Basics of
Geophysical Well Logs:
Fundamentals

Electrical conductivity in subsurface rocks

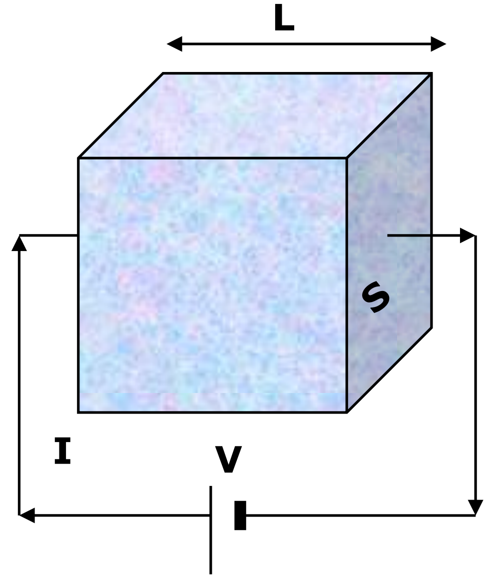
Electrical current flows through underground rocks mostly for the presence, within the pores, of the formation water and its content in dissolved ions (electrolytic conduction).

More rarely, electrical conductivity of underground rocks is due to the presence of conductive metals such as pyrite or iron bearing cementing material such as for the presence of siderite (movements of electrons).

In presence of clay minerals within the rock, the ionic conductivity is due to the movements of ions on top of the clay surface (surface conductivity) that can strongly influence the bulk conductivity of the formation.

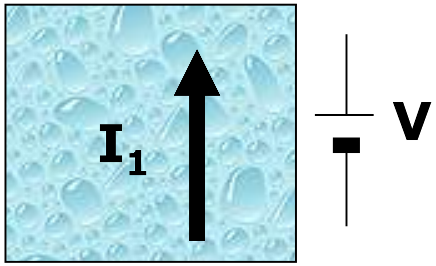
In the well logging process, the measured formation property is Resistivity (the inverse of Conductivity).

Formation Resistivity is expressed in ohm m, while Formation Conductivity is expressed in S/m.



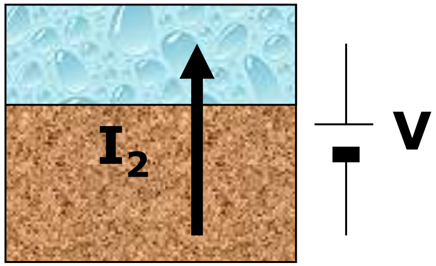
$$r = R\,(L/S)$$
$$V = r\,I$$
$$R = K\,(V/I)$$

Relationships between electrical resistance and resistivity



PHI = 100%

Rw = V/I_1

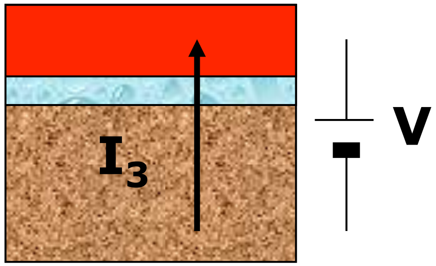


PHI = 30%

Sw = 100%

Ro = V/I_2

Ro > Rw



PHI = 30%

Sw = 20%

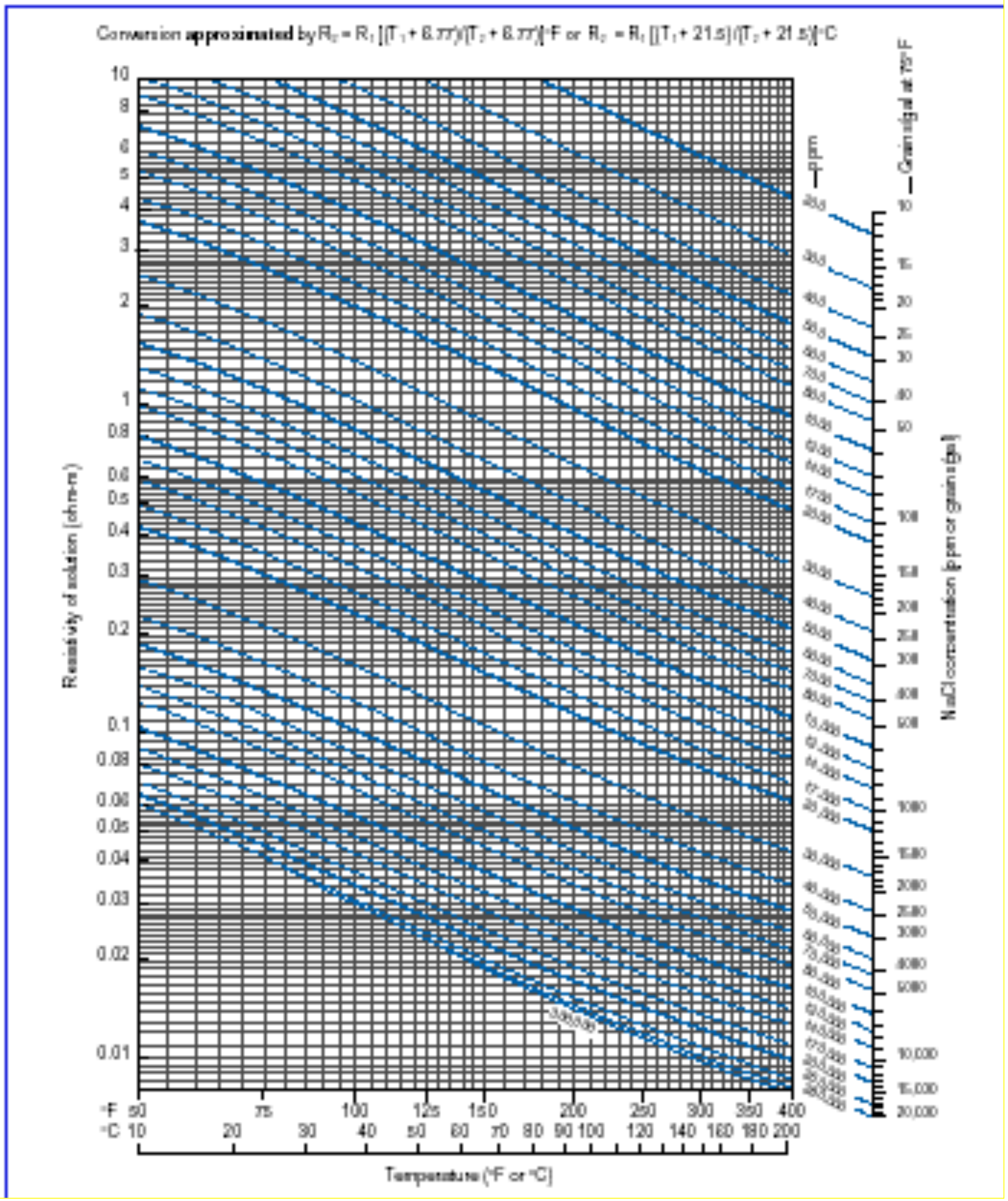
Rt = V/I_3

Rt >> Ro

Example

Basics of Geophysical Well Logs_Fundamentals

Resistivity of NaCl Solutions



Example of Water Analysis report

General information

Water sample from well:	Good well 1, sampled by D.S.T. # 1
Interval:	m. 948,5 -952,5
Point of sampling:	Sampler
Date of sampling:	day_month_year

General Characters

Colour:	limpid	Resistivity @ 20 °C:	0,08 ohmm
Smell:	hydrocarbons	Salinity NaCl:	102230 mg/l
Fluorescence:	bluish	Residue a 110 °C:	105850 mg/l
Sp. weight @ 15° C:	1,0697	Residue a 180 °C:	103360 mg/l
pH @ 20° C:	6,94	Residue a 600 °C:	94855 mg/l
Eh @ 20° C:	n.d.		

Analysis

Cations	mg/l	***Anions***	mg/l
Na	31089,0	Cl	62017,0
K	123,0	SO4	47,0
Li	n.d.	CO3	absent
Ca	3273,0	HCO3	n.d.
Mg	2319,0	OH	absent
Ba	101,0	NO3	absent
Sr	239,0	F	absent
Fe	0,9	Br	315,0
Mn	n.d.	Al	n.d.
NH_4	100,0	H3BO3	51,0
SiO_2	10,9		

Exercise:
using the Schlumberger *chart* Gen-9, evaluate the resistivity of the formation water at the Formation temperature of 50 °C.

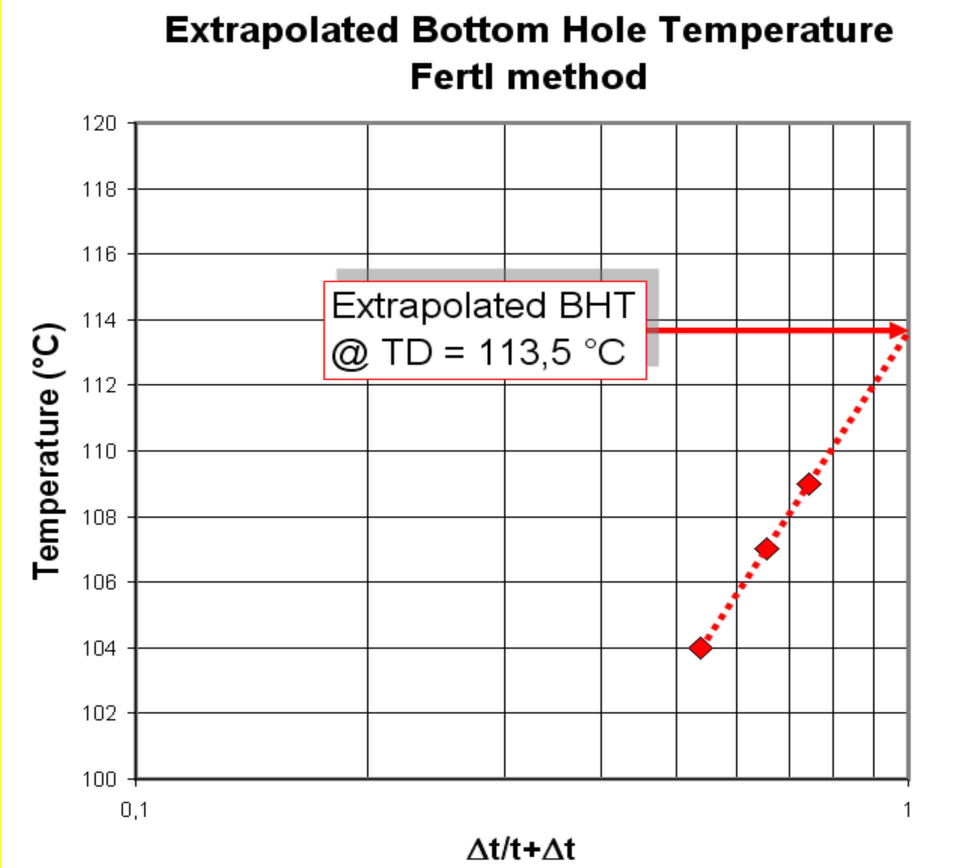
BHT (Bottom Hole temperature) extrapolated

t	Δ t	Δt/(t + Δt)	T (°C)
6	7,0	0,538	104
6	11,5	0,657	107
6	19,5	0,765	109

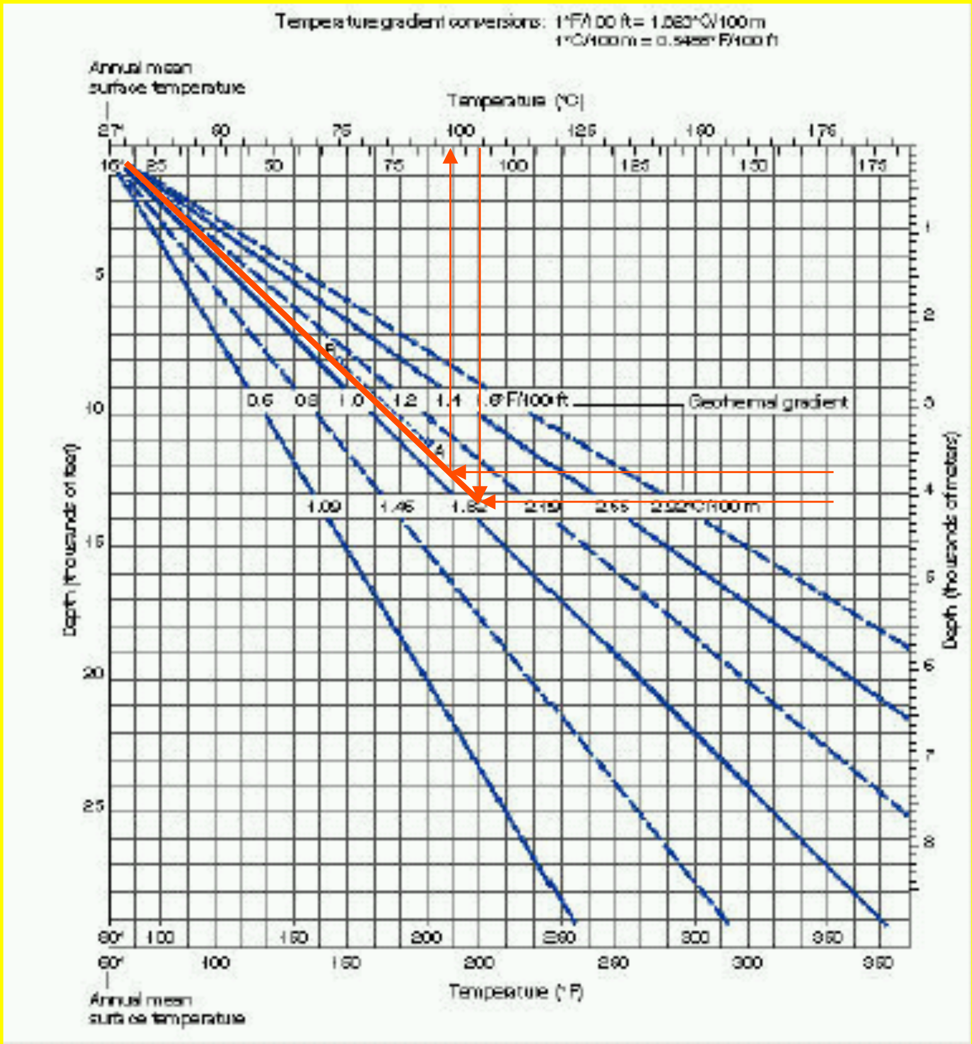
t = circulation time
time circulation stopped @ h 20,00 11.03.98
Δt = time Logging tool @ TD - time circulation stopped

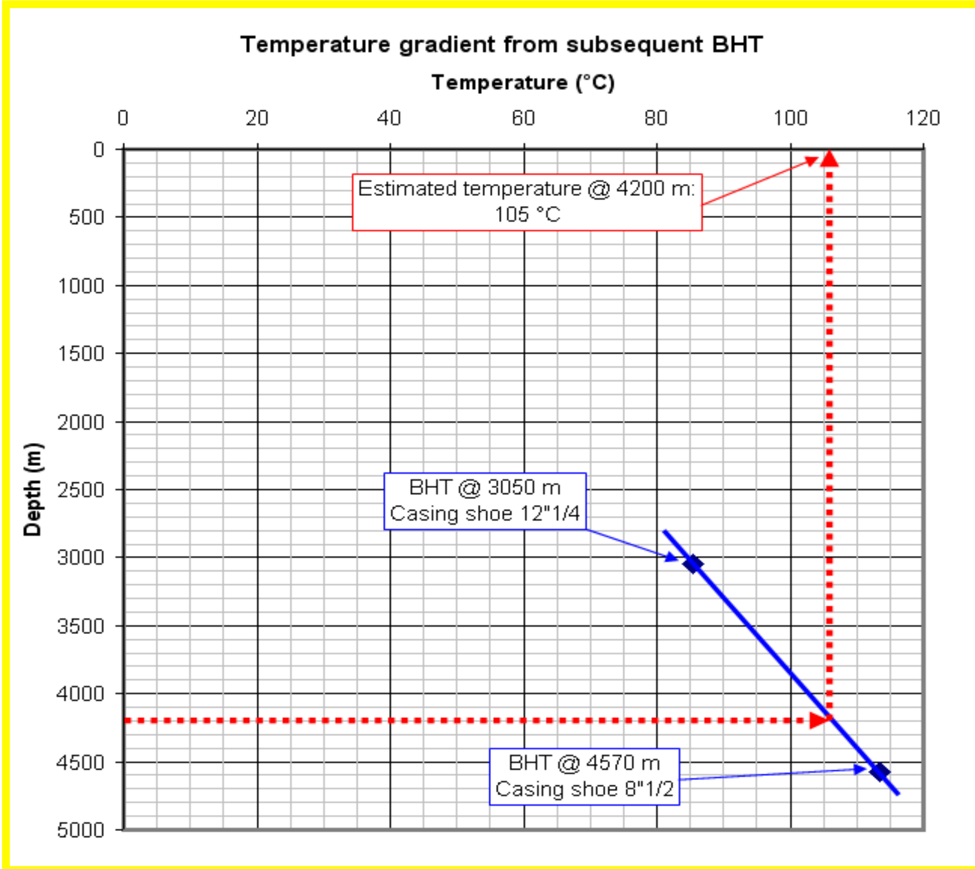
Run 1 - Logging tool @ TD; h 03,00 12/03/98
Run 2 - Logging tool @ TD: h 07,30 12/03/98
Run 3 - Logging tool @ TD: h 15,30 12/03/98

Run 1 - Max. Recorded Temperature: 104 °C
Run 2 - Max. Recorded Temperature: 107 °C
Run 3 - Max. Recorded Temperature: 109 °C

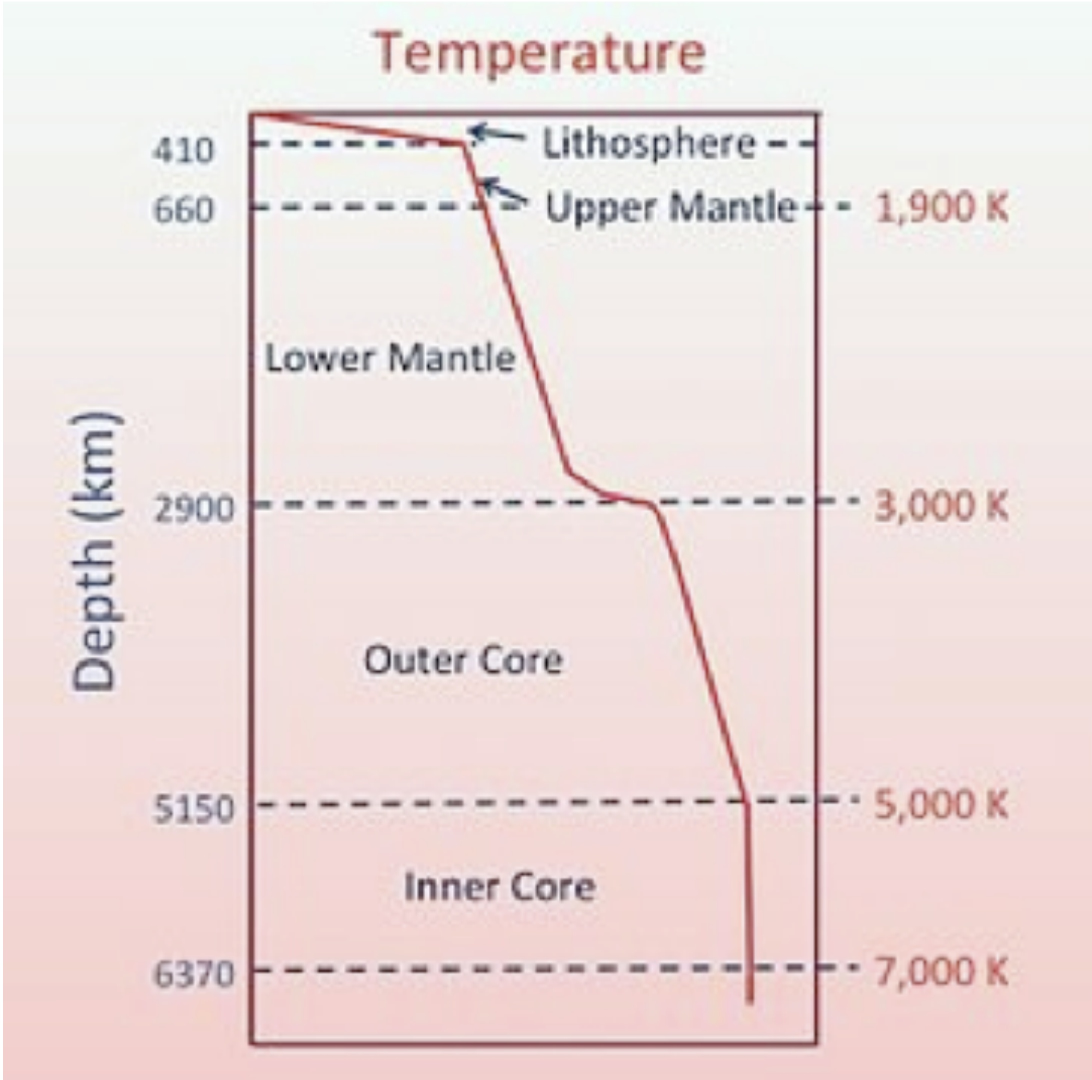


Estimation of formation temperature at any given depth





Geothermal gradient



1627 ◦C

6727 ◦C

Archie relationships in clean formations

In reservoir rocks completely saturated by water (Sw=100%)

Ro = (F* Rw) i.e. **Ro/Rw = F**

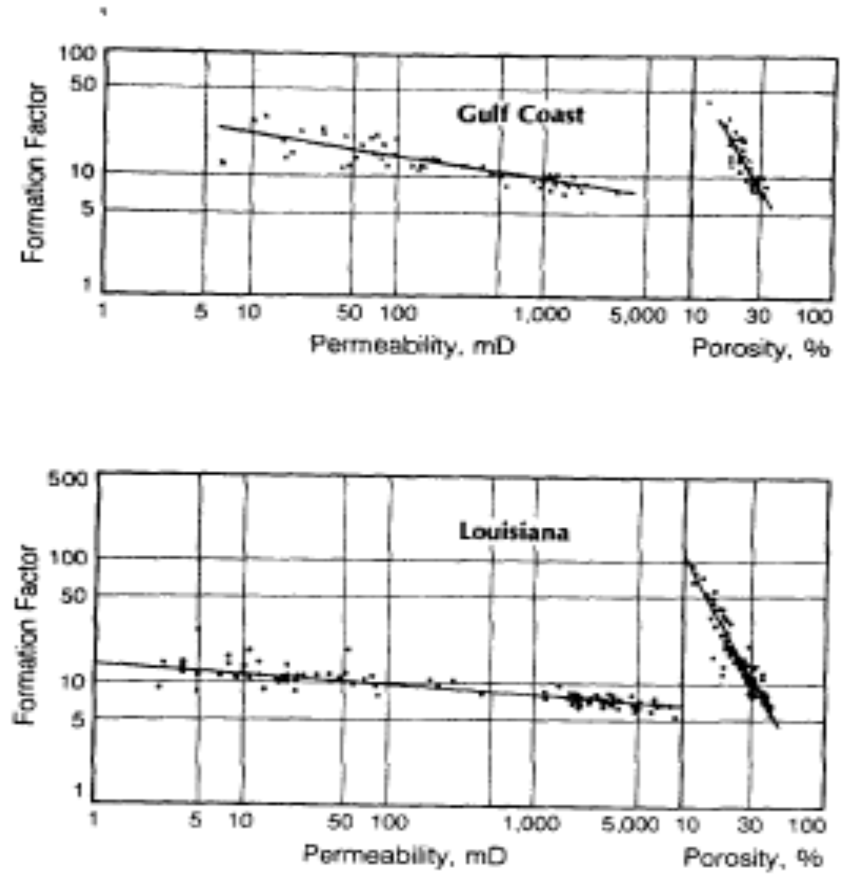
where $\mathbf{F = (a / \Phi_t^m)}$,

Nomenclature

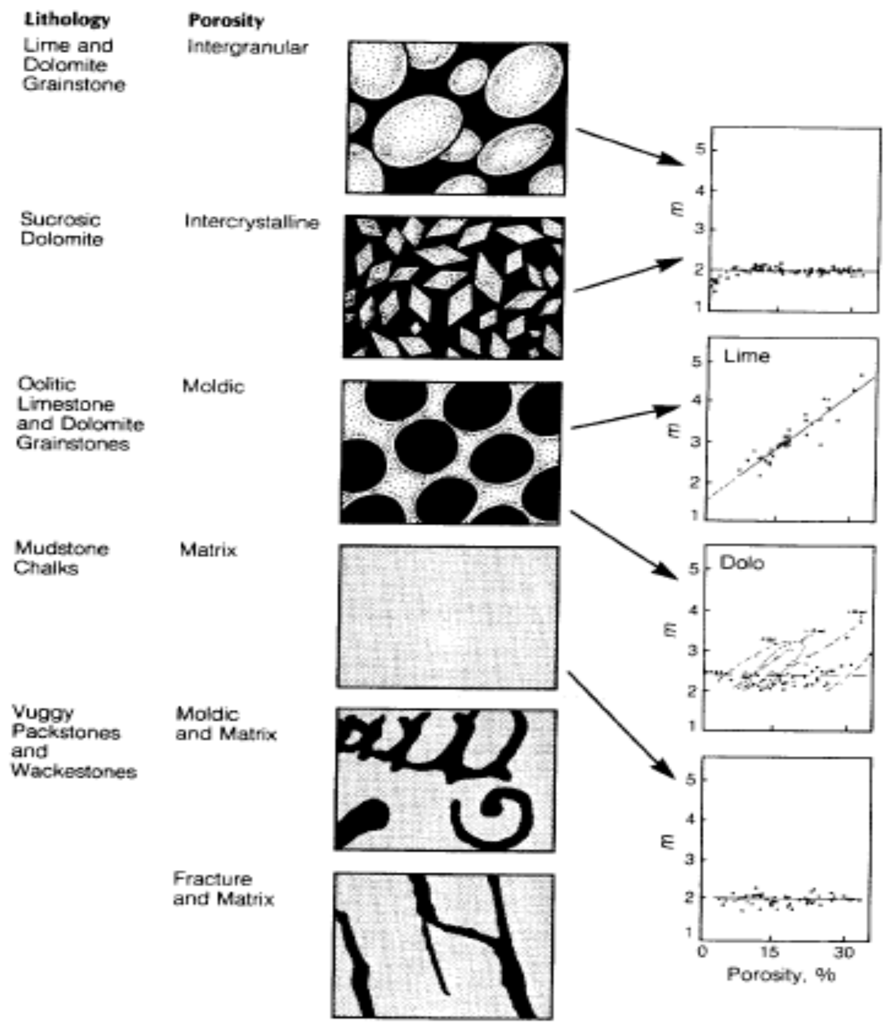
Ro	= Resistivity of the rock water saturated;
Rw	= Resistivity of formation water;
F	= Formation Resistivity Factor;
Φ_t	= total porosity;
a	= lithology coefficient;
m	= cementation exponent;

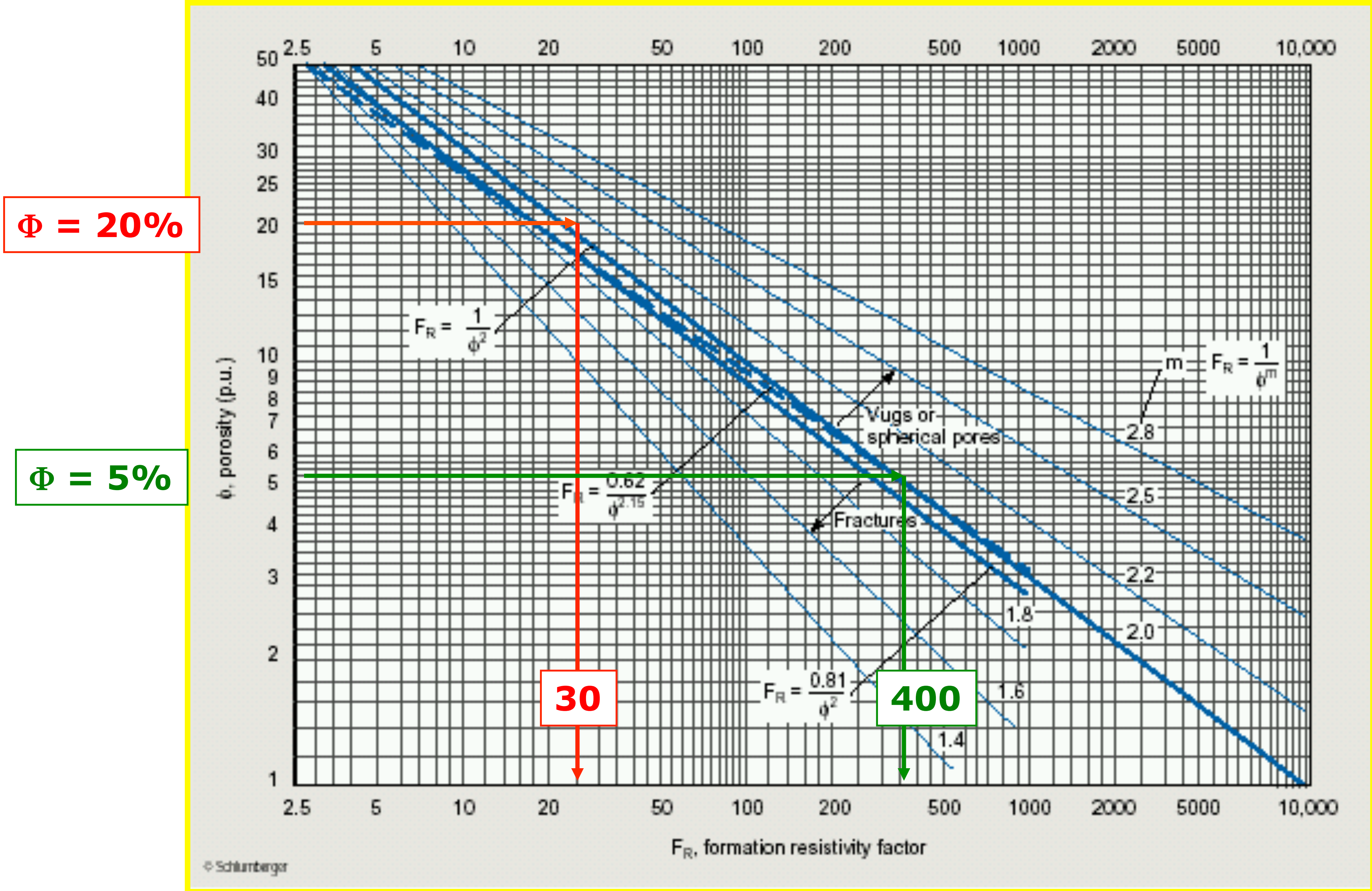
Formation Resistivity Factor:

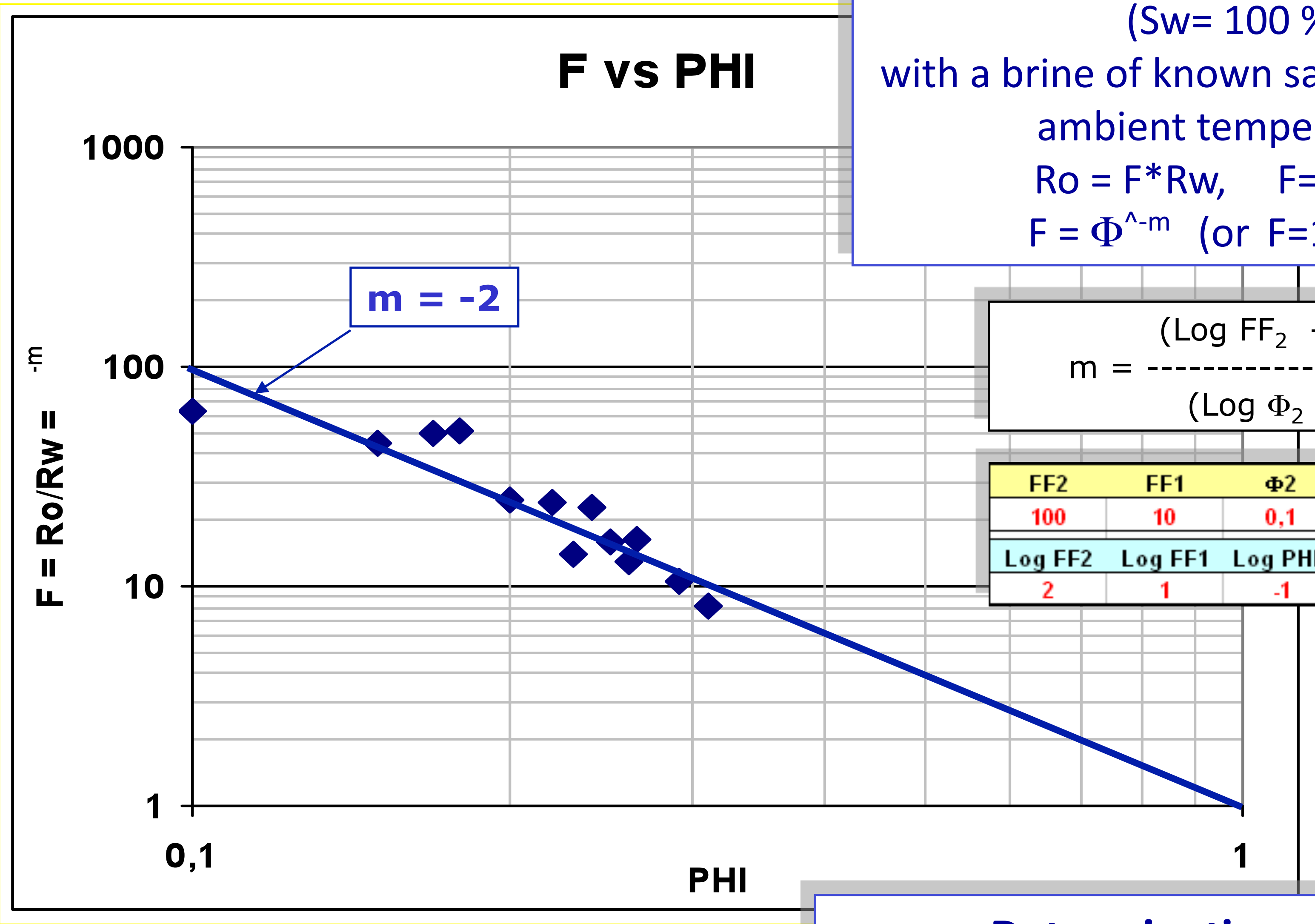
relationships between porosity and resistivity



Archie's plots of electrical formation factor, F, versus permeability, K, and porosity, ϕ, for Gulf Coast and Louisiana sandstones. The linear porosity trends prompted him to suggest $F = \frac{1}{\phi^m}$ as a general relationship. Porosity exponent m is a constant. (From reference 7.)




Φ = 20%
Φ = 5%
30
400
φ, porosity (p.u.)
F_R, formation resistivity factor
$F_R = \frac{1}{\phi^2}$
$F_R = \frac{0.62}{\phi^{2.15}}$
$F_R = \frac{0.81}{\phi^2}$
m
$F_R = \frac{1}{\phi^m}$
Vugs or spherical pores
Fractures
2.8
2.5
2.2
2.0
1.8
1.6
1.4
© Schlumberger



The sample is saturated by water (Sw= 100 %) with a brine of known salinity @ known ambient temperature.

Ro = F*Rw, F=Ro/Rw

$F = \Phi^{\wedge -m}$ (or $F=1/\Phi^{\wedge m}$)

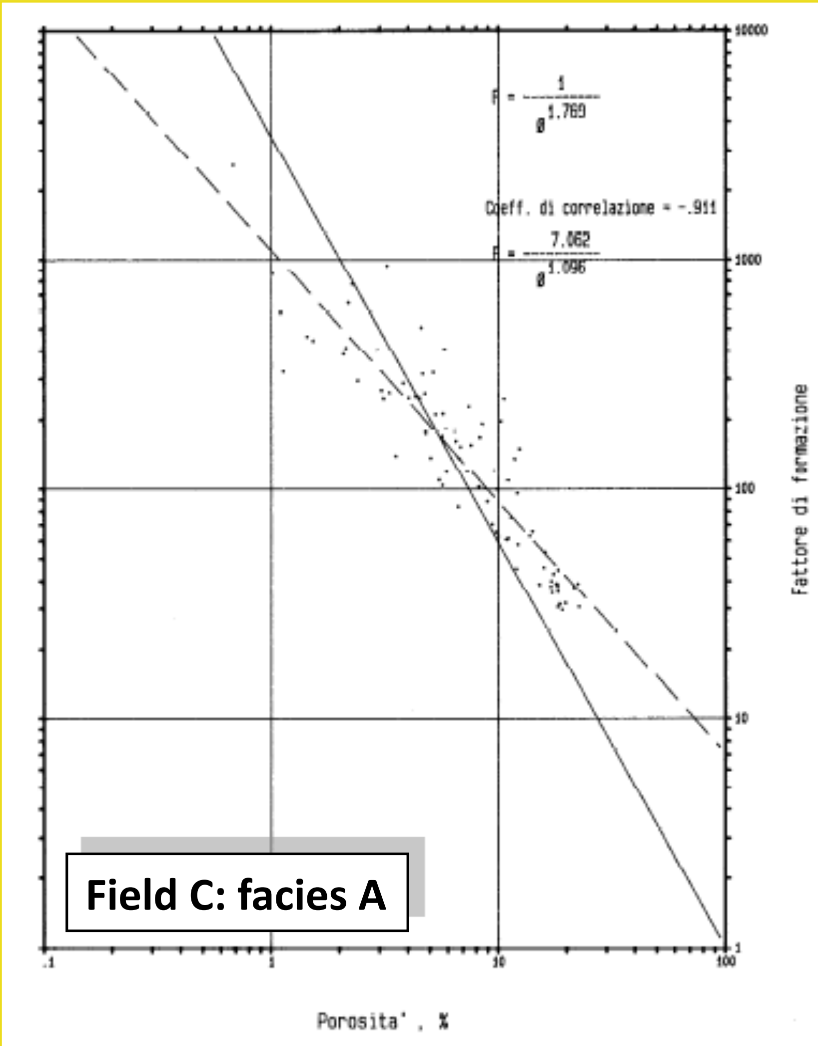
$$m = \frac{(\text{Log } FF_2 - \text{Log } FF_1)}{(\text{Log } \Phi_2 - \text{Log } \Phi_1)}$$

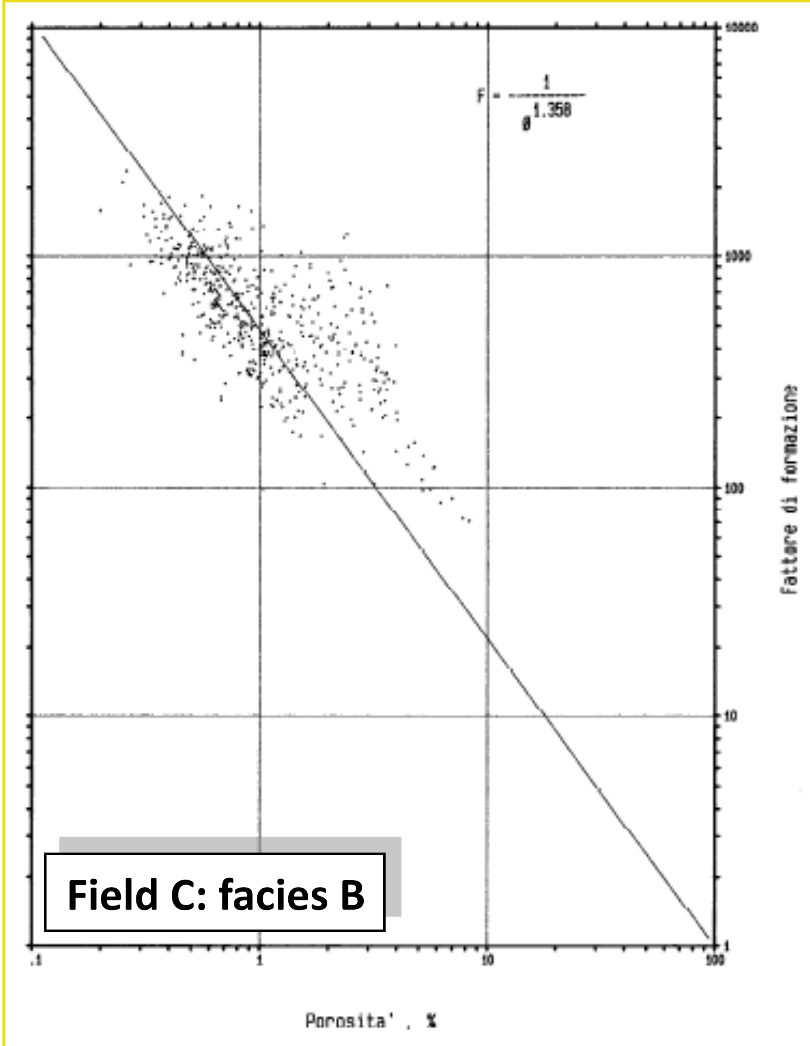
FF2	FF1	Φ2	Φ1	
100	10	0,1	0,31	

Log FF2	Log FF1	Log PHI2	Log PHI1	m
2	1	-1	-0,5	-2,0

Determination of “m” by means of core analysis

Formation Factor vs porosity in carbonates





Archie relationships in clean formations

$$\mathbf{Rt = (F^{*}\ Rw\ /\ Sw^{n})}$$

or $\mathbf{Rt/Ro = Sw\wedge^{-n}}$ i.e. $\mathbf{RI = Sw\wedge^{-n}}$

where $\mathbf{F = (a\ /\ \Phi_t^{\ m})}$,

and $\mathbf{Sw = [(a/\ \Phi_t^{\ m})\ *\ (Rw\ /Rt)]^{1/n}}$

Nomenclature

Rt = true formation resistivity

Rw = formation water resistivity

Sw = water saturation of the formation water

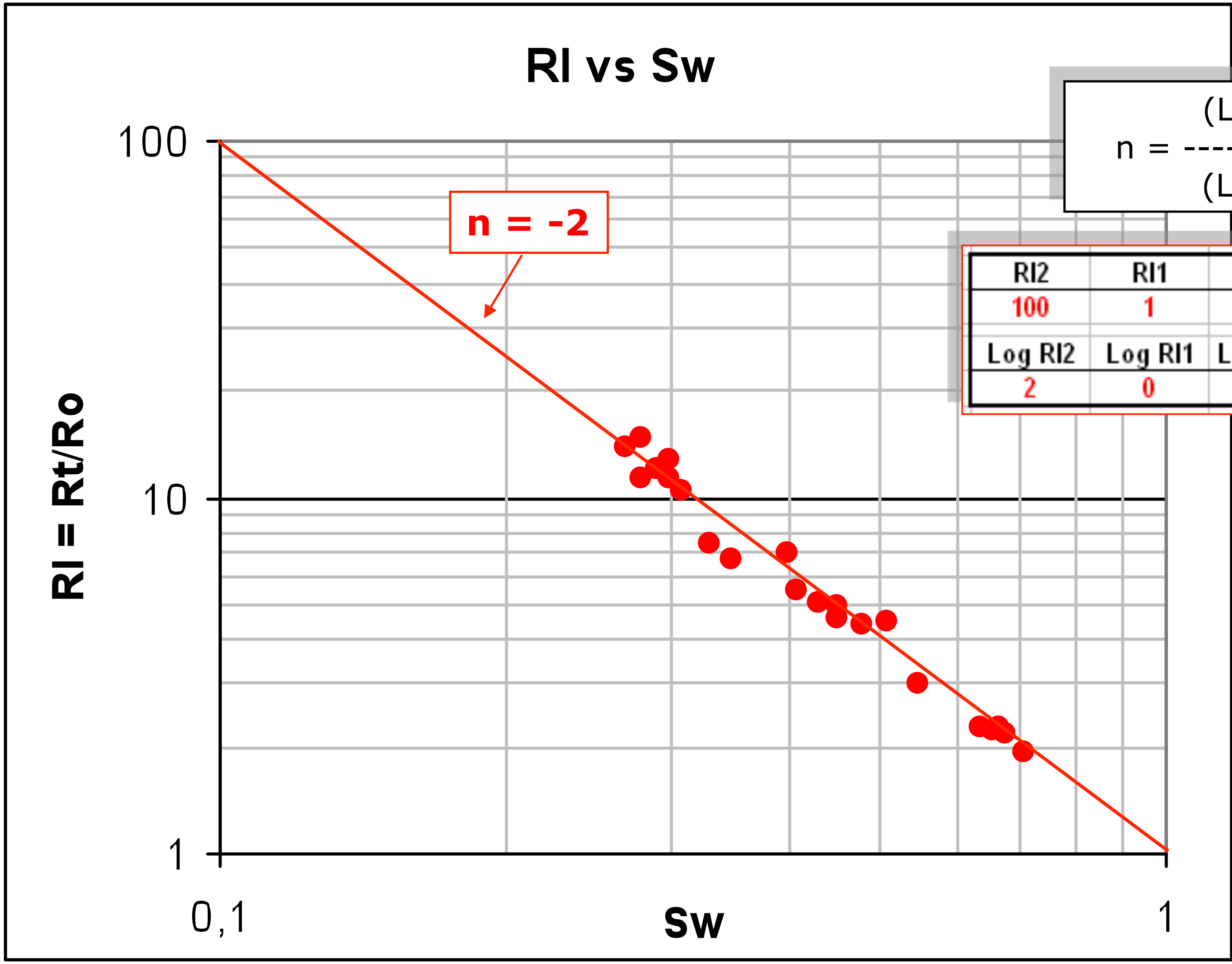
Sh = hydrocarbon saturation (Sh = 1- Sw)

F = formation resistivity factor

Φ_t = total porosity

m = cementation exponent

n = saturation exponent

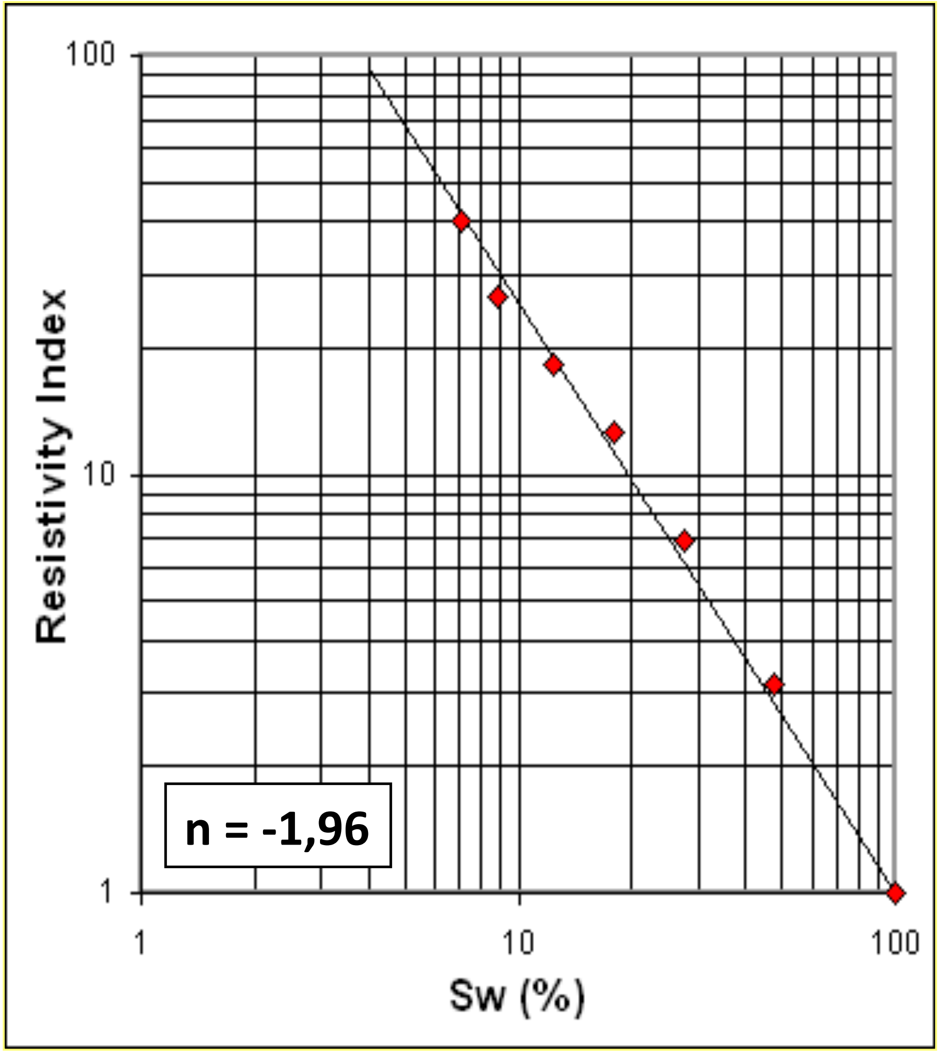


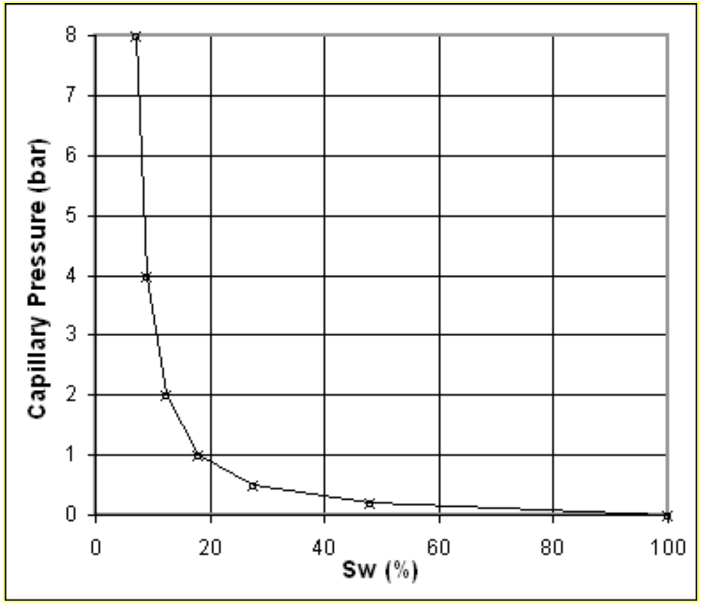
$$n = \frac{(\mathrm{Log}\ RI_2 - \mathrm{Log}\ RI_1)}{(\mathrm{Log}\ Sw_2 - \mathrm{Log}\ Sw_1)}$$

RI2	RI1	Sw2	Sw1	
100	1	0,1	1	
Log RI2	Log RI1	Log Sw2	Log Sw1	n
2	0	-1	0	-2

Determination of “n”
by means of core measurements

Resistivity Index vs Sw (n exponent)



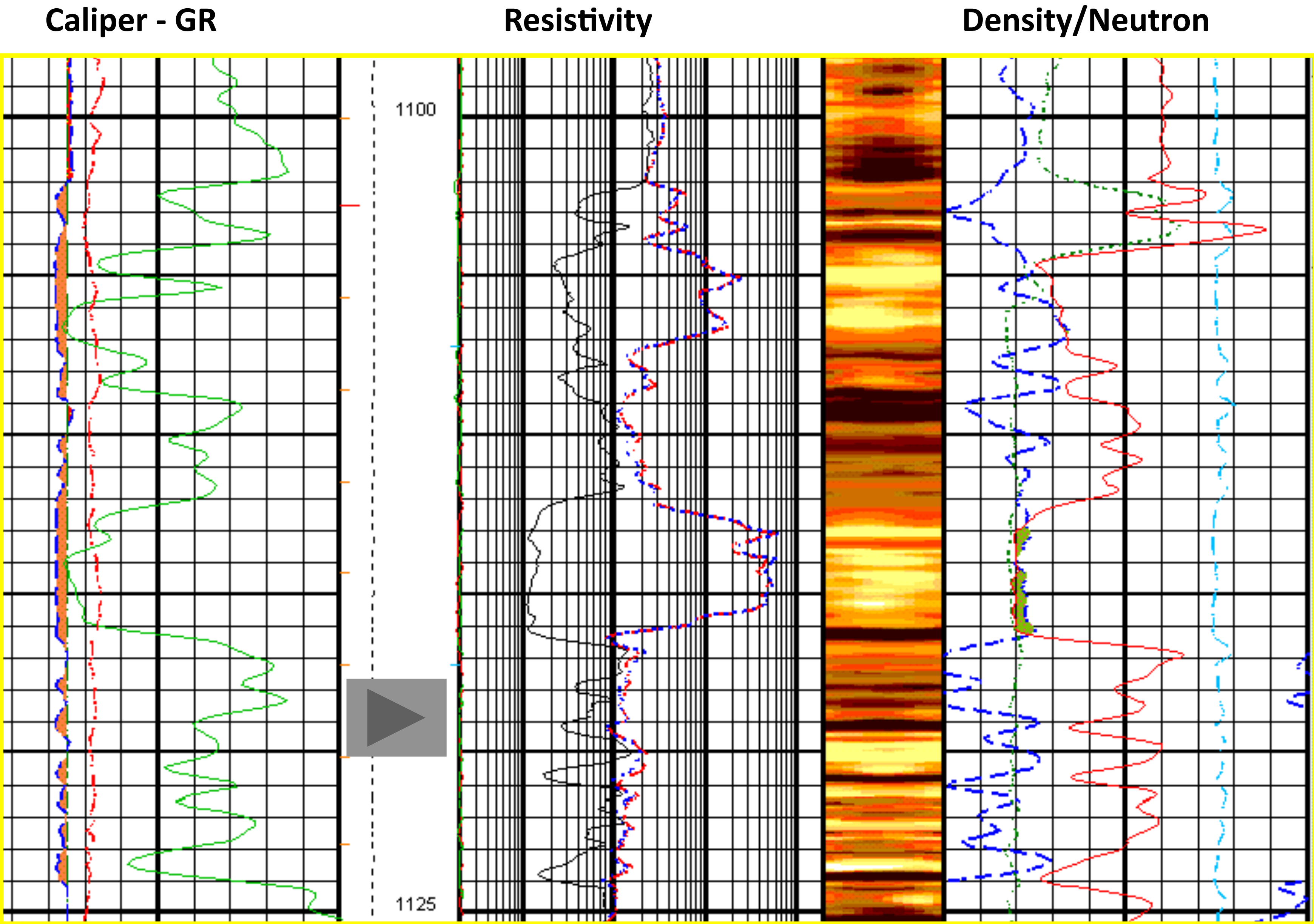


Sw (%)	RI	Pc (bar)	Sw (%)
100,0	1,0	0	100,0
48,0	3,2	0,2	48,0
27,5	7,0	0,5	27,5
17,8	12,6	1	17,8
12,5	18,2	2	12,5
8,8	26,7	4	8,8
7,0	40,6	8	7,0

Exercise on Rt & Ro relationhips at different Sw

Phi	Rw	a	m	n	Sw	Ro	Rt	Rt/Ro
0,3	0,1	1	1,9	2	1	0,99	0,99	1,0
0,3	0,1	1	1,9	2	0,5	0,99	3,94	4,0
0,3	0,1	1	1,9	2	0,4	0,99	6,16	6,3
0,3	0,1	1	1,9	2	0,3	0,99	10,95	11,1
0,3	0,1	1	1,9	2	0,2	0,99	24,63	25,0
0,3	0,1	1	1,9	2	0,1	0,99	98,51	100,0
0,15	0,1	1	1,9	2	1	3,68	3,68	1,0
0,15	0,1	1	1,9	2	0,5	3,68	14,71	4,0
0,15	0,1	1	1,9	2	0,4	3,68	22,98	6,3
0,15	0,1	1	1,9	2	0,3	3,68	40,85	11,1
0,15	0,1	1	1,9	2	0,2	3,68	91,91	25,0
0,15	0,1	1	1,9	2	0,1	3,68	367,64	100,0
0,3	0,05	1	1,9	2	1	0,49	0,49	1,0
0,3	0,05	1	1,9	2	0,5	0,49	1,97	4,0
0,3	0,05	1	1,9	2	0,4	0,49	3,08	6,3
0,3	0,05	1	1,9	2	0,3	0,49	5,47	11,1
0,3	0,05	1	1,9	2	0,2	0,49	12,31	25,0
0,3	0,05	1	1,9	2	0,1	0,49	49,25	100,0

Open hole well logs: an example



Well log interpretation: not only petrophysics!

- Since the physical properties of the logged formations are influenced by their mineralogical composition, by the distribution of the different components, by the fluid content, by the structural setting, etc., well logs can provide important geological information about the reservoir rock.
- The geological characters that can be derived by using well logs are:
  - compositional,
  - textural,
  - structural.

Logging measurements and sedimentary characters

Log Type	*Composition*	*Texture*	*Sedimentary Structure*	*Fluid*	*As Vshale indicator*
Resistivity	☺☺	☺☺☺	☺☺	☺☺	Good clean sands indicator in strong Rt vs Rsh contrasts
SP	☺	☺☺	☺☺	☺☺☺	Poor vertical resolution and very weak in hydrocarbon bearing zones or in case of no or little Rm vs Rw contrasts, good indicator of permeable levels
EPT (Transit Time)	☺☺	☺	☺	☺☺☺	Good clean sand indicator in case of constant Sxo saturation
EPT (Attenuation)	☺☺	☺	☺	☺☺☺	Good clean sand indicator in case of constant Sxo saturation
GR	☺☺	☺	☺	☺	Good sand vs clay indicator when only clay minerals are radioactive
Spectral GR	☺☺☺	☺	☺	☺	Good sand vs clay indicator when clay minerals are "residual"
ECS	☺☺☺	☺	☺	☺	Very good sand vs clay indicator in many different sedimentary env.
Neutron log (CNL)	☺☺	☺☺	☺	☺☺	Good clean sand indicator in gas bearing levels
Neutron log (APS)	☺	☺☺	☺	☺☺☺	Being less affected by composition is a weaker sand/clay indicator with respect to CNL
Density log	☺☺☺	☺☺	☺	☺☺☺	Very lithe use as Vsh indicator if not in combination with Neutron
PEF	☺☺☺	☺	☺	☺	Very good sand vs clay indicator in light mud systems
NMR	☺☺	☺	☺	☺☺☺	Very good indicator of clay bound water saturation and, hence, related to clay volume
HDT/SHDT	☺	☺☺	☺☺☺	☺	Very used in thin bed analysis but as binary indicator
Caliper	☺	☺☺	☺	☺	Fair indicator of permeable intervals, hence, of sand intervals
Sonic log DT	☺☺	☺☺☺	☺	☺☺	Very little use as standalone clay indicator. Most used in combination with Neutron responses and valid in gas bearing intervals
Sonic Vp/Vs	☺☺☺	☺☺☺	☺	☺☺	Measurement quite sensitive to mineralogy, very seldom used
Sonic (Attenuation)	☺	☺☺	☺☺	☺☺☺	Of no use as clay indicator
GST	☺☺☺	☺☺	☺	☺☺☺	Quite sensitive to lithology variation, but generally Vsh as to be known for other OH logs when used for through casing Sw evaluation
TDT (Σ)	☺☺	☺☺	☺	☺☺☺	Less sensitive to mineralogical composition with respect to GST but with similar constraints
HRT	☺☺	☺☺☺	☺☺☺	☺☺	Good indicator of permeable levels in high geothermal gradient

Comparative response of well log to the four, main geological parameters used in facies recognition (from O. Serra & Abbott, 1980, modified by M. Gonfalini)

Well logs: when?

Well logs are acquired and used in different phases of an E&P process:

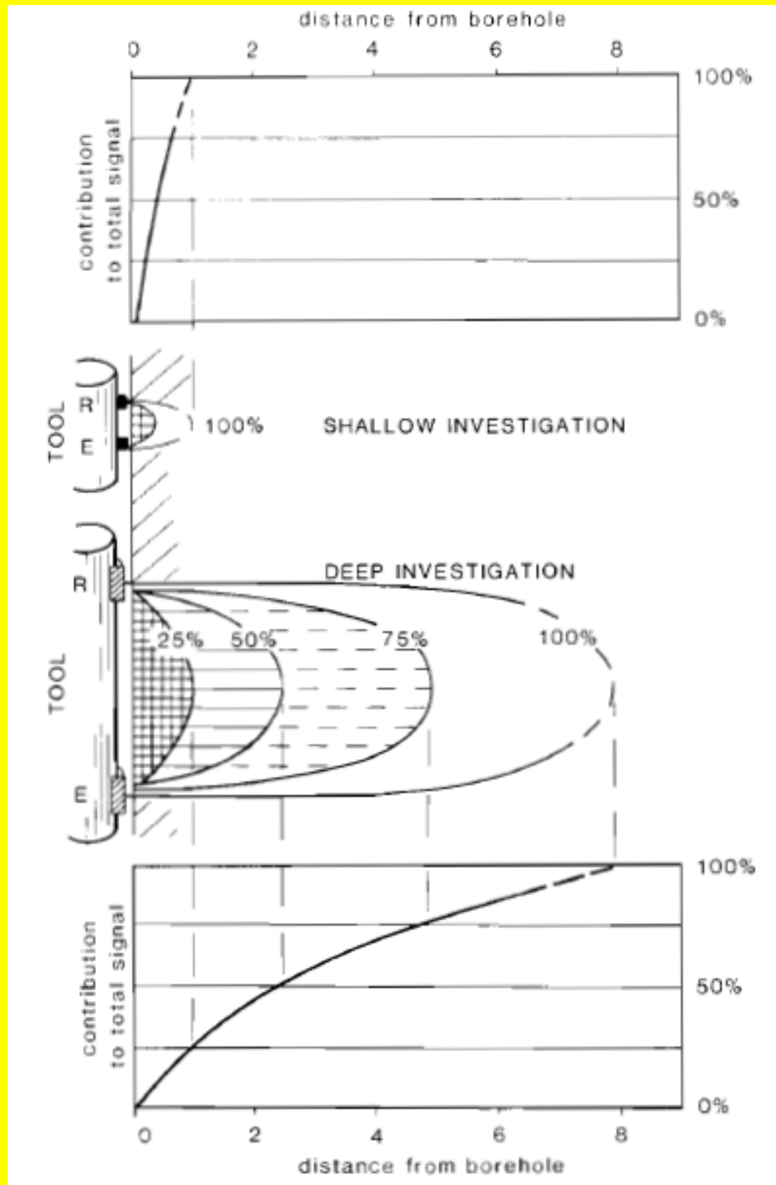
- during the drilling phase (Logging While Drilling).
- soon after the drilling phase (Open Hole Wire Line Logging)
- after the completion of the well and during the exploitation phase up to the end of the reservoir life. (Cased Hole Wire Line Logging and Production Logging)

Depth of Investigation (DOI)

Depth of investigation is the distance away from the borehole axis to which the formation is having effects on a tool reading.

Depth of investigation of a tool is a function of:

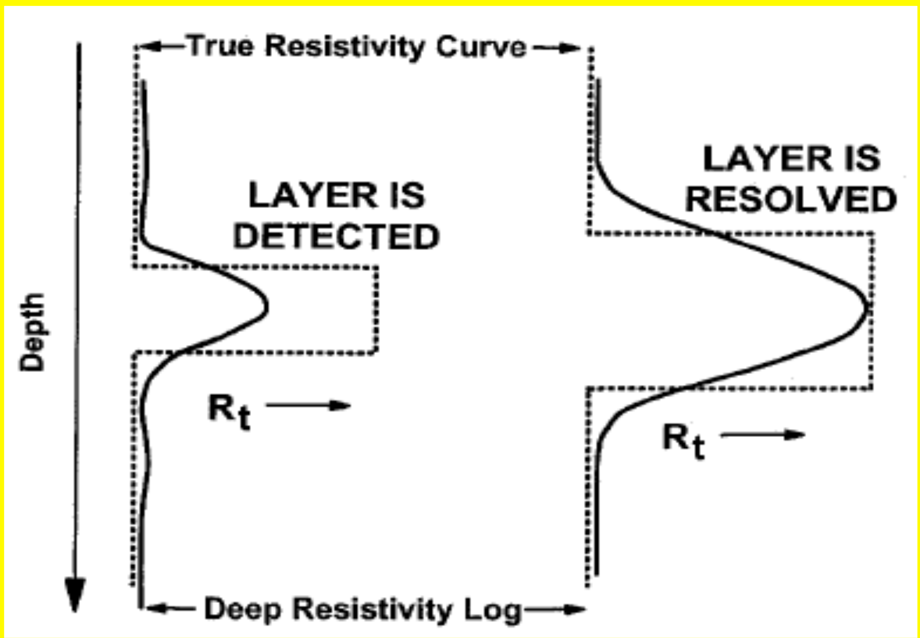
- tool physics
- sensors' geometry
- formation properties

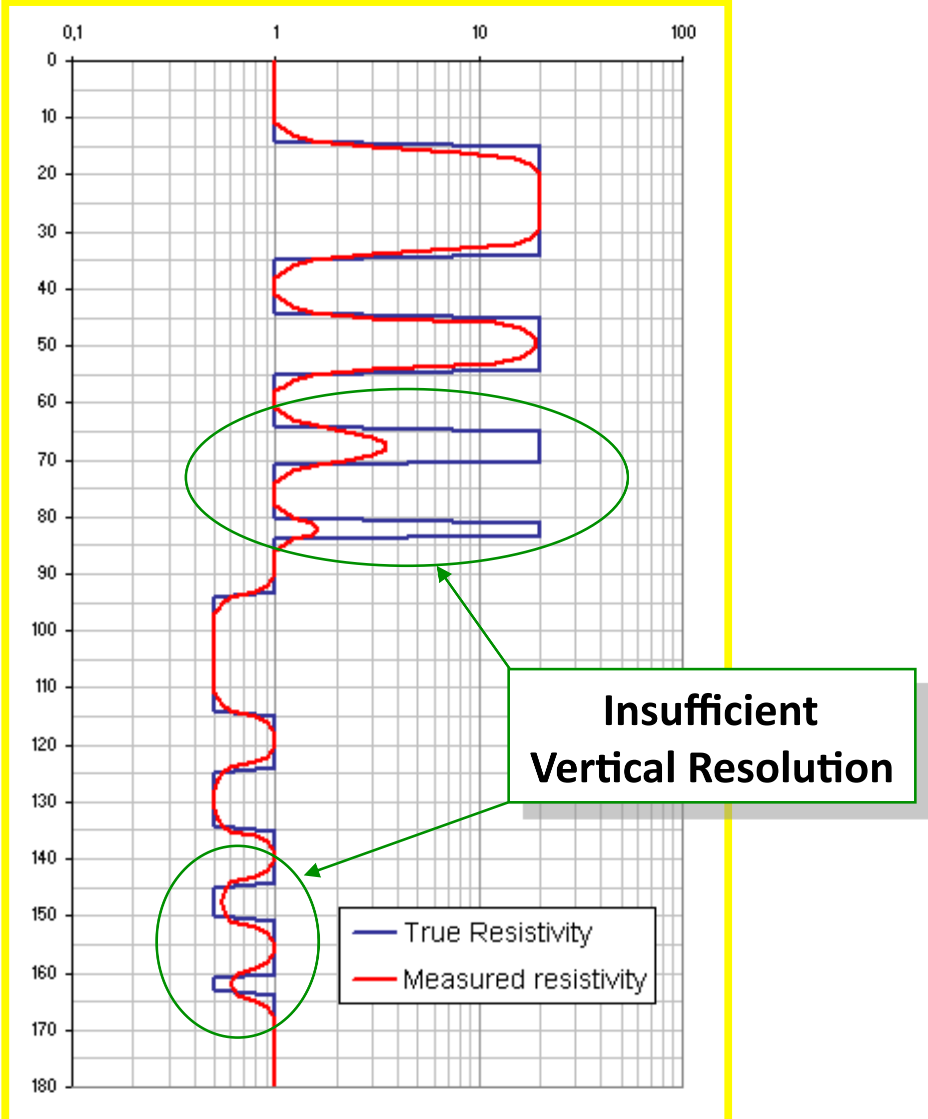


Some definition: vertical resolution

Vertical resolution is the capability to resolve thin beds.

Often expressed as the minimum thickness of formation that can be distinguished by a tool under operating conditions.





Vertical resolution vs depth of investigation

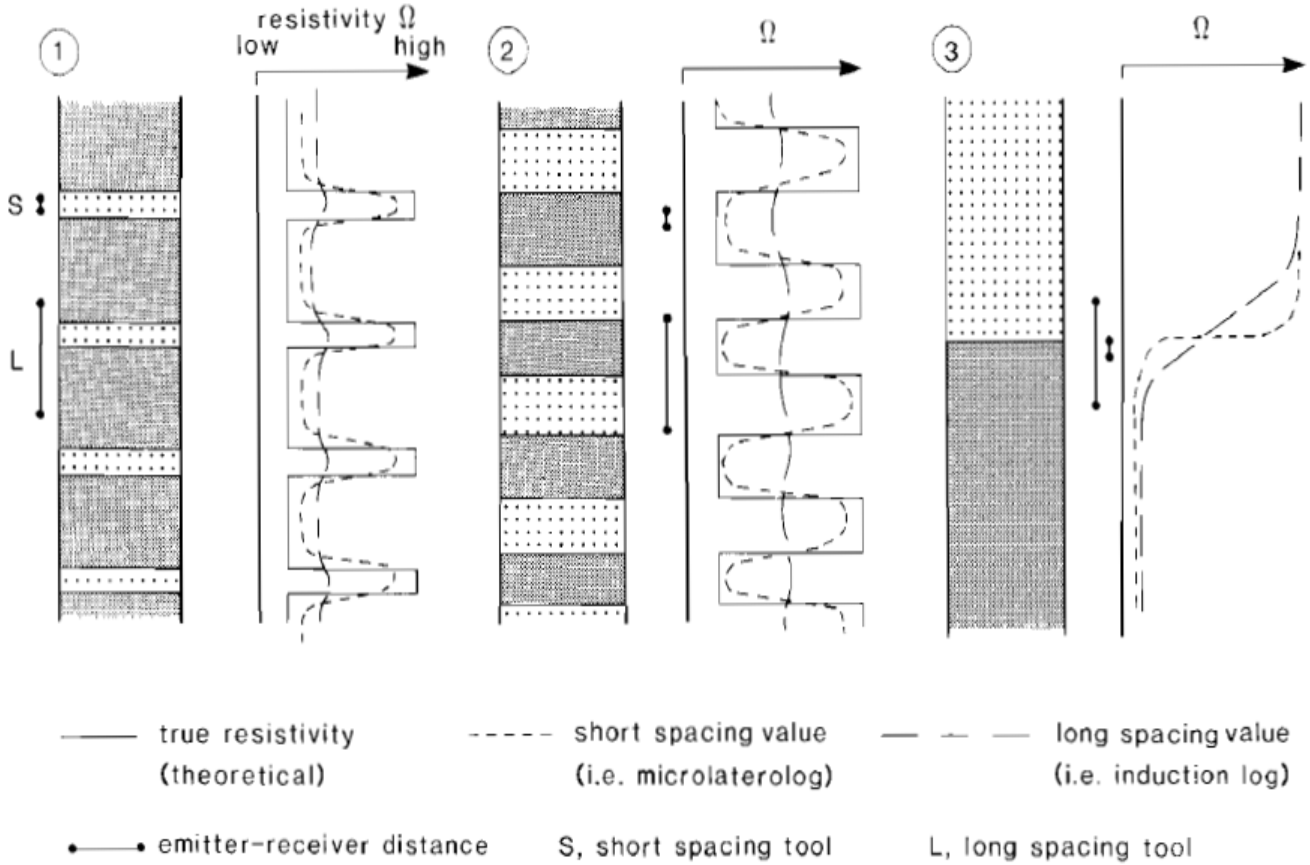


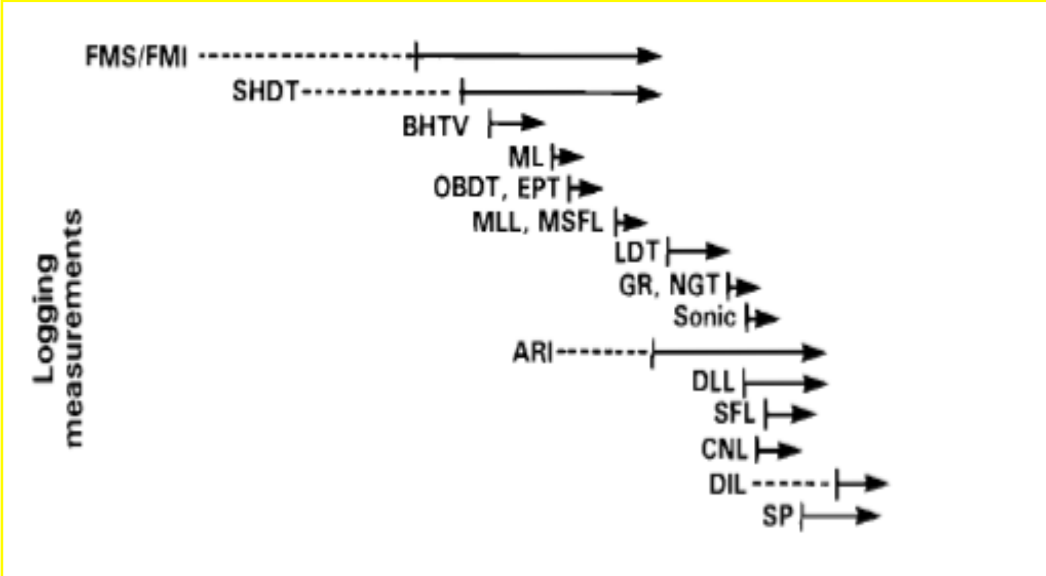
Figure 2.10 The effect of minimum bed resolution on logging-tool values in various scales of interbedding. (1) Fine interbeds; (2) coarse interbedding; (3) single bed boundary (schematic).

Relationships between vertical resolution and depth of investigation

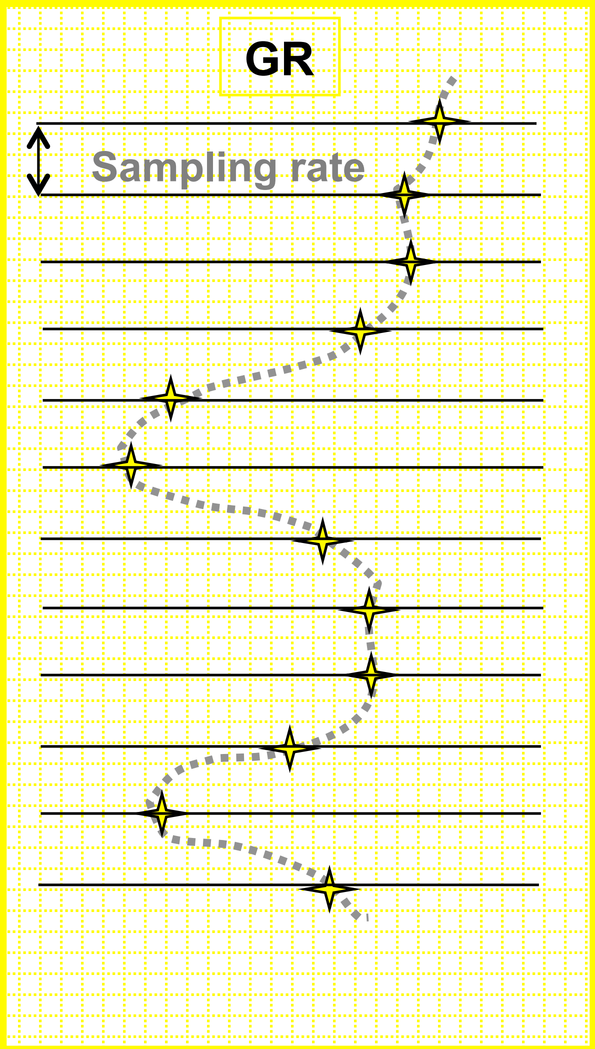
M. Reider: The geological interpretation of well logs

Vertical resolution vs depth of investigation

Logging tool measurement	Vertical Resolution inches	cm
FMS/FMI (individual electrodes)	0.2"	0.5cm
SHDT dipmeter curves	0.4"	1.0cm
HDT dipmeter curves	0.5"	1.3cm
Microlog	2"-4"	5cm-10cm
Micro Spherically Focused Resistivity	2"-3"	5cm-7.6cm
Phasor Induction SFL:		
deep	84"-96" (7'-8')	2.0m
medium	60"-72" (5'-6')	1.5m
Spherically Focused Resistivity	30" (2'6")	76cm
Laterolog	24" (2')	61cm
Litho-Density tool	15" (1'3")	38cm
Litho-Density Pef	2"	5cm
Compensation Neutron tool	15" (1'3")	38cm
Gamma ray	8"-12"	20cm-31cm
Array sonic:		
standard mode	48" (4')	1.2m
six inch mode	6"	15cm
Borehole Compensated Sonic	24" (2')	61cm



Sampling rate

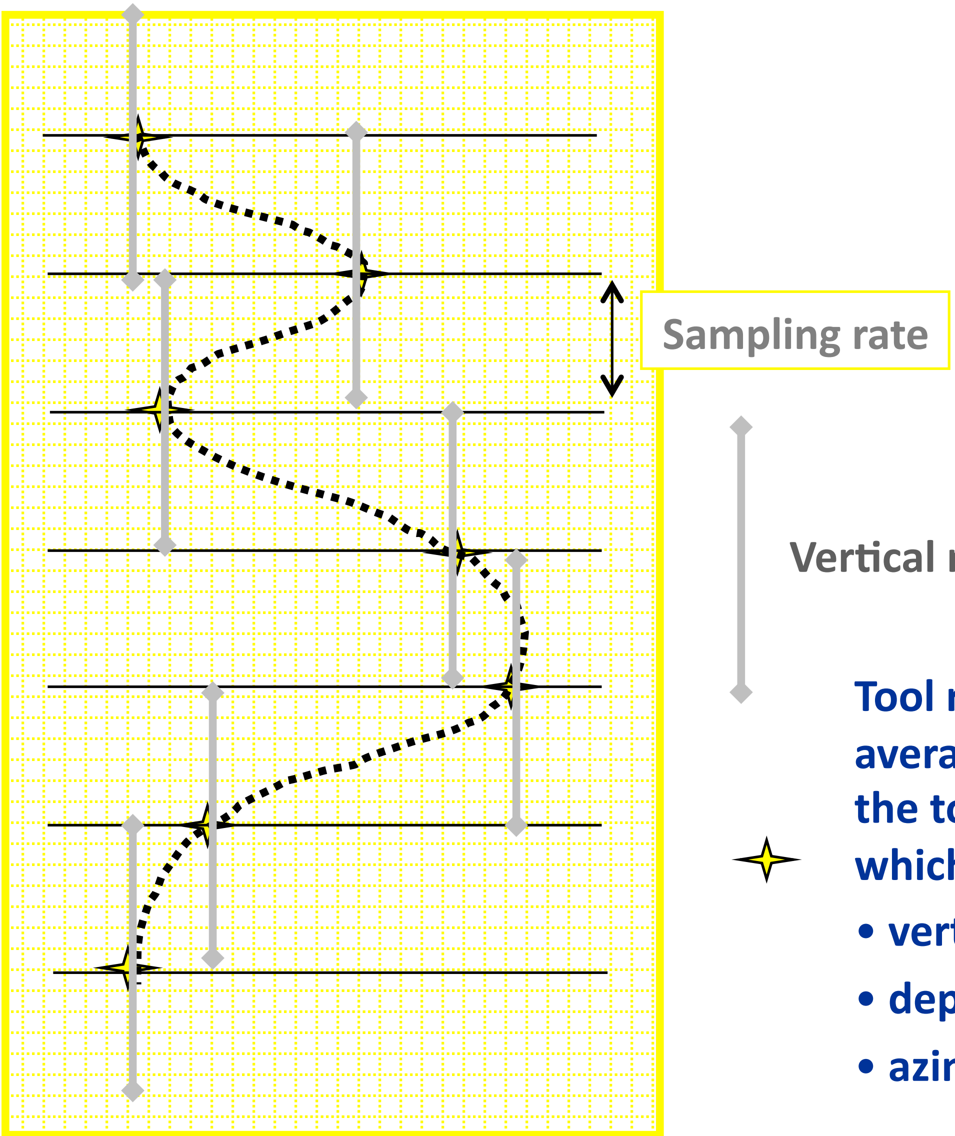


Standard sampling rate : 1 sample each ½ ft (@15 cm).
High sampling rate: 3-6 samples per ft.
Very high sampling rate: up to 10 samples per inch.

	CMR	EPT	R_{xo}	PEF	RHOB	Σ	APS	CNL	DT
Azimuth (degree)	23	23	23	23	45	45	45	360	360
Depth of investigation (inch)	1.5	1.5	3	3	4	6	7	9	9
Vertical resolution	1	1	1	1	1	1	1	2	2.5

Relationships between vertical resolution and depth of investigation

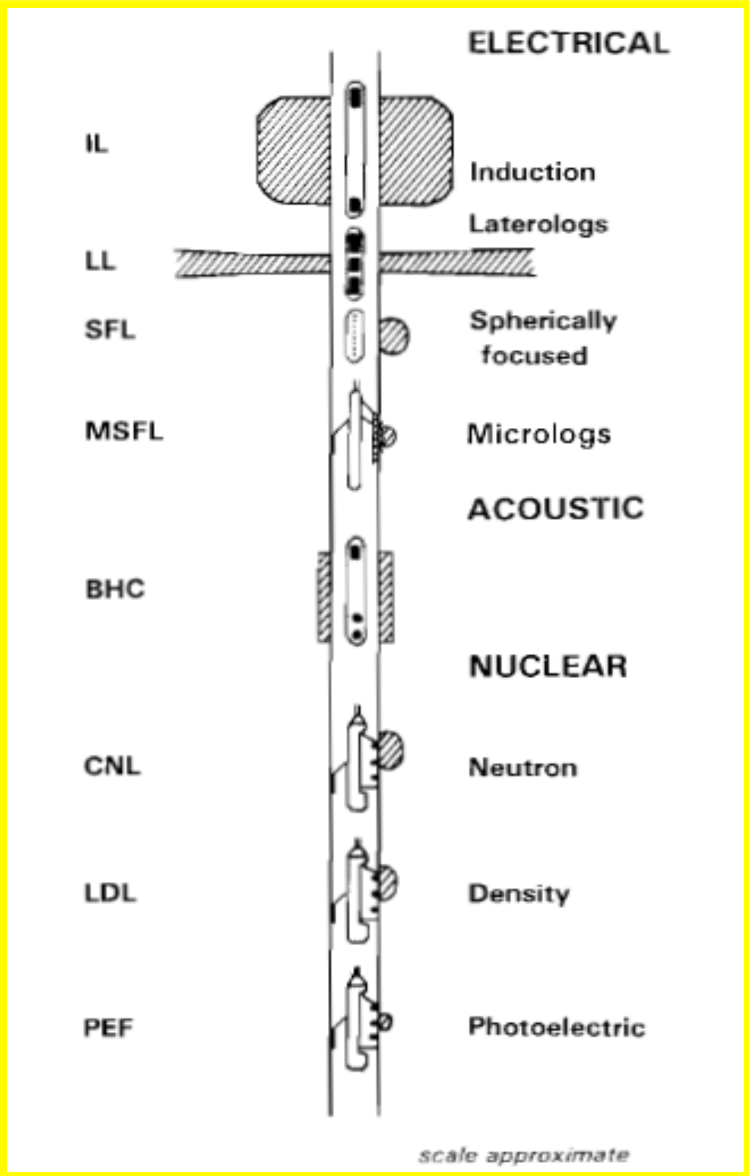
What a log measure represents?

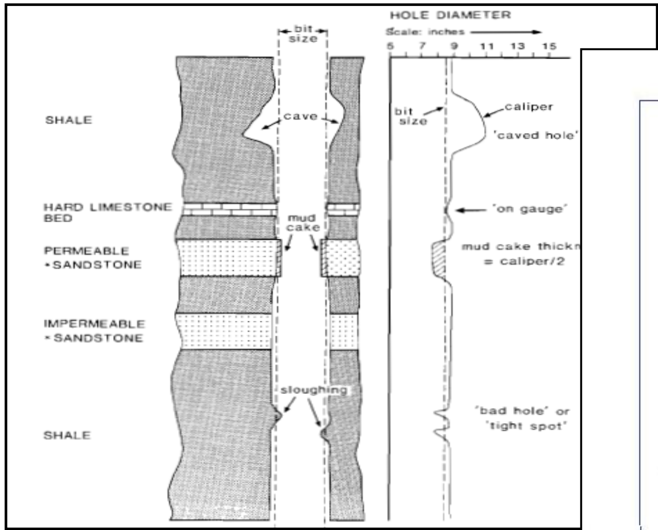


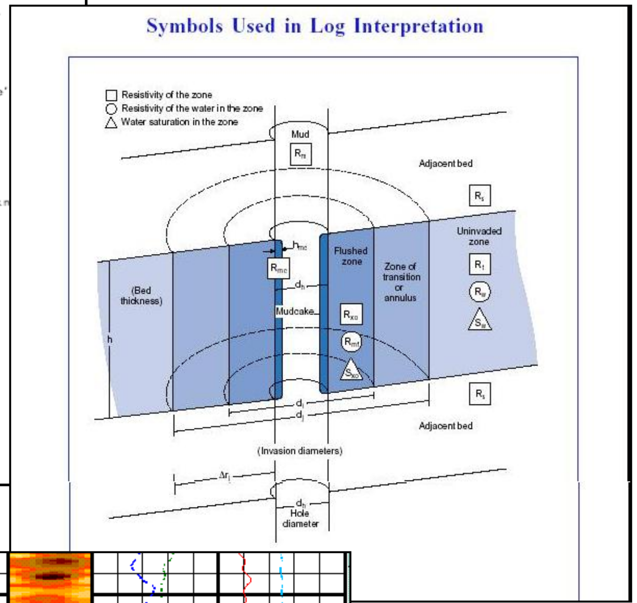
Tool response at each depth point represents the average value of the physical parameter measured by the tool in the volume of formation investigated which is a function of:

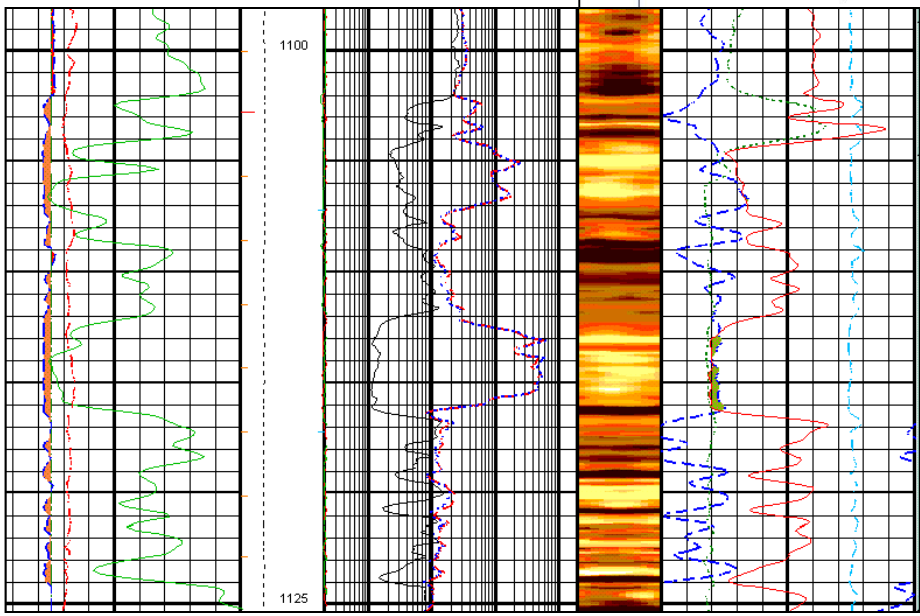
- **vertical resolution**
- **depth of investigation**
- **azimuthal aperture.**

Investigation Geometry & Borehole environment









Log Type	min logging speed (ft/h)	Max logging speed (ft/h)
DIL	1800	3600
DLL	1800	3600
Array Induction	1800	3600
Array Laterolog	1800	3600
Density	900	1800
Neutron	900	1800
GR/Spectral GR Sonic	900	1800
Sonic	900	3600
Nuclear Magnetic Resonance	300	600

Log Open Hole WL: typical logging speeds

Well logs: who?

- Today, due to the very high technological content, the complexity of the technologies which requires very large investments (research, design, manufacturing, facilities, education and training of the field personnel, etc.), the acquisition of well logs is performed by **Service Companies**.
- **Service Companies** can also provide as a service both processing and interpretation of the acquired data.
- In general the major **Oil Companies** have, in their organization, internal technical services and the interpretation of the well logging data is performed by their specialists using dedicated Software and Hardware environments.

Well logs: who?

- The interpretation can be produced immediately after the logs (Quick Look interpretation), at the well site and/or at the Oil Company headquarters.
- In this phase, the analyst generally uses a limited number of well data, with standard parameters and simplified petrophysical models.
- Today this interpretation is often performed by using digital data sent via Internet or satellites to the headquarters of the Oil company, but it can be also performed by using the field prints and picking a limited number of measurements getting use of calculators and graphical solution.
- This interpretation is generally used for operational decisions such as casing/liner setting, side wall coring, formation testing, well abandonment.

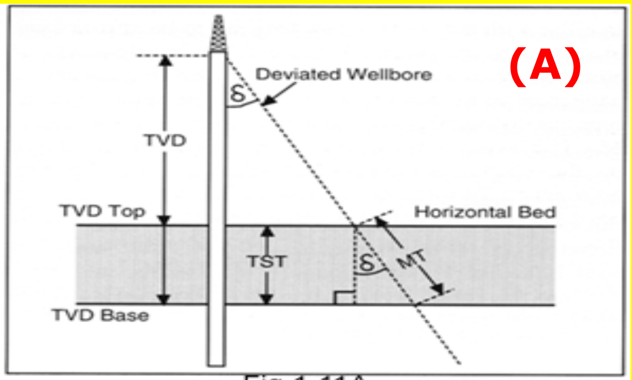


Fig 1-11A
TVD principle for a vertical well and horizontal bed

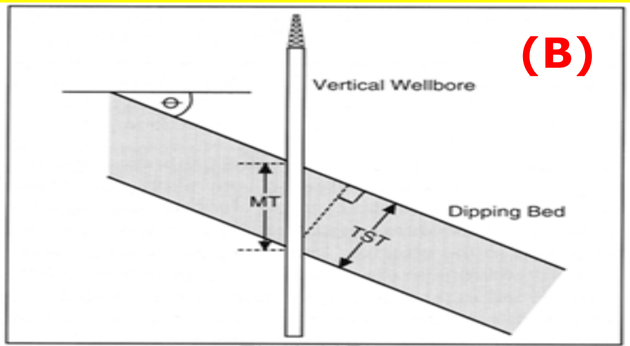


Fig 1-11B
TVD principle for a vertical well and a dipping bed

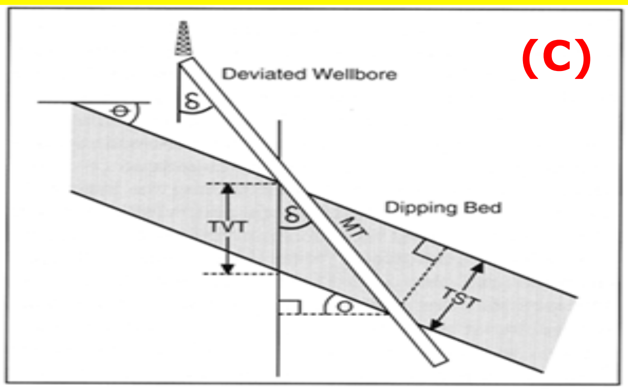


Fig 1-11C
TVD principle for a deviated well and a dipping bed

An important statement

Lithology logs are often used to accurately define the thickness of the reservoir.

Primary information given by the direct interpretation of well logs are *top* and *bottom* of the levels of interest.

In case of a vertical well and horizontal levels, the thickness of the geological units is sufficiently accurate.

When the well deviated more than 5°, it is necessary to correct the measured vertical thickness (MT) in order to obtain the vertical thickness (TVT) by using the relative angle of the layer relative to the well axis (A).

When the layers dip due to the presence of folds and/or faults, the measured thickness need to be corrected to obtain the true stratigraphic thickness (TST).

When the well is deviated and the layers dip, the correction is more complex and additional data are required.

Some of the most common logging grids