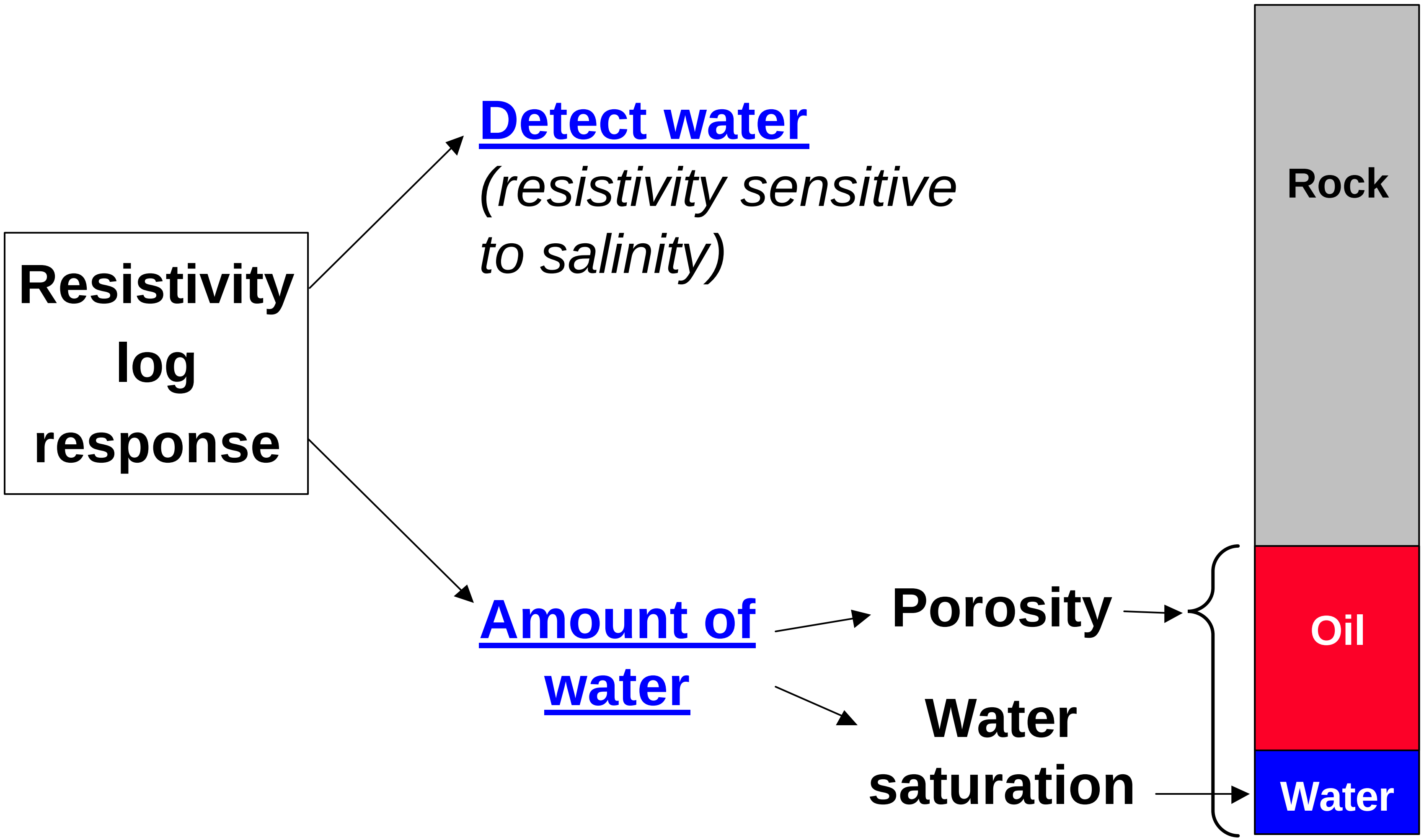
Porosity tools

Density: First choice
Required: matrix & fluid densities

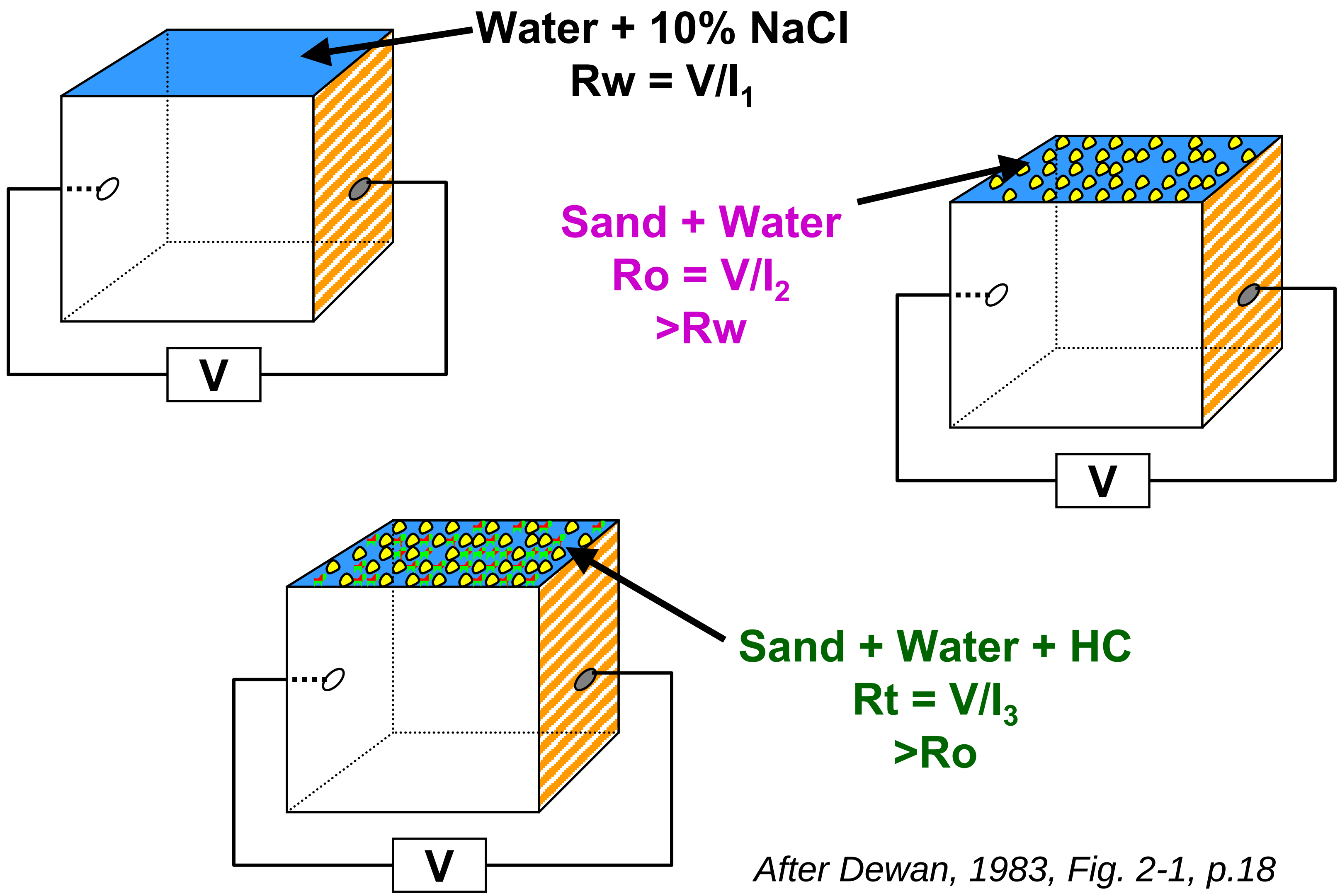
Neutron: In combination with density
Limestone scaling
Many corrections
Used for gas/oil & shale discrimination

Sonic: Used for seismic calibration
Porosity tool if density not available
Required: matrix & fluid travel times

HC saturation from logs



Definition of Resistivities



After Dewan, 1983, Fig. 2-1, p.18

Resistivity Definitions

- **Rw: Resistivity of the formation water**
  - **A function of salinity and temperature**
    - The higher these two variables, the lower the resistivity of the water (the water will be more conductive)
- **Ro: Resistivity of the water-bearing formation**
  - **Ro > Rw (more rock, less water)**
- **Rt: Resistivity of the hydrocarbon-bearing formation**
  - **Rt > Ro (rock and hydrocarbon are non-conductive)**

Archie Equation (1)

- **Formation Factor**
  - Ro must be proportional to Rw: only the water conducts. Thus:
    - $Ro = F \cdot Rw$ ………(1)

    The proportionality constant, F, is termed the *Formation Factor.*
  - F must be related to Φ by a relation of the form:
    - $F = 1/\Phi^m$ …………..(2)

    Because when $\Phi = 1$ (all water, no rock), $Ro = Rw$, and when $\Phi = 0$ (no pore water, all rock), Ro is infinite (the rock is an insulator). Equation 2 satisfies these conditions regardless of the value of m, which is termed the *cementation exponent.* The value of m reflects the tortuosity of the pore system (the current flow path through the rock). If all the pores were cylindrical tubes, m would equal 1. In porous rocks, measurements reveal that m generally approximates 2.0
  - The constant, 1, is called the *cementation factor,* and is designated, a, in general equations
  - Accepted relations in logging are:

    $F = 1/\Phi^{2.0}$ for carbonates…………………(3)

    $F = 0.81/\Phi^{2.0}$ or $0.62/\Phi^{2.15}$ for sands…….(4)

Archie Equation (2)

- **Water Saturation: Sw, the fraction of pore space containing water, can be calculated if Ro and Rt are known**
  - There must be a relation of the form
    - $Rt = Ro/Sw^{n}$ ....(5)

    because when Sw = 1 (all water in the pores), Rt = Ro, and when Sw = 0 (all hydrocarbon in the pores), Rt must be infinite. Equation 3 satisfies these conditions regardless of the value of the exponent n. The *saturation exponent* n is close in value to m because the flow of current cannot distinguish between displacement of water by sand grains or by hydrocarbon globules of like size since neither conducts electricity. Laboratory measurements reveal that n = 2, on average. Thus water saturation is given by:
    - $Sw = \sqrt{Ro/Rt}$ ....(6)

    This relation can be used to calculate the Sw of a hydrocarbon-bearing zone when an obvious water bearing zone of the same porosity and having the same salinity is near. An example would be a thick sand with an obvious fluid contact in the middle of the sand

Archie Equation (2) Continued

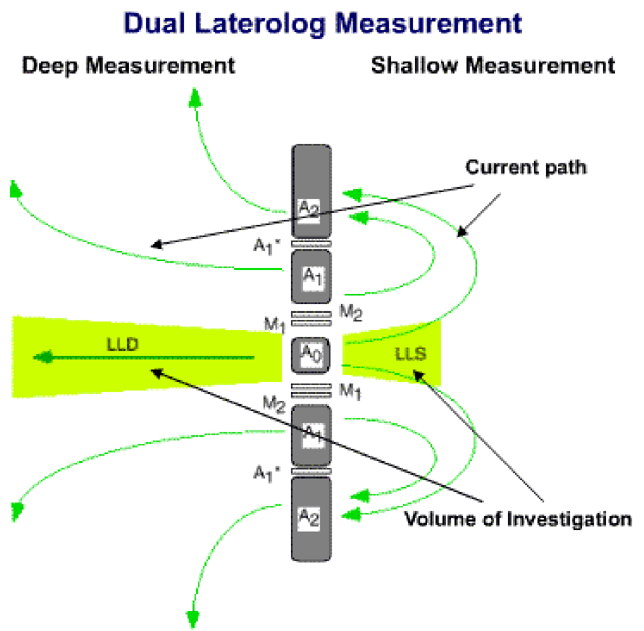
- In most cases, there is not a suitable interval to give Ro, so equation 4 will not apply
  - Replacing Ro by equation 1 gives
    - $Sw = \sqrt{FRw/Rt}$ ……(7)
  - Replacing F by equation 3 gives

$$Sw = c\sqrt{Rw/(Rt \cdot \Phi^m)} \quad \ldots\ldots\ (8)$$

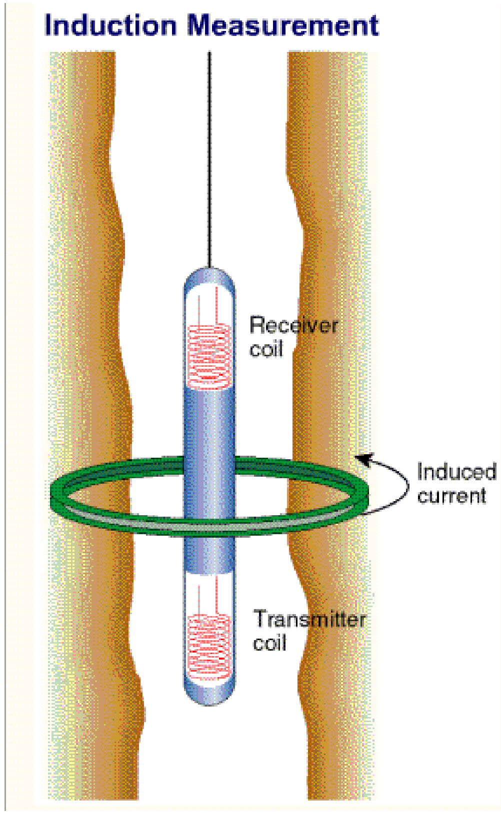
Where c = 1.0 for carbonates and 0.90 for sands

This is the "Archie Equation" the basic equation of log analysis. It was developed by G. E. Archie of Shell and is the fundamental basis of well log evaluation. This equations shows that the volume of HC in place can be calculated if there are sufficient logs to give Rw, Rt and Porosity. Rw is obtained from water sample measurements, catalogs, or from log calculations, Rt is obtained from deep resistivity readings, and porosity is obtained from porosity logs (density, neutron, sonic)

How to Measure Resistivity ?



The dual laterolog tool (DLT) represents one of the technologies used to measure formation resistivity. The tool is designed to function in conductive drilling mud environments. The tool sends focussed current into the formation to measure the voltage in a specific volume of the formation. This voltage is related to the resistivity of the formation. The volume represents a shallow and a deep depth of investigation and the tool provides a shallow (LLS) and a deep (LLD) resistivity measurement.



In non-conductive mud environments, the DLT is not able to function and induction-principles based tools are used. The induction tool (DIT) induces an electromagnetic current loop in the formation which is detected by the receiver coils. The strength of the induced current is related to the conductivity of the formation. The induction tool also provides two volumes of investigation representing the induction medium (ILM) and induction deep (ILD) resistivity.

Saline mud:

DLL= Dual Latero Log:

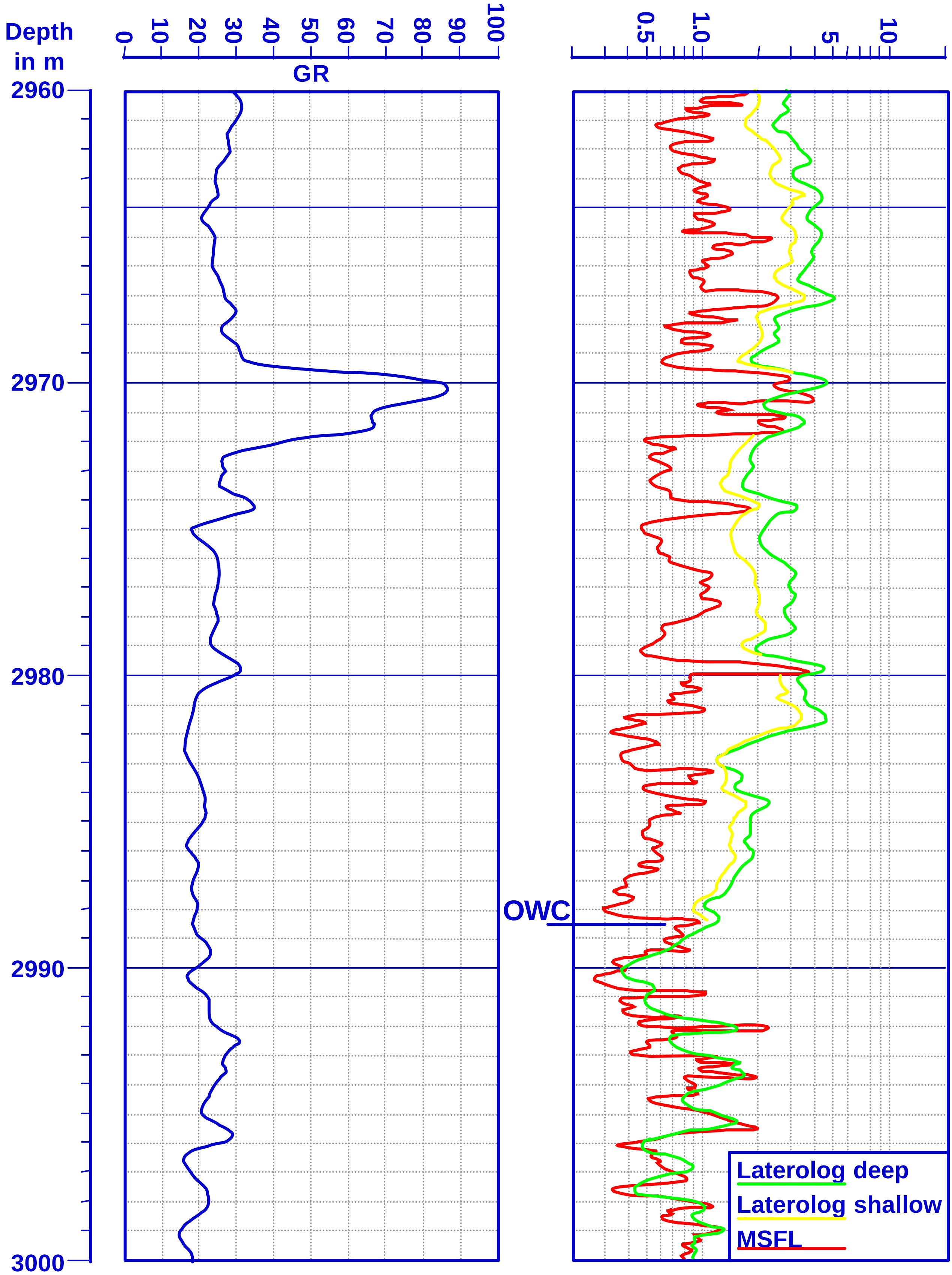
- LLD=Laterolog deep
- LLS=Laterolog shallow
- MSFL=Micro-spherically focused log

Non-conductive mud:

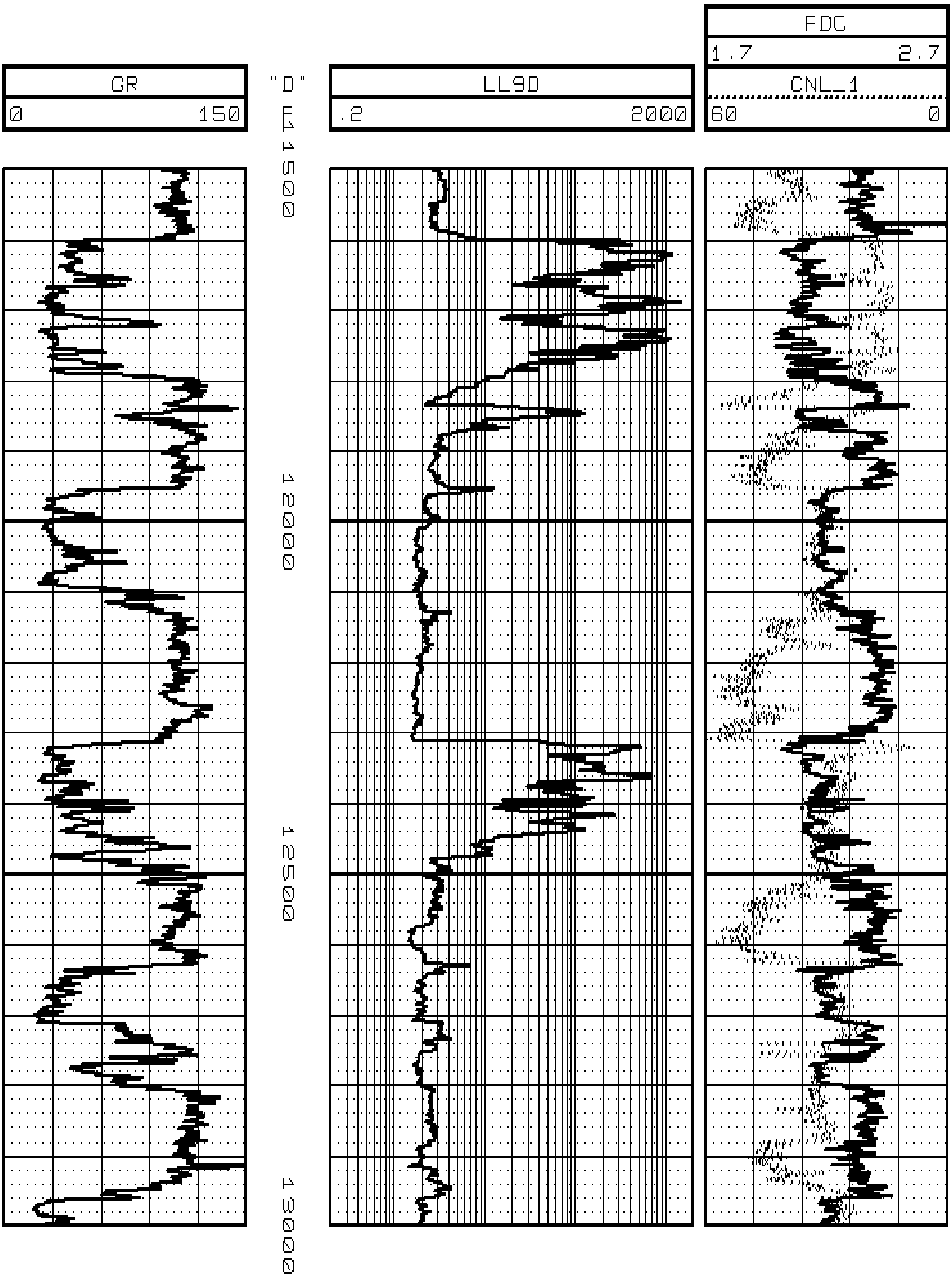
DIL=Dual Induction Log:

- ILD=Induction log deep
- ILM=Induction log medium

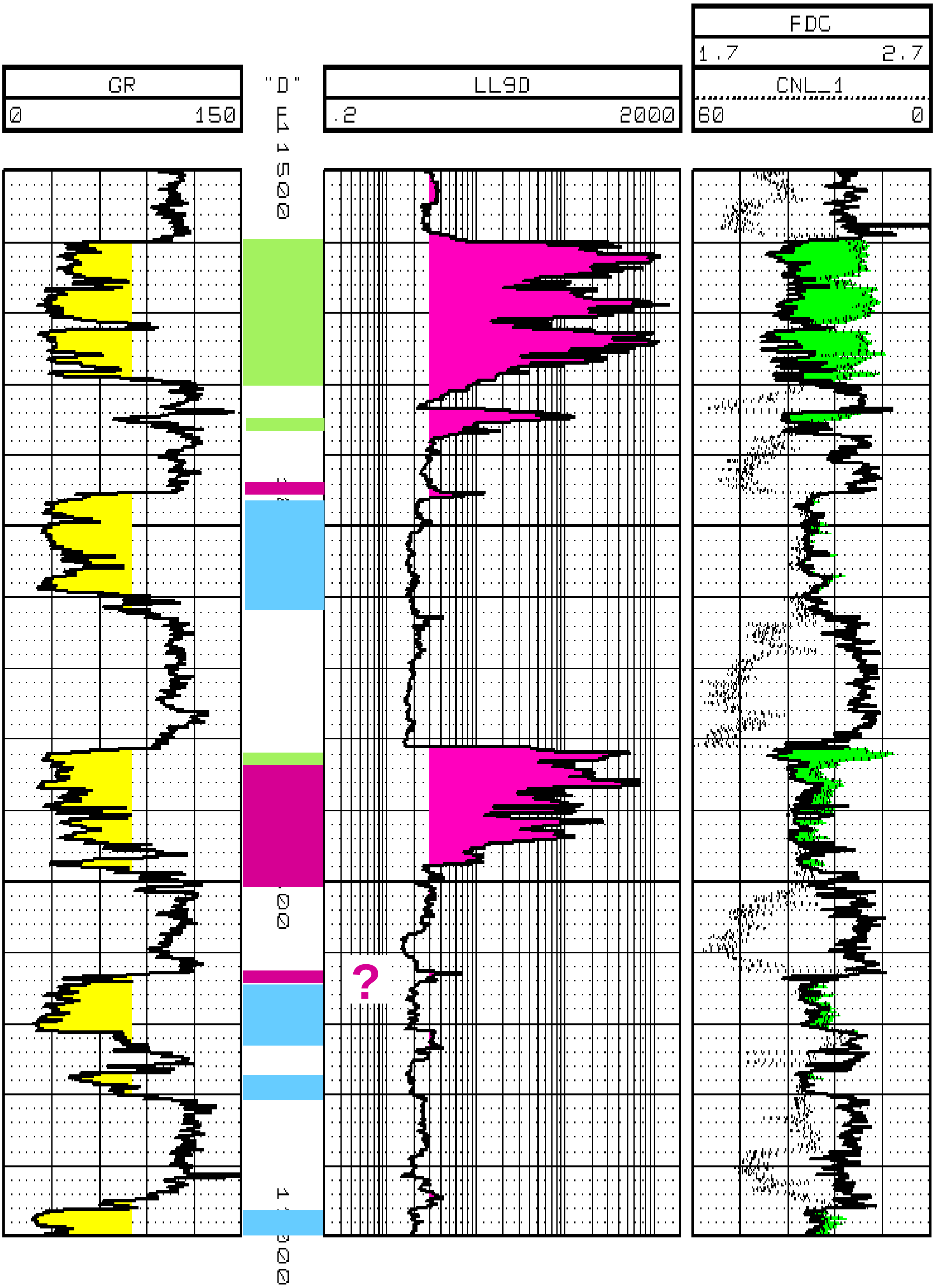
Overview of Tools: How to Measure Resistivity ? Laterolog Readings over an Oil and Water Bearing Sand



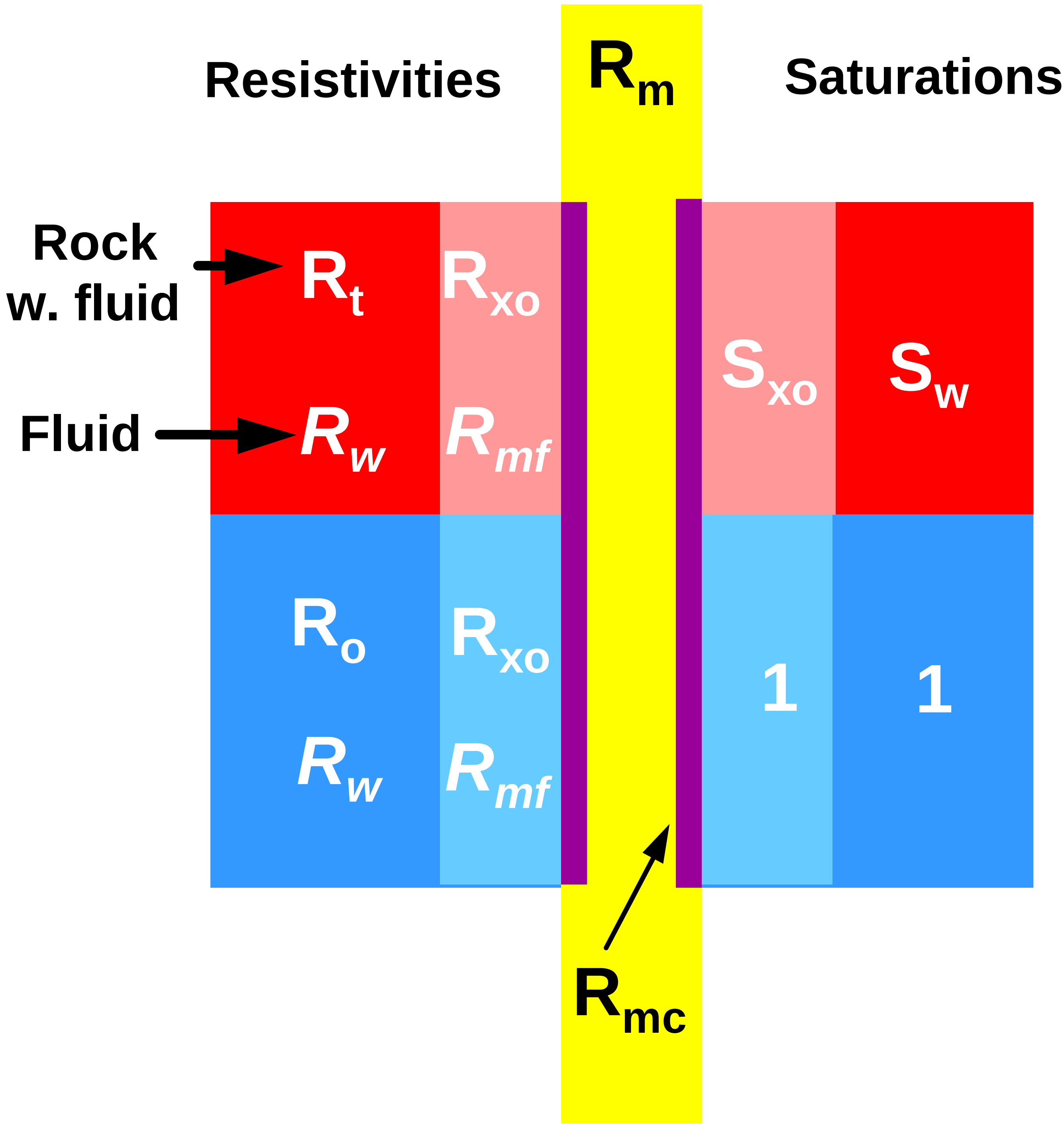
Identify the Fluid Contacts



Define fluid contacts



Symbols used in resistivity logging



Hydrocarbon saturation

Saturation S = fraction of pore volume

$$S_{hc} = 1 - S_w$$

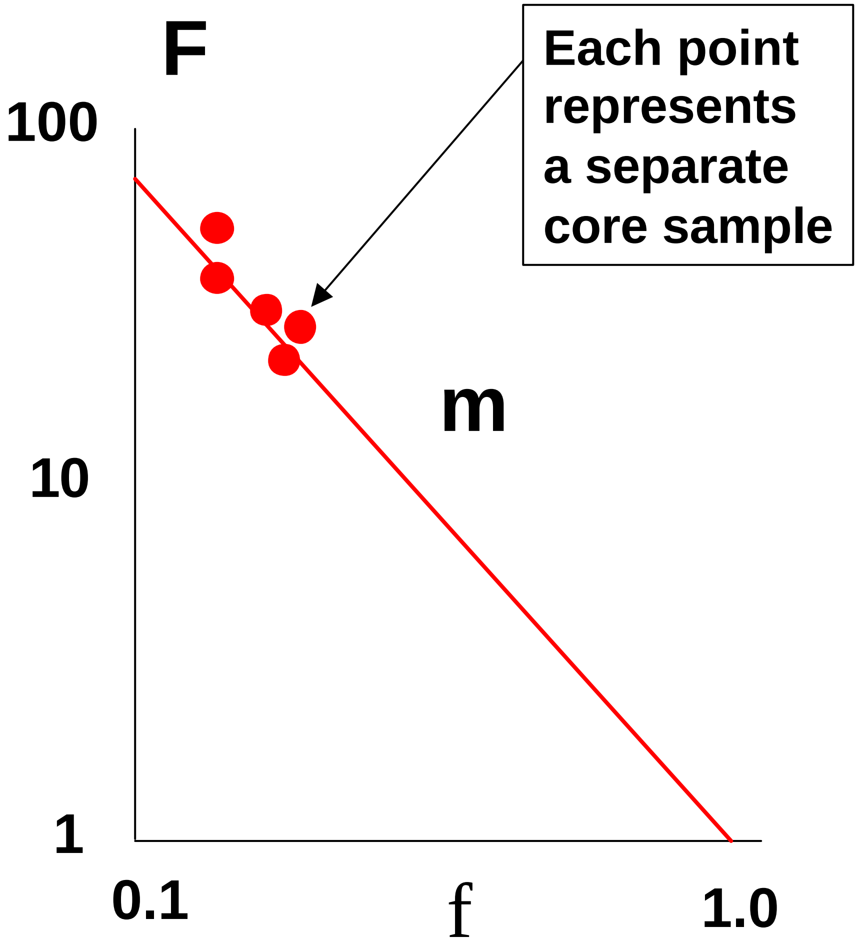
Resistivity of HC bearing rock depends on:

- **resistivity of the formation brine** R_w
- **porosity** ϕ
- **water saturation** S_w
- **lithology** m, n
- ***amount and type of shale*** Q_v

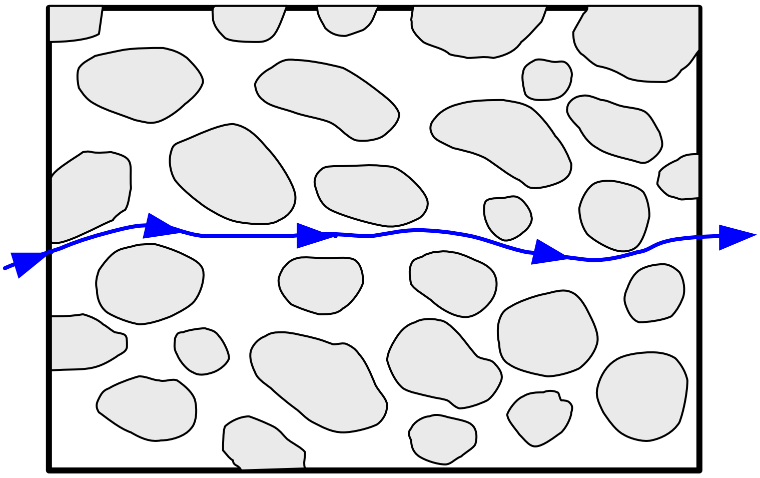
Archie I

$$F = R_o / R_w = \phi^{-m}$$

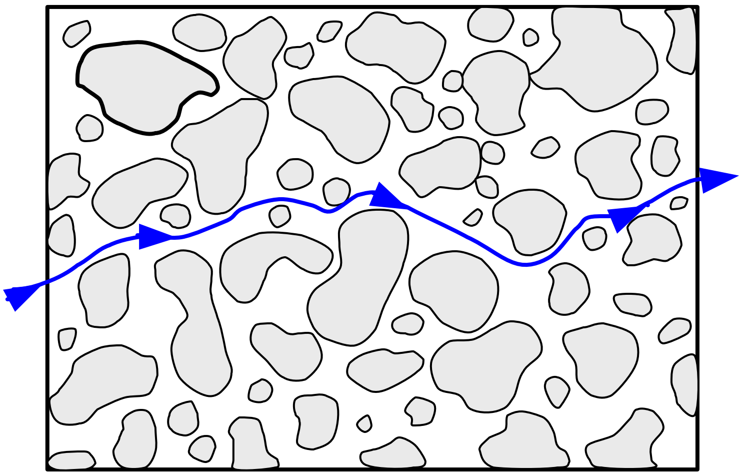
F	=	Formation resistivity factor (FRF)
R_o	=	Resistivity of 100 % brine saturated rock
R_w	=	Brine resistivity (Ωm)
ϕ	=	Porosity
m	=	Cementation factor



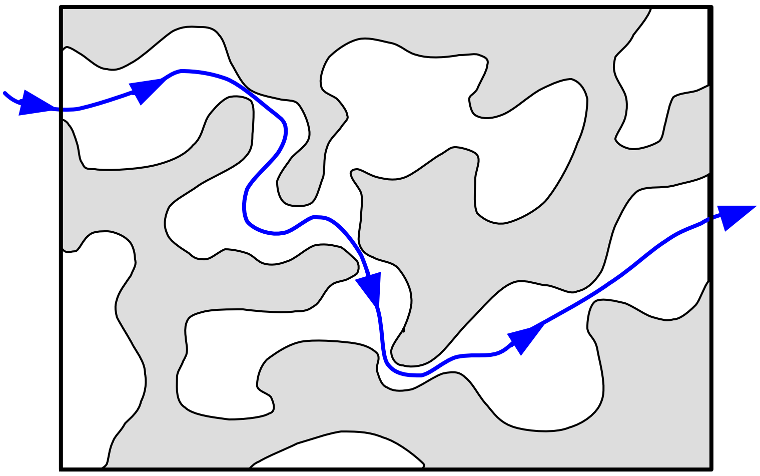
Porosity constant



F low
(@ 10)



F moderate
(@ 50)



F high
(@ 300)

m-values of common reservoir rocks

Lithology		m
Sandstones	unconsolidated	1.4
	loosely consolidated	1.6
	friable	1.7
	average	1.8
	very hard	2.0
Carbonates		2.0-2.2

Use of Archie I to determine R_w

Resistivity of formation brine R_w

Resistivity of porous rock filled with brine R_o

$$R_w = \phi^m * R_o$$

Example:

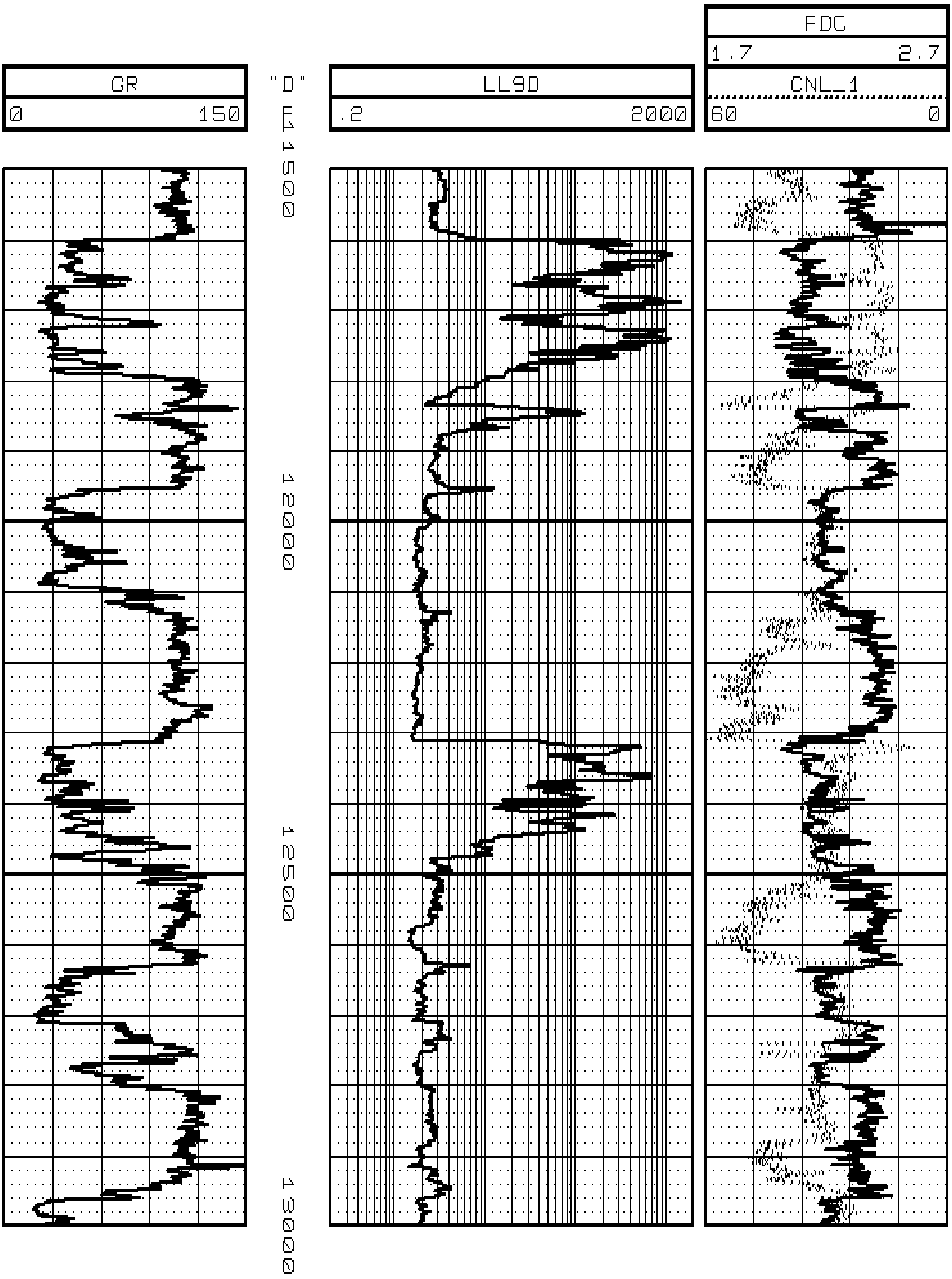
$R_o = 5$ Ohmm

$\phi = 0.25$

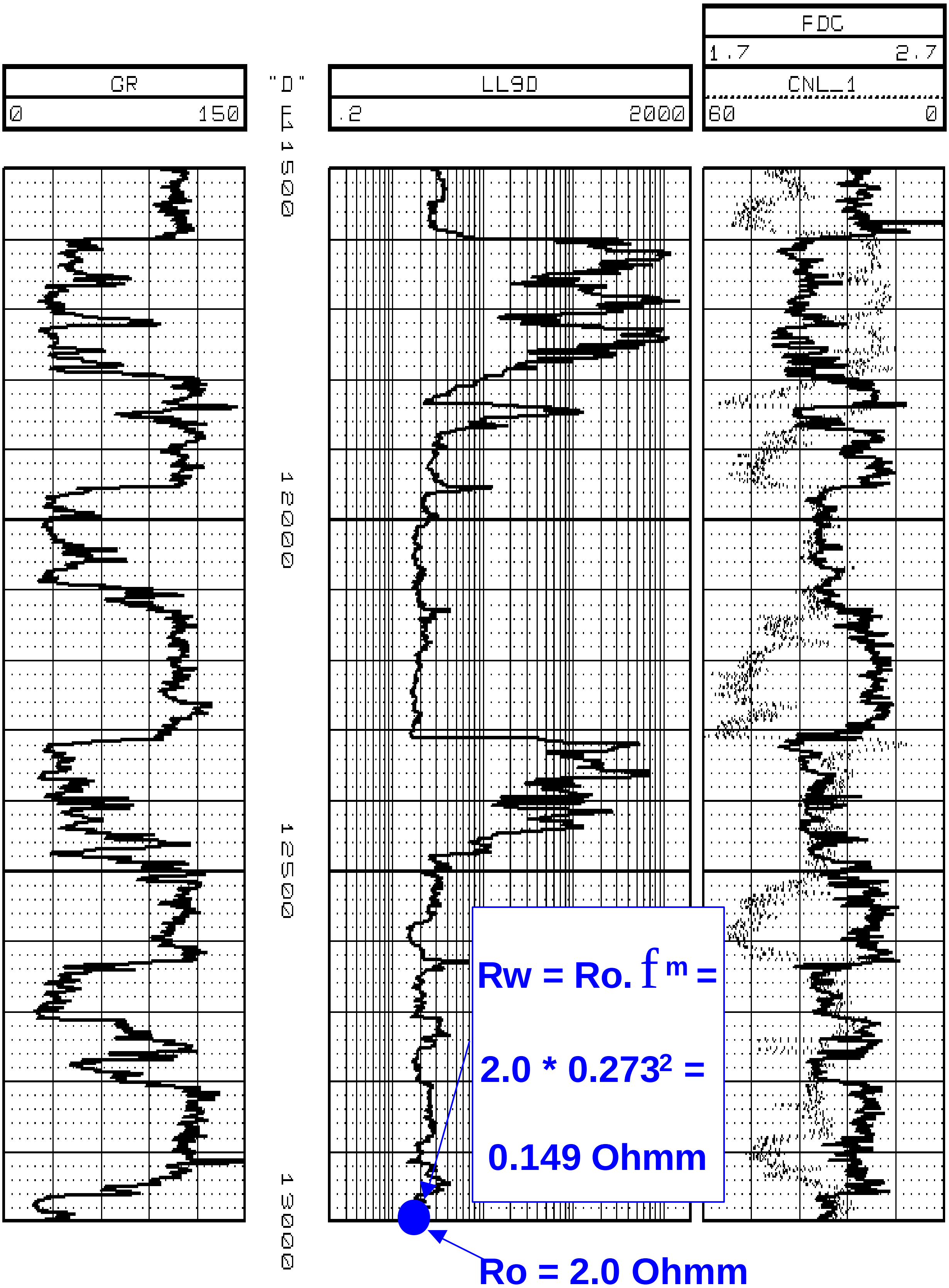
$m = 2$

$R_w = 0.25^2 * 2 = 0.0625 * 5 = 0.3125$ Ohmm

Calculate Rw @ 13000'



Calculate Rw at 13000 ft



Rw = Ro. f^{m} =

$2.0 * 0.273^2$ =

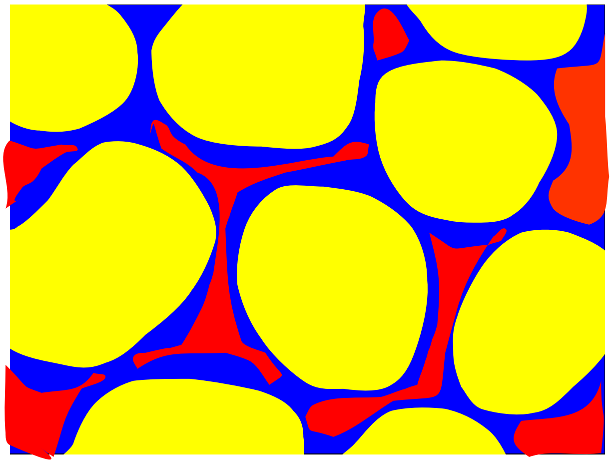
0.149 Ohmm

Ro = 2.0 Ohmm

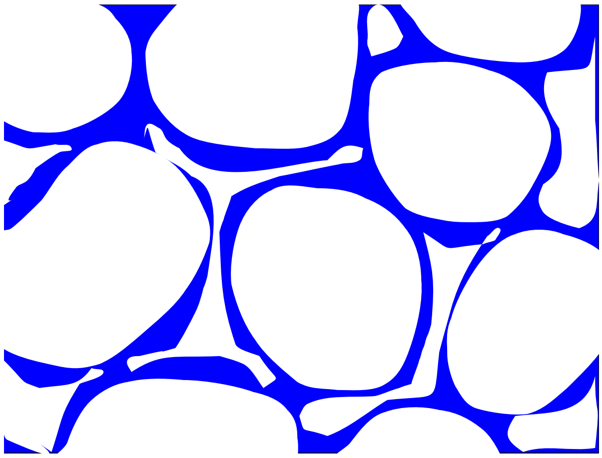
exercise

Oil bearing

Formation:



Conductor:

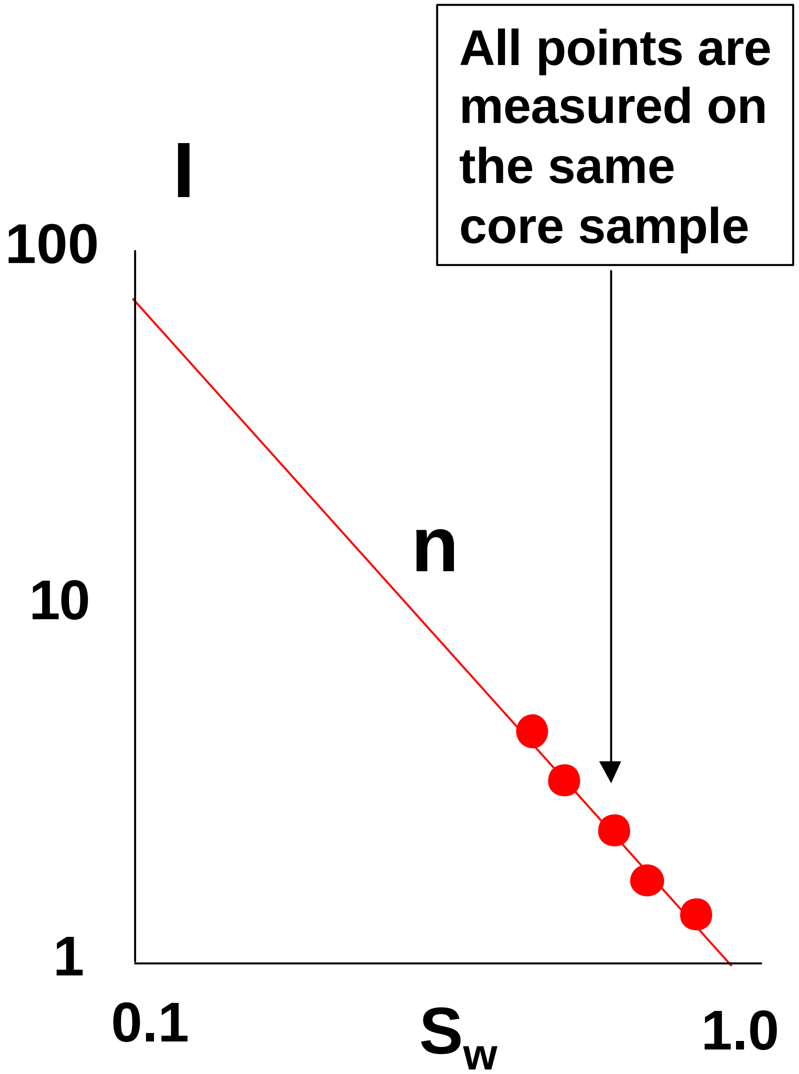


Resistivity: $R_t = R_w \, F^{-m} S_w^{-n}$

Archie II

$$I = R_t / R_o = S_w^{-n}$$

I	=	Resistivity index
R_t	=	Resistivity of partly brine saturated rock
R_o	=	Resistivity of fully brine saturated rock
S_w	=	Water saturation
n	=	Saturation exponent



Archie II: effect of saturation

Resistivity of porous rock fully filled with brine R_o

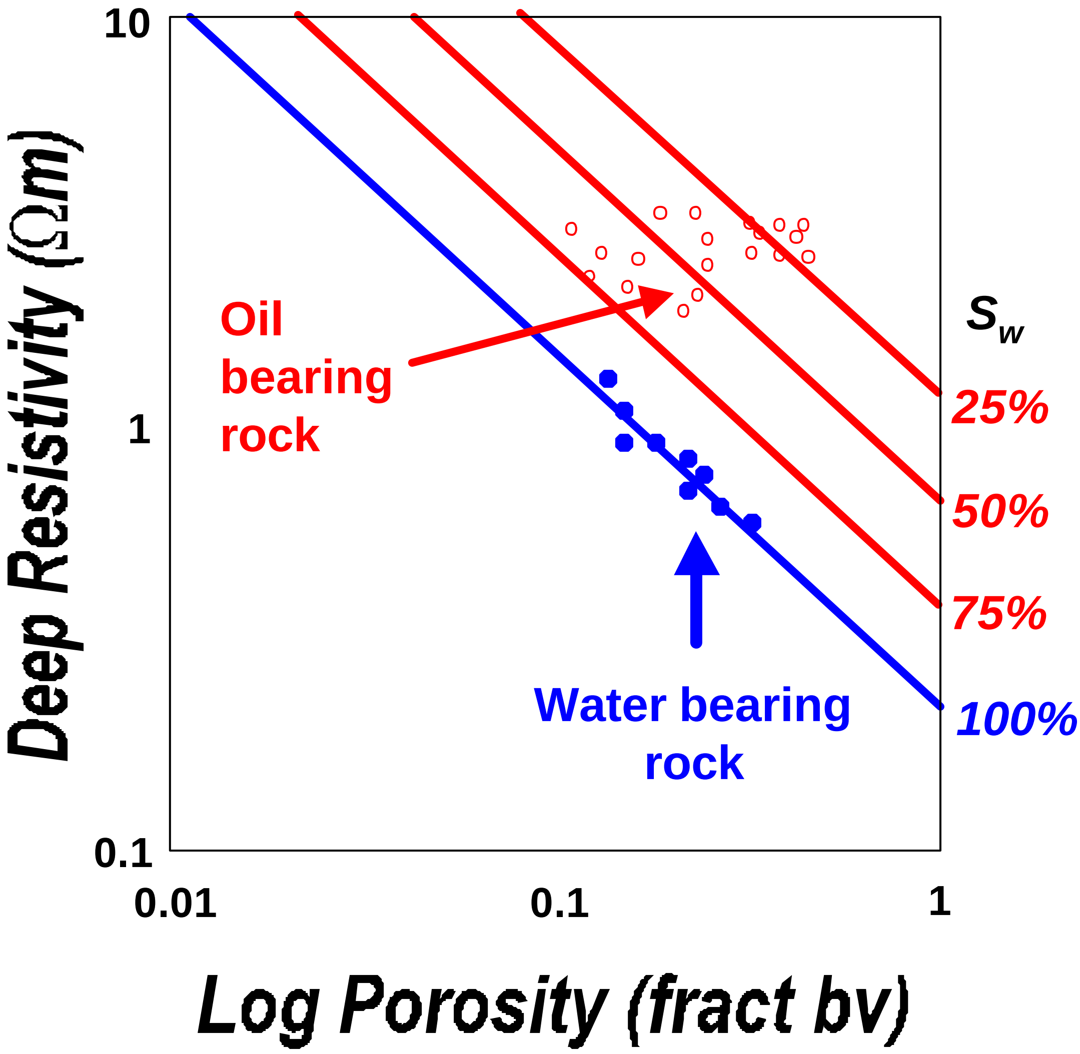
Resistivity of porous rock partly filled with brine R_t

$$\boxed{R_t = I * R_o}$$

I = Resistivity Index

S_w	$1/S_w$	$1/S_w^2$
0.1	10	100
0.5	2	4
0.9	1.1	1.2

Pickett Plot



Archie equations combined

Resistivity measured by logging tool

First Archie equation:

influence of porosity

Second Archie equation:

influence of water saturation

$$R_t = R_w \, \phi^{-m} \, S_w^{-n}$$

Archie Equations

Water Bearing

deep resistivity

sst. 1.8
carb. 2.0

$$R_w = R_o \phi^m$$

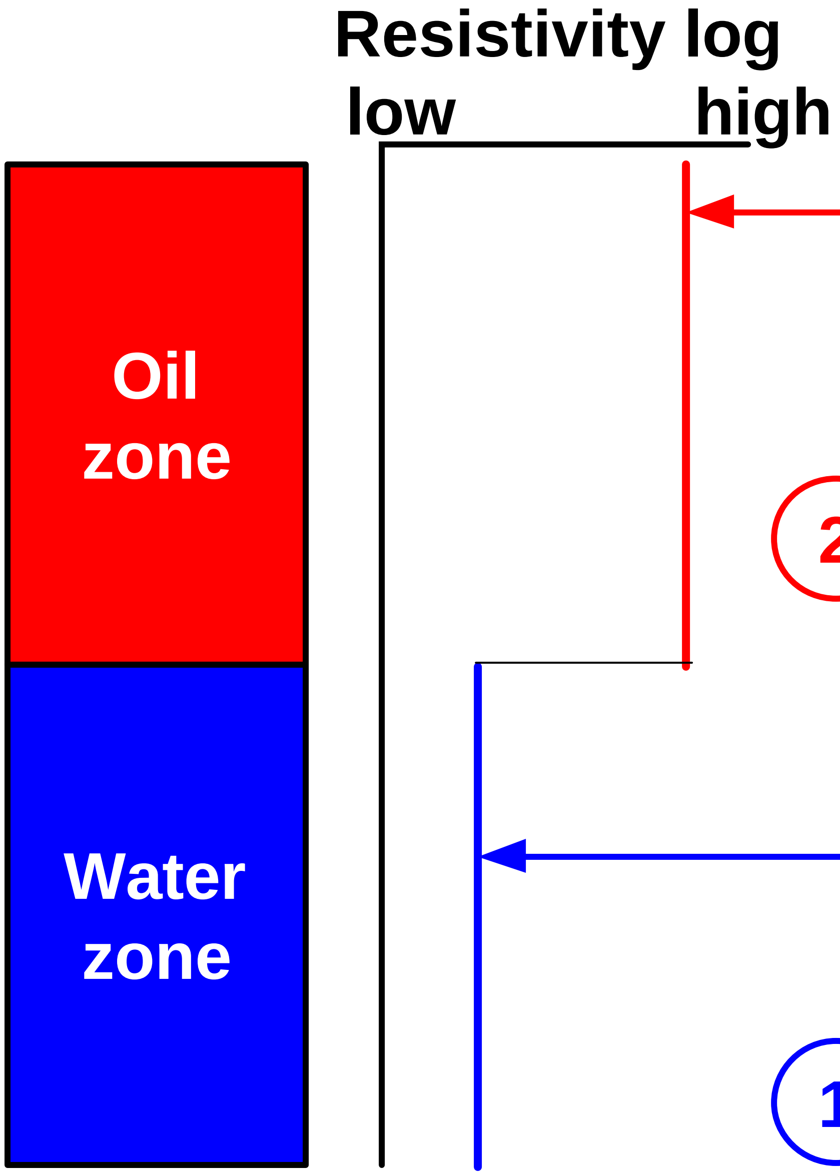
Hydrocarbon Bearing

$$S_w = \left\{ \frac{R_w}{R_t \phi^m} \right\}^{1/n}$$

assume = m

$$S_h = 1 - S_w$$

The Application of “Archie”



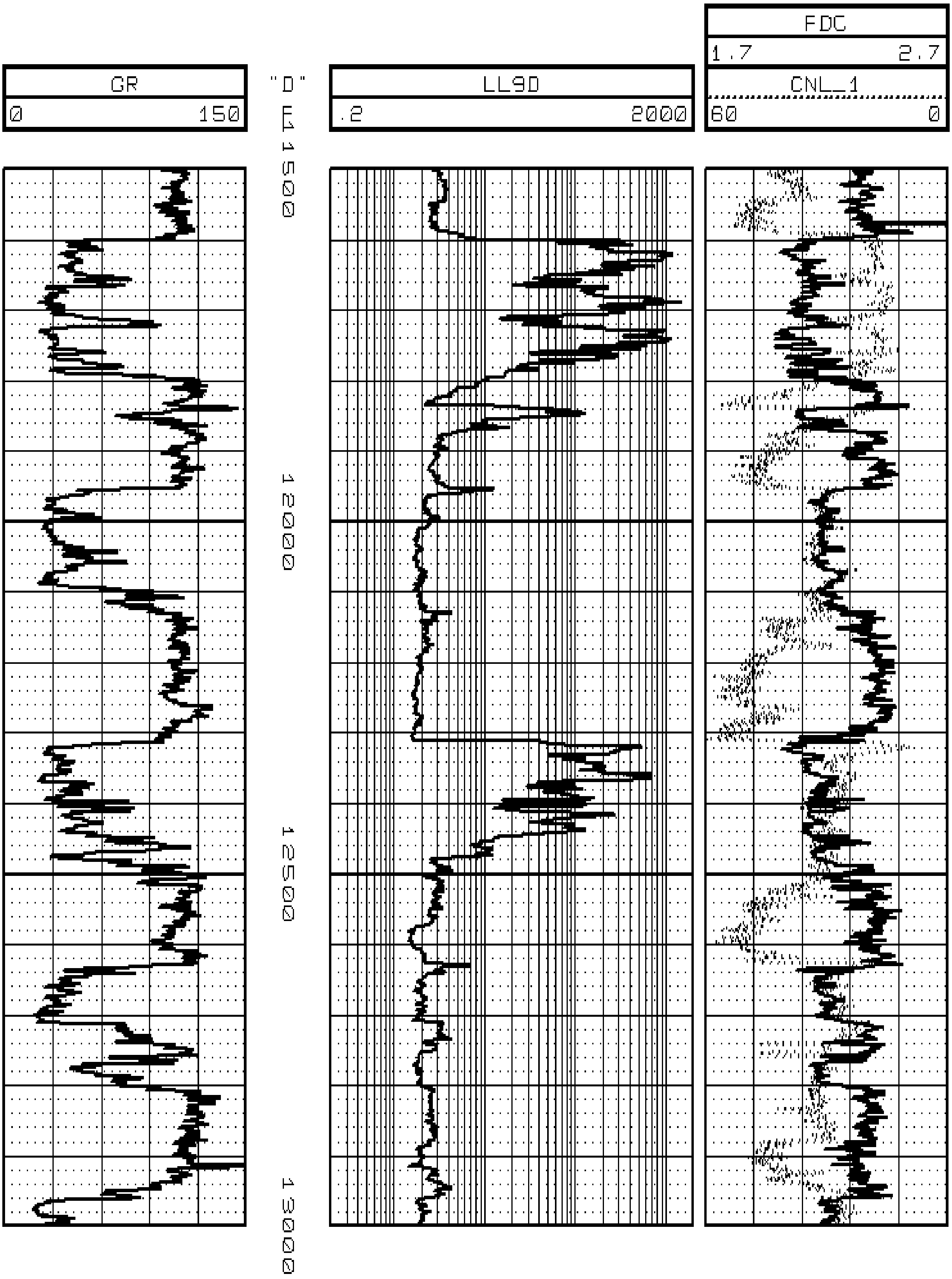
Resistivity depends on:
- Porosity
- Constants m & n
- *Water resistivity*

2 - Water saturation

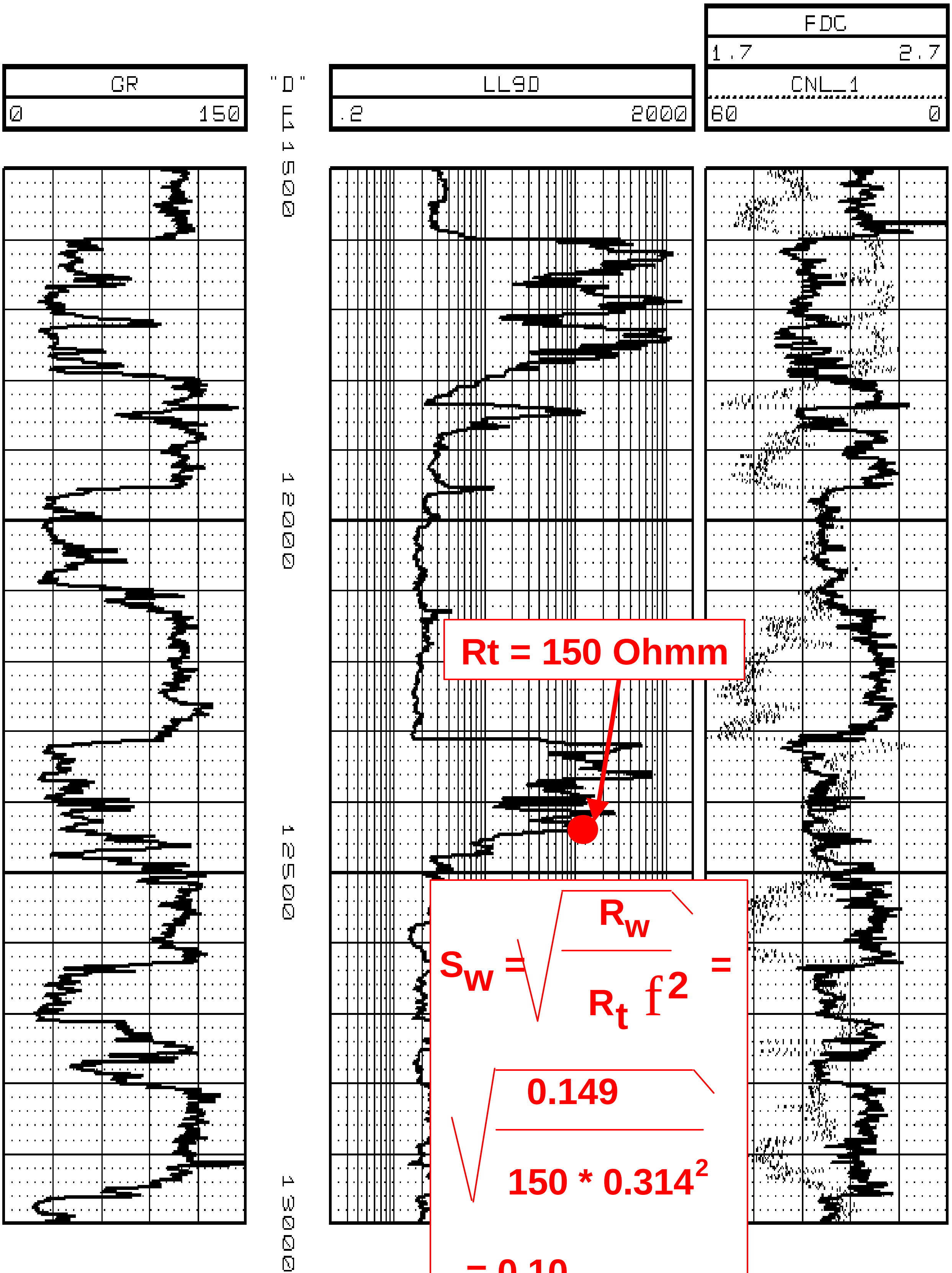
Resistivity depends on:
- Porosity
- Constant m (» 1.8 - 2.0)

1 - *Water resistivity*

Calculate Sw @ 12440’



Calculate S_w at 12440 ft



$$S_w = \sqrt{\frac{R_w}{R_t \, f^2}} =$$

$$\sqrt{\frac{0.149}{150 * 0.314^2}}$$

$$= 0.10$$

exercise

Example Archie calculation

Resistivity in water bearing sand:

R_o = 2.0 W m

Porosity of that sand: 27 %

Calculated **water resistivity:**

$R_w = R_o * f^m = 2.0*0.27^2 = 0.15$ Wm

Resistivity in oil-bearing sand:

R_t = 150 Wm

Porosity of that sand: 31 %

Calculated **water saturation:**

$S_w = (0.15 / [150*0.31^2])^{1/2} = 0.10$

exercise

Petrophysical evaluation

- **Discriminate reservoir** *(sand, carbonate)* **from non-reservoir: Gamma-ray (GR)** ***and/or Density/Neutron***

- **Discriminate between water-bearing and hydrocarbon-bearing reservoir intervals: Resistivity** *(also look for* anti - correlation*)*

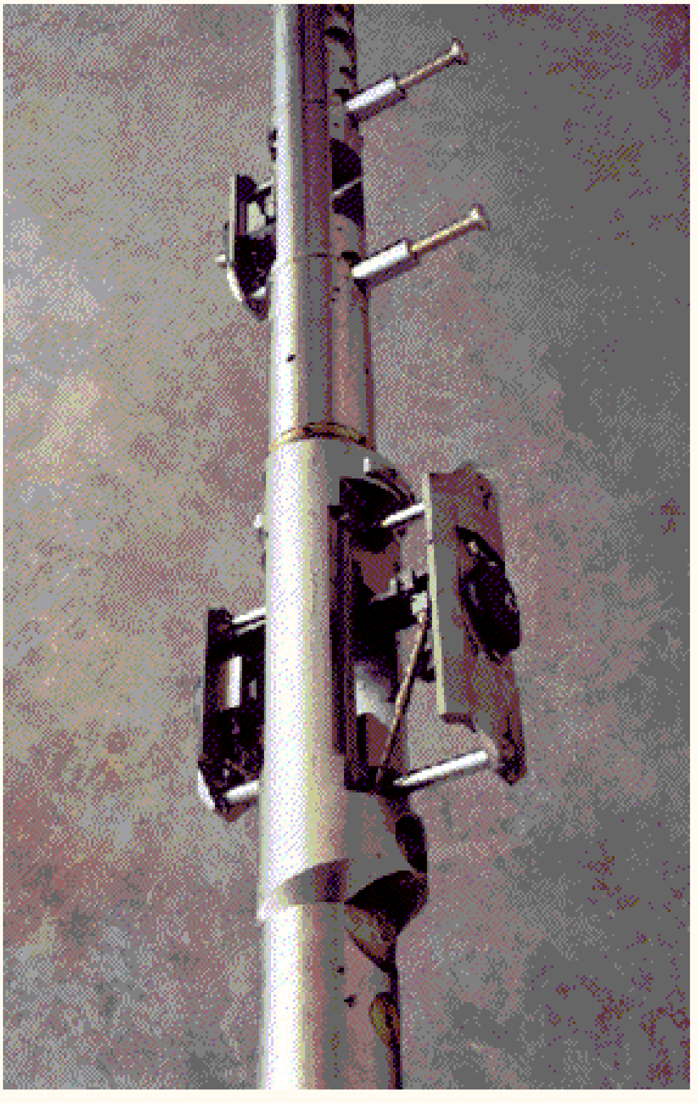
- **Discriminate between gas-bearing and oil-bearing reservoir intervals: Density/Neutron separation** *(+ Sonic*)

- **Evaluate reservoir porosity: Density** ***(and Neutron),*** **or Sonic Correct for gas-effect in gas-bearing intervals**

- **Calculate R_w from Resistivity, using Archie 1 or Pickett plot, in water-bearing interval**

- **Evaluate reservoir water saturation S_w from Resistivity, using Archie 2**

Wireline Formation Testers



Wireline Formation Testers have a diverse range of applications. The most common are to

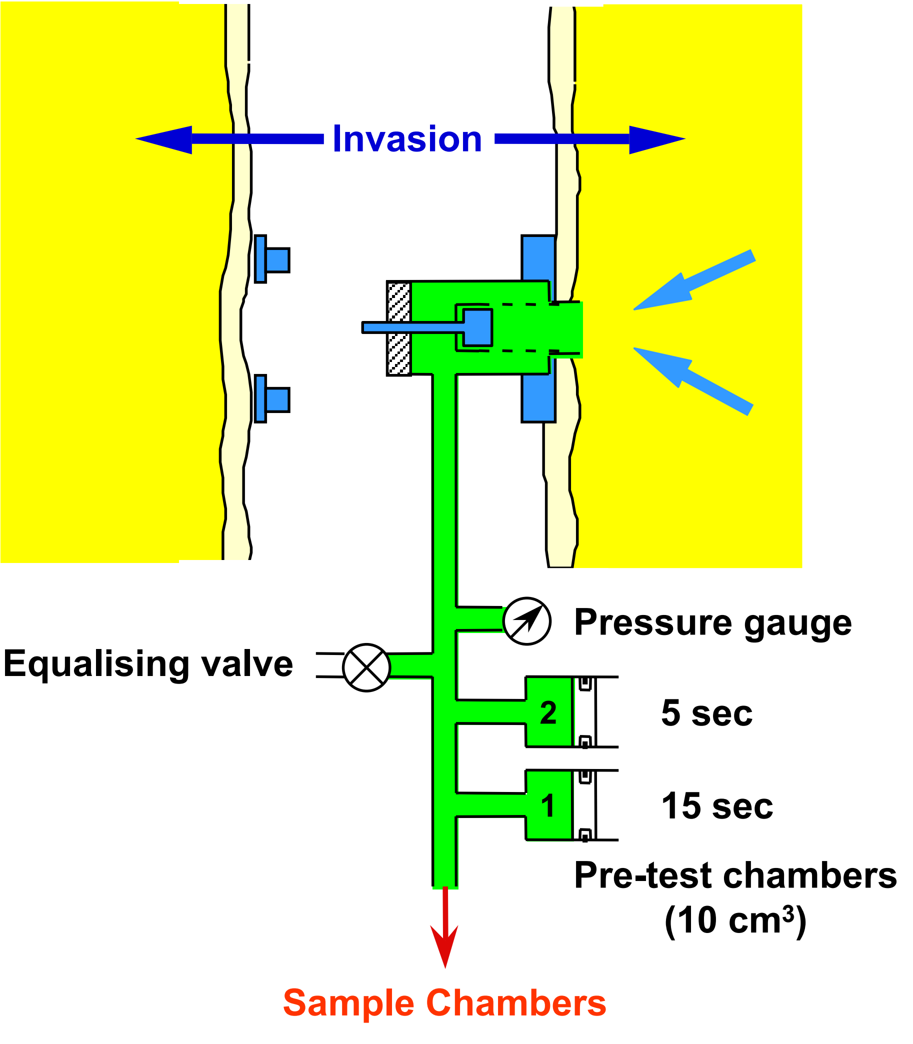
1. take pressure measurements for determining the
   - formation fluid density and
   - fluid contact levels.
2. take formation fluid samples for analysis.

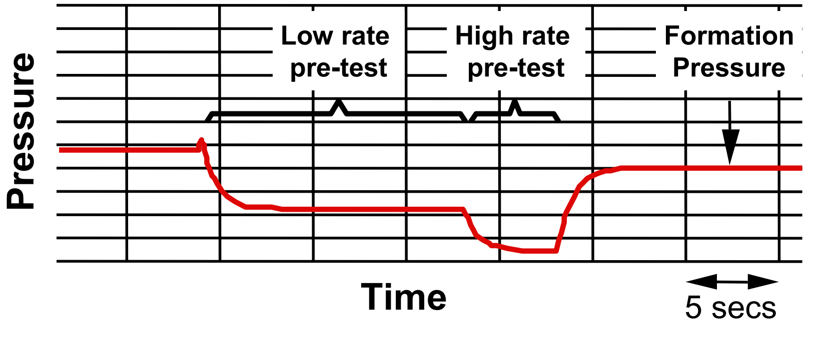
courtesy of Schlumberger

MDT = Modular Formation Tester, Schlumberger
RCI = Reservoir Characterisation Instrument, Baker Atlas
RDT = Reservoir Description Tool, Halliburton

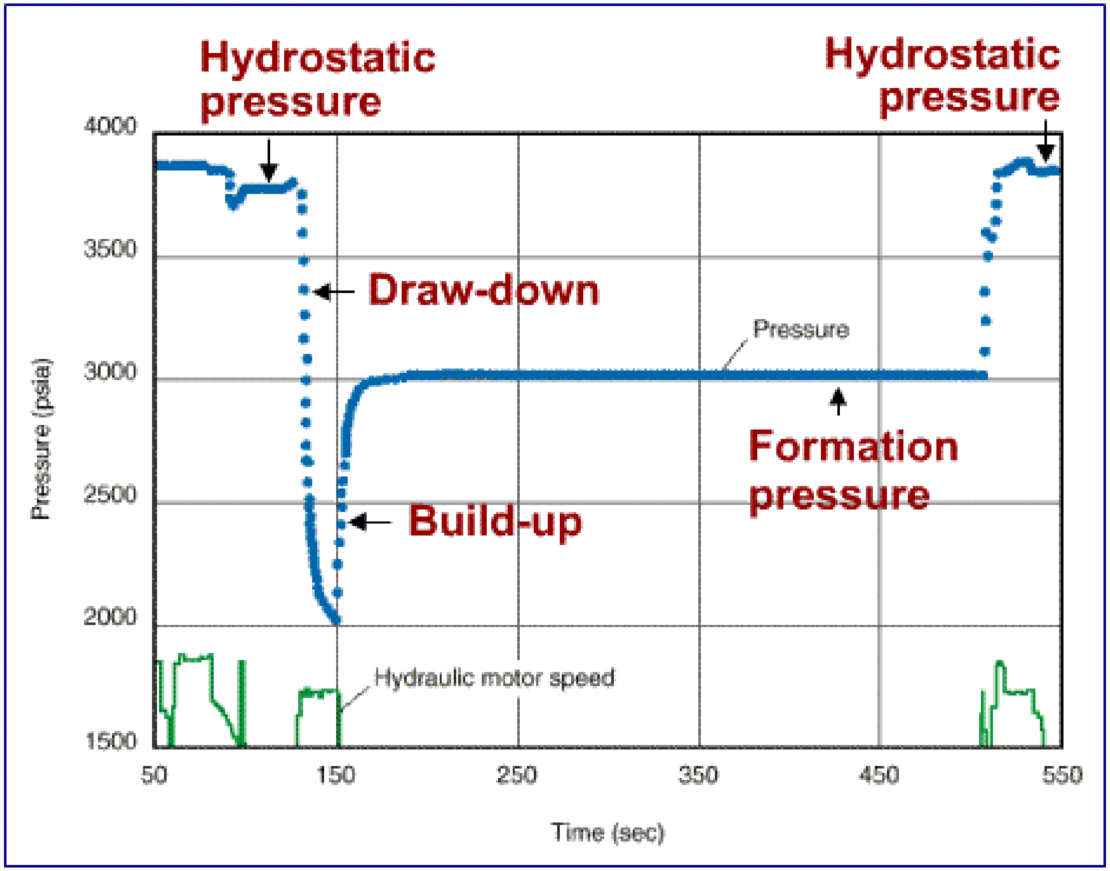
features: pump-out module, fluid analysis, multiple probes...

Wireline Pressure Measurements





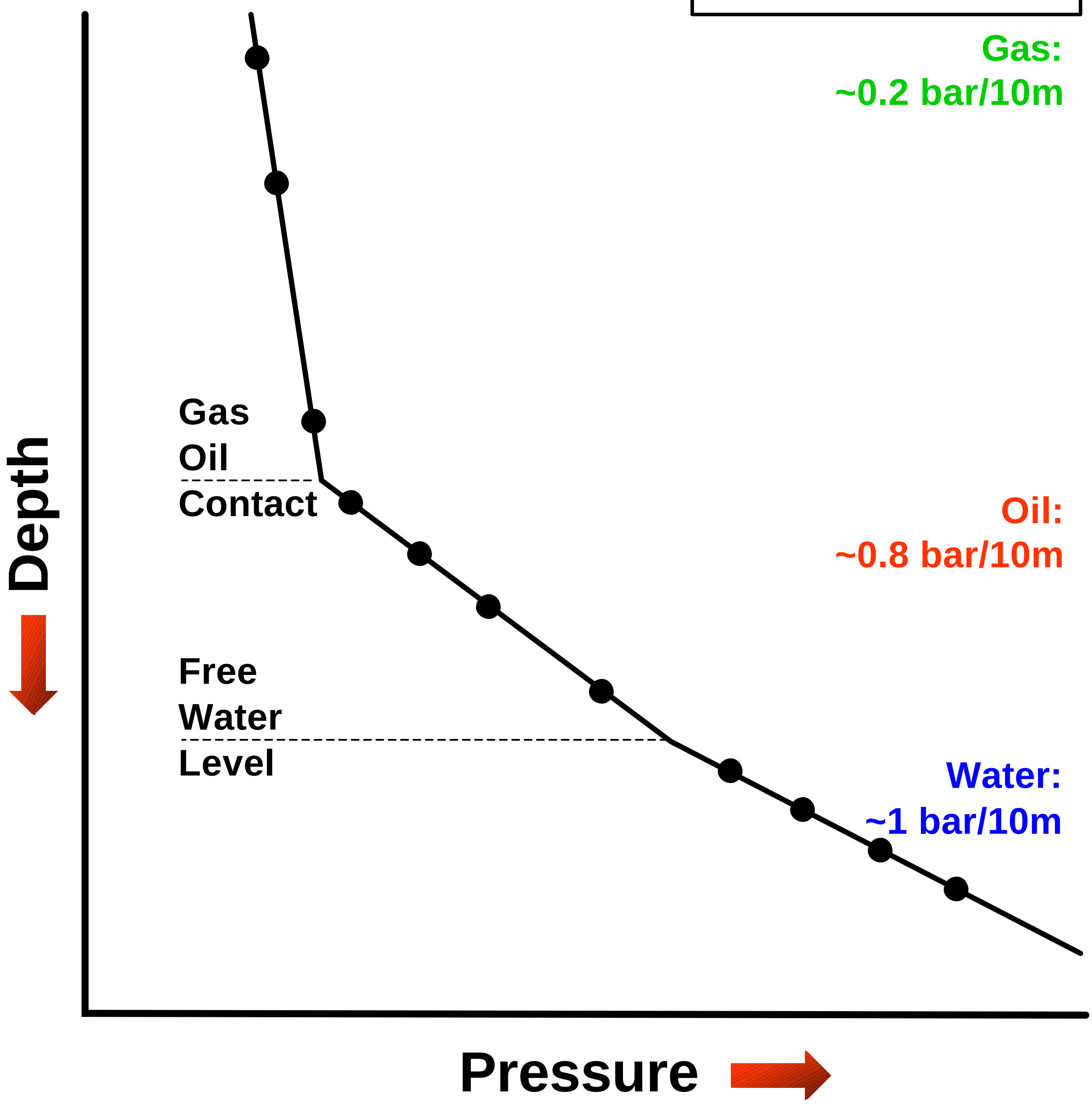
Wireline Pressure Measurement



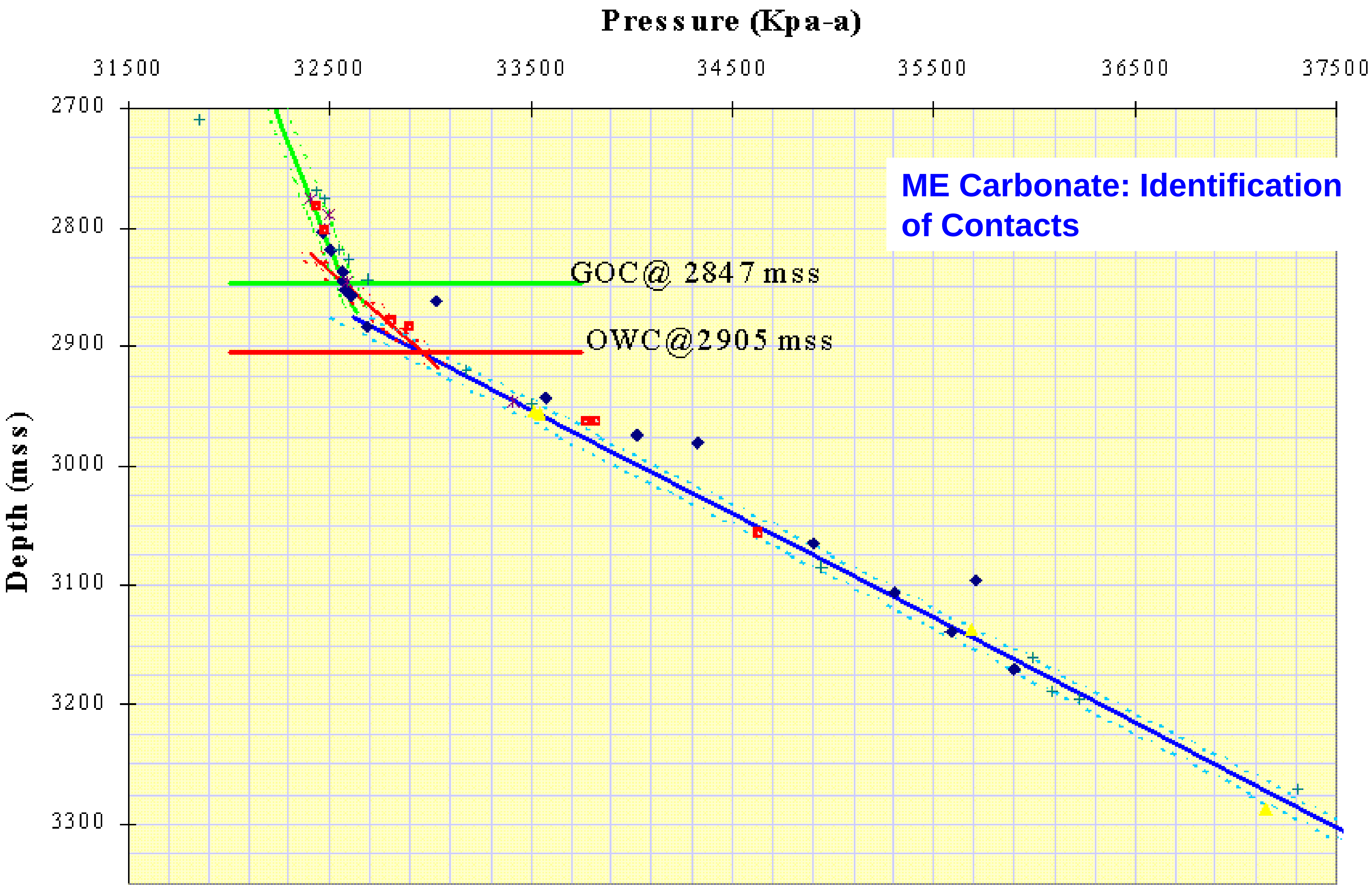
The tool is positioned at the desired depth and the formation pressure is obtained by withdrawing a small amount of fluid from the formation to generate a short transient test. The pressure response is recorded throughout the transient test to determine the formation pressure, which is the stable pressure reached after the shut-in.

Fluid Distribution from a Pressure vs. Depth plot

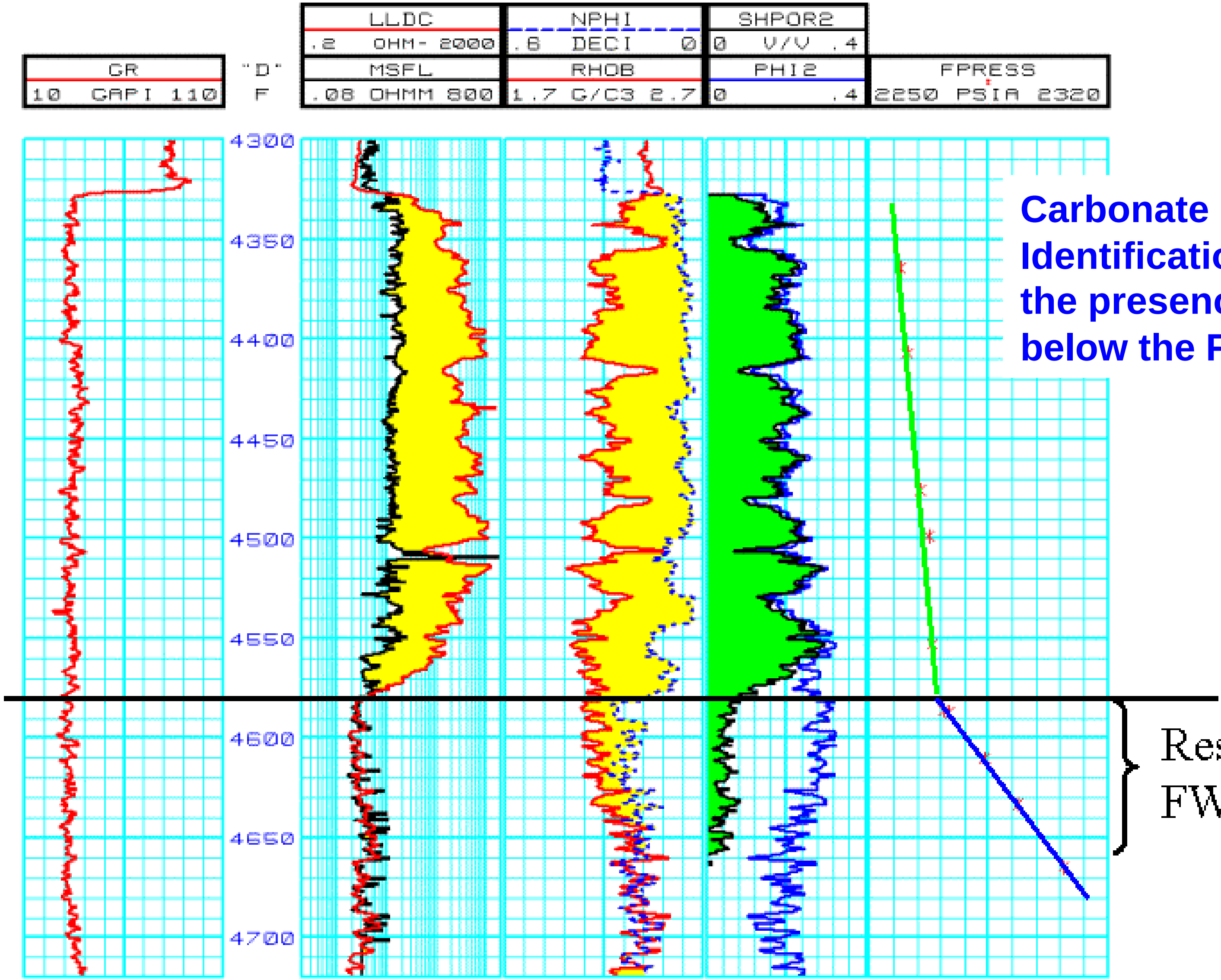
< 0.13 psi/ft: gas
0.13 - 0.30 condensate
0.30 - 0.43 oil
0.43 - 0.52 water



Formation Pressures - Example



Formation Pressures - Example



Carbonate Reservoir: Identification of Contact; note the presence of residual gas below the FWL

Residual gas below FWL