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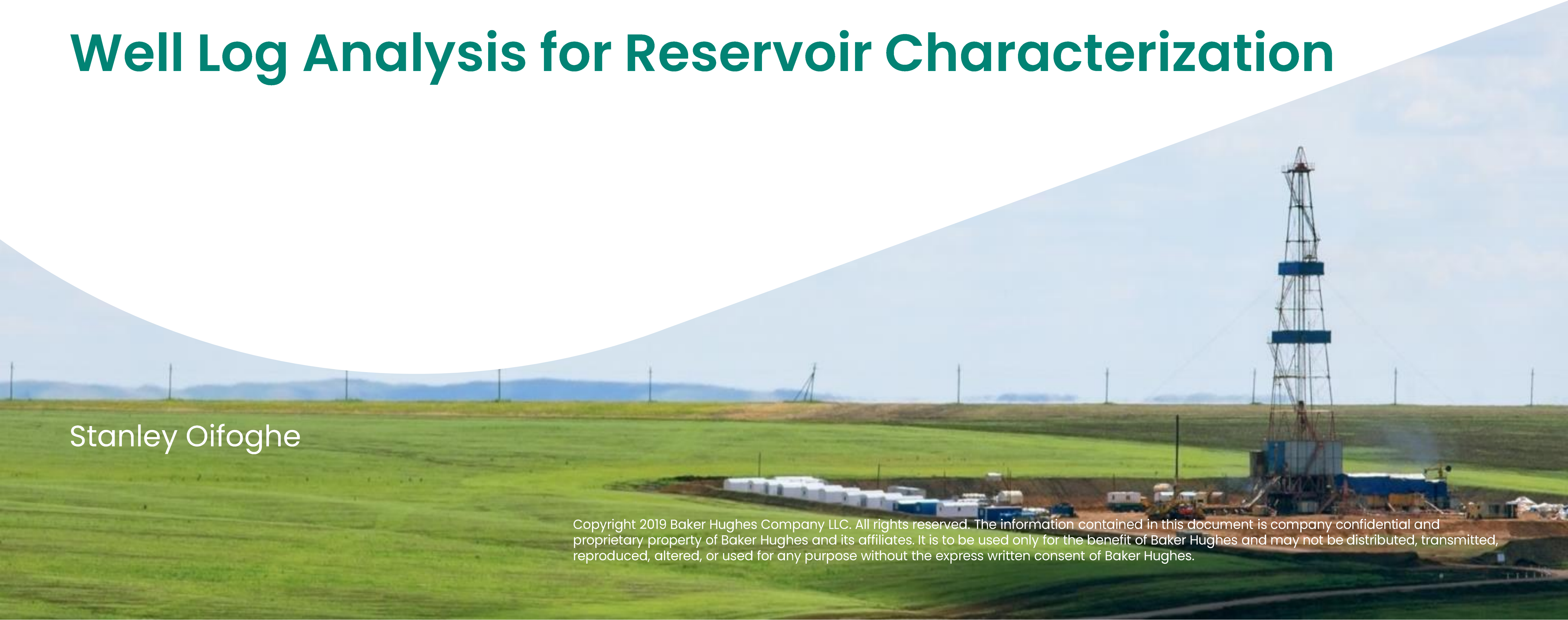
Well Log Analysis for Reservoir Characterization



Stanley Oifoghe

Outline

- Introduction
- Lithological Interpretation
- Shale Volume Computation
- Porosity Determination
- Saturation Computation
- Permeability Calculation
- Elasticity Determination
- Reflectivity Estimation
- Case Study

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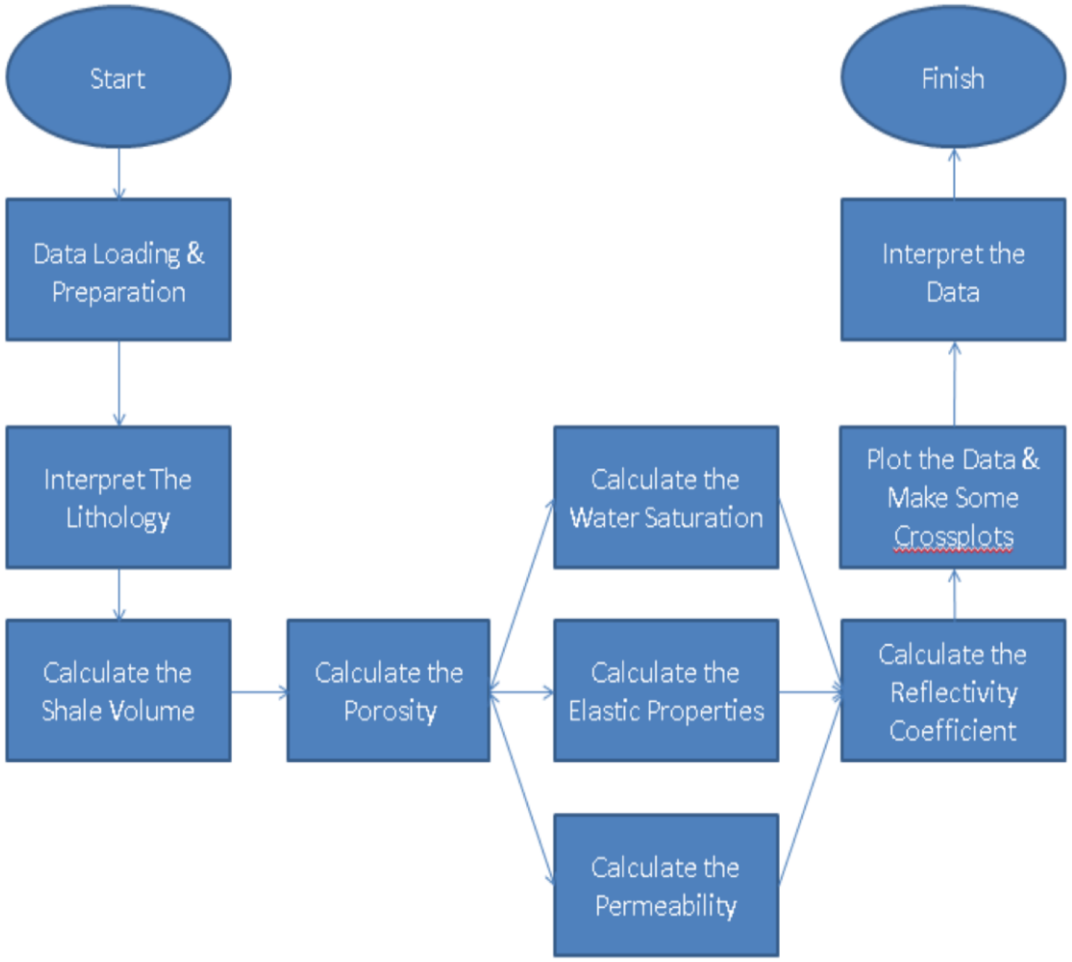
Introduction

- Well logs are commonly used for reservoir characterization in the oil and gas industry.
- They are useful in detecting hydrocarbon bearing zones, calculating hydrocarbon volumes, and many other applications.
- Some of the properties needed for reservoir characterization are:
  - shale volume (V_{sh})
  - water saturation (S_w)
  - porosity (φ)
  - permeability (k)
  - elasticity (v, AI, SI, etc.)
  - reflectivity (R)

Introduction

- Interpretation of well log data involves several sequential steps.
- It is unwise to analyze well log data without following the logical steps as this could introduce errors in the result.
- Two classes of properties for reservoir characterization are:
  - Petrophysical (related to rock physics): shale volume, water saturation, permeability, etc.
  - Geomechanical (related to earth physics): elasticity, wave velocity, etc.



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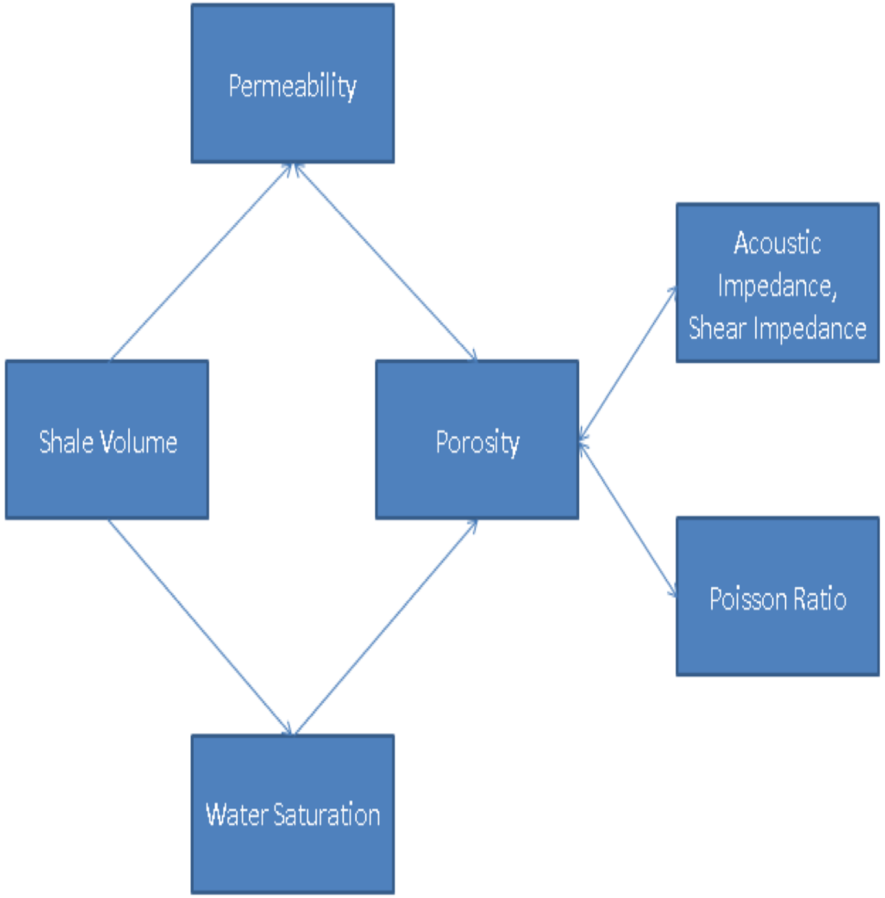
Introduction

- Rock properties are related to each other and the relationship can be presented as a “fish diagram”.
- There are several techniques employed in reservoir identification.
- Some of these techniques are:
  - Density-Neutron Crossplots
  - Reflectivity
  - Acoustic Impedance anomaly
- Every technique has its challenges.
- A combination or comparison of results from various techniques tend to reduce the overall uncertainty.

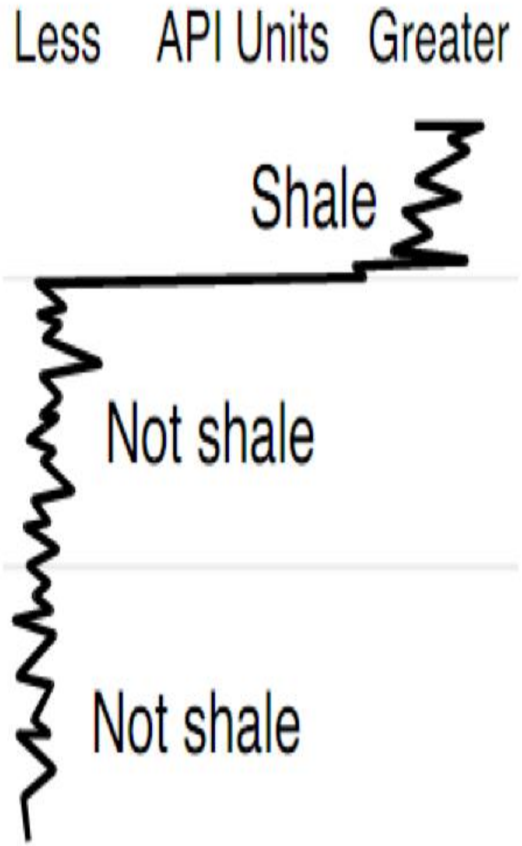


Log Application in Reservoir Characterization

Name	Uses
Gamma Ray (GR)	Lithology interpretation, shale volume calculation, permeability calculation, porosity calculation, wave velocity calculation, etc.
Spontaneous Potential (SP)	Lithology interpretation, R_w and R_{we} calculation, detection of permeable zone, etc.
Caliper (CALI)	Detect permeable zone, locate a bad hole
Shallow Resistivity (LLS and ILM)	Lithology interpretation, determine hydrocarbon bearing zone, calculate water saturation, etc.
Deep Resistivity (LLD and ILD)	Lithology interpretation, determine hydrocarbon bearing zone, calculate water saturation, etc.
Density (RHOB)	Lithology interpretation, determine hydrocarbon bearing zone, porosity calculation, rock physics properties (AI, SI, *v*, etc.) calculation, etc.
Neutron Porosity (NPHI)	Determine hydrocarbon bearing zone, porosity calculation, etc.
Sonic (DT)	Porosity calculation, wave velocity calculation, rock physics properties (AI, SI, *v*, etc.) calculation, etc.
Photoelectric (PEF)	Mineral determination (for lithology interpretation) *not used in this presentation

Lithological Interpretation

- Lithology refers to the general physical characteristics of rocks.
- Though GR and SP are the main lithology logs, resistivity and density logs are used to validate the interpreted lithologies.
  - High GR reading indicates a shale or shaly formation
  - Low GR reading indicates a clean formation (sand, carbonate, evaporite, etc.)
- Lithology interpretation is the first step in reservoir characterization.
- If the lithological interpretation is wrong, every other property such as porosity and water saturation will be wrong.



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Shale Volume Computation

- Shale volume estimation (Vsh) is the second step in reservoir characterization.
- Shale is usually more radioactive than sand or carbonate
- GR can be used to calculate Vsh in porous reservoirs.
- Petrophysicists will not classify a formation with high Vsh as a good reservoir because of its low permeability.
- Vsh is important because, it is useful in water saturation (Sw) calculation.
- The presence of shale in a reservoir such as a deltaic sandstone, increases the Sw due to bound water in shales.

Larionov (1969) formulas for Vsh from GR:

$$I_{GR} = \frac{GRlog - GRmin}{GRmax - GRmin}$$

Larionov (1969) for tertiary rocks:

$$V_{sh} = 0.083(2^{3.7 I_{GR}} - 1)$$

Larionov (1969) for older rocks:

$$V_{sh} = 0.33 \times (2^{2 I_{GR}} - 1)$$

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Porosity Determination

- Porosity or void fraction is a measure of the void spaces in a material, and is a fraction of the volume of voids over the total volume.
- Pores are useful for storing fluids such as oil, gas, and water.
- Porosity calculation is the third step in reservoir characterization.
- Porosity can be calculated from density log, sonic log, neutron log, or a combination of them.
- The most commonly used combination is neutron-density log.

Formulas for calculating porosity from neutron-density logs:

$$\Phi d = \frac{\rho matrix - \rho log}{\rho matrix - \rho fluid}$$

For hydrocarbon reservoirs:

$$\Phi nd = \sqrt{\frac{\Phi d^2 + \Phi n^2}{2}}$$

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Porosity Determination

Matrix and fluid density reference table (Halliburton, 1991).

Lithology	Value (gr/cm3)	Fluid	Value (gr/cm3)
Sandstone	2.644	Fresh Water	1.0
Limestone	2.710	Salt Water	1.15
Dolomite	2.877	Methane	0.423
Anhydrite	2.960	Oil	0.8
Salt	2.040		

Saturation Computation

- Water saturation (Sw) is the ratio of water volume to pore volume.
- We calculate Sw from the effective porosity and the resistivity log.
- Hydrocarbon saturation (So or Sg) is 1 - Sw.
- Most oil and gas reservoirs are water wet (water coats the surface of each rock grain).
- Archie's equation, and Simandoux's equation are common Sw equations.

Simandoux's (1963) equation (Shaly Sand):

$$SW_{\text{Simandoux}} = \frac{a \,.\, Rw}{2 \,.\, \phi^m} \left[\sqrt{\left(\frac{Vsh}{Rsh}\right)^2 + \frac{4\ \phi^m}{a \,.\, Rw \,.\, Rt}} - \frac{Vsh}{Rsh} \right]$$

Archie's (1942) equation (Clean Sand):

$$SW_{\text{Archie}} = \left(\frac{a}{\phi^m} \cdot \frac{Rw}{Rt} \right)^{(1/n)}$$

Tortuosity factor (a), cementation exponent (m), and saturation exponent (n) are derived from Pickett plot.

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Saturation Computation

Other Shaly Sand Saturation Equations:

Indonesian equation:

$$SW_{\text{Indonesia}} = \left\{ \frac{\sqrt{\frac{1}{Rt}}}{\left(\frac{Vsh^{(1-0.5Vsh)}}{\sqrt{Rsh}}\right) + \sqrt{\frac{\phi_e^m}{a.Rw}}} \right\}^{(2/n)}$$

1971 Poupon-Leveaux (Indonesia) equation may work well with fresh formation water.

Fertl equation:

$$SW_{Fertl} = \phi_e^{(-m/2)} \left\{ \sqrt{\frac{a.Rw}{Rt} + \left(\frac{\alpha.V\text{shale}}{2}\right)^2} - \left(\frac{\alpha.V\text{shale}}{2}\right) \right\}$$

The Fertl (1975) equation for shaly sands has the advantage that does not depend upon R_{shale}.
It rather uses a reservoir dependent empirically adjusted parameter α ($0.25 \leq \alpha \leq 0.35$).

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Saturation Computation

Sw, So and Sg trend increases or decreases with varying a, m, n, Salinity, Rw, Rt, Vsh, Rsh, φ, α, and Qv.

	↑ **Parameter increases**	***SW***	***SO* or *SG***
1	*a*	↑	↓
2	*m*	↑	↓
3	*n*	↑	↓
4	*Rw*	↑	↓
5	Salinity (*Rw* ↓)	↓	↑
6	*Rt*	↓	↑
7	*φ*	↓	↑
8	*Vsh* (φ_e ↓)	↑	↓
9	*Vsh* (Sat. correction)	↓	↑
10	*Rsh*	↓	↑
11	Fertl *α*	↓	↑
12	Grain density (*φ* ↑)	↓	↑
13	CEC *Qv*	↓	↑

	Parameter decreases ↓	***SW***	***SO* or *SG***
1	*a*	↓	↑
2	*m*	↓	↑
3	*n*	↓	↑
4	*Rw*	↓	↑
5	Salinity (*Rw* ↑)	↑	↓
6	*Rt*	↑	↓
7	*φ*	↑	↓
8	*Vsh* (φ_e ↑)	↓	↑
9	*Vsh* (Sat. correction)	↑	↓
10	*Rsh*	↑	↓
11	Fertl *α*	↑	↓
12	Grain density (*φ* ↓)	↑	↓
13	CEC *Qv*	↑	↓

Saturation Computation

Tortuosity factor (a) and cementation exponent (m) reference table (Asquith et al, 2004).

Lithology	a (tortuosity factor)	m (cementation exponent)
Carbonate	1.0	2.0
Consolidated Sandstone	0.81	2.0
Unconsolidated Sandstone	0.62	2.15
Average Sand	1.45	1.54
Shaly Sand	1.65	1.33
Calcareous Sand	1.45	1.70
Carbonate (Carothers, 1986)	0.85	2.14
Pliocene Sand	2.45	1.08
Miocene Sand	1.97	1.29
Clean, granular formation	1.0	$\varphi(2.05-\varphi)$

Permeability Calculation

- Permeability is the property of rocks that is an indication of the ability for fluids (gas or liquid) to flow through rocks.
- Permeability is affected by the pressure in a rock.
- Permeability is also affected by shale volume, effective porosity, and many others factors.
- The most common equation for permeability calculation is Coates's (1981) equation:

$$k = 100 \times \frac{\Phi^2 \times (1 - Swirr)}{Swirr}$$

- From the formula, if the irreducible water saturation = 1, the permeability = 0, irrespective of the porosity of the rock.

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Elasticity Determination

- Elasticity refers to the ability of a material to undergo stress, deform, and then recover and return to its original shape after the stress ceases.
- Once stress exceeds the yield stress or elastic limit of a material, permanent deformation occurs and the material will not return to its original shape when the stress is removed.
- Some elastic properties of rocks are Acoustic Impedance (AI), Shear Impedance (SI), Poisson's Ratio (*v*), etc.
- Most elastic properties depend on the wave velocity and rock bulk density.
- Theoretically, a formation with high density will have low transit time (Δtlog), which implies high seismic wave velocity.
- Density and seismic wave velocity are expected to increase with depth.
- An anomalous trend of density and wave velocity may indicate the presence of fluids in a formation.

Elasticity Determination

Acoustic Impedance: $AI = \rho \times V\rho$

Shear Impedance: $SI = \rho \times Vs$

Poisson's Ratio:

$$\nu = \frac{\left(\frac{V_P}{V_S}\right)^2 - 2}{2\left(\frac{V_P}{V_S}\right)^2 - 2}$$

According to Castagna et al (1985),

P-wave velocity: $Vp(km/s) = 5.81 - 9.42 \times \Phi s - 2.21 \times Vclay$

$Vp(ft/s) = (5.81 - 9.42 \times \Phi s - 2.21 \times Vclay) \times 300$

S-wave velocity: $Vs(km/s) = 3.89 - 7.07 \times \Phi s - 2.04 \times Vclay$

$$\Phi s = \frac{\Delta tlog - \Delta tmatrix}{\Delta tfluid - \Delta tmatrix}$$

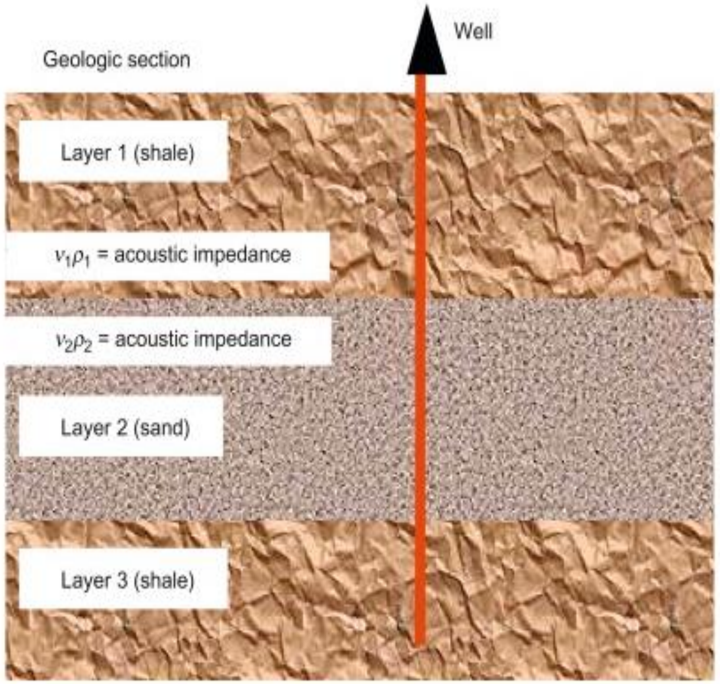
$$Vclay = \frac{0.5 \times Vsh}{1.5 - Vsh}$$

Matrix and fluid transit time reference table

Lithology	Value (µs/ft)	Fluid	Value (µs/ft)
Consolidated Sandstone	55.5	Fresh Water	218
Unconsolidated Sandstone	51.5	Salt Water	189
Limestone	47.5	Oil	238
Dolomite	43.5	Methane	626
Anhydrite	50.0		
Gypsum	52.0		
Salt	67.0		

Reflectivity

- The reflection coefficient or reflectivity is the proportion of seismic wave amplitude reflected from an interface to the wave amplitude incident upon it.
- If 10% of the amplitude is returned, then the reflection coefficient is 0.10.
- The reflectivity is derived from density and sonic log.
- If the reflectivity is high, more seismic wave will be reflected from the surface of the rock, which implies presence of a bright spot.
- Low reflectivity implies a dim spot.
- Reflectivity could be used as hydrocarbon indicator.
- The formula is: $$\mathrm{R} = \frac{\rho 2 \times Vp2 - \rho 1 \times Vp1}{\rho 2 \times Vp2 + \rho 1 \times Vp1} = \frac{AI2 - AI1}{AI2 + AI1}$$



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Case Study

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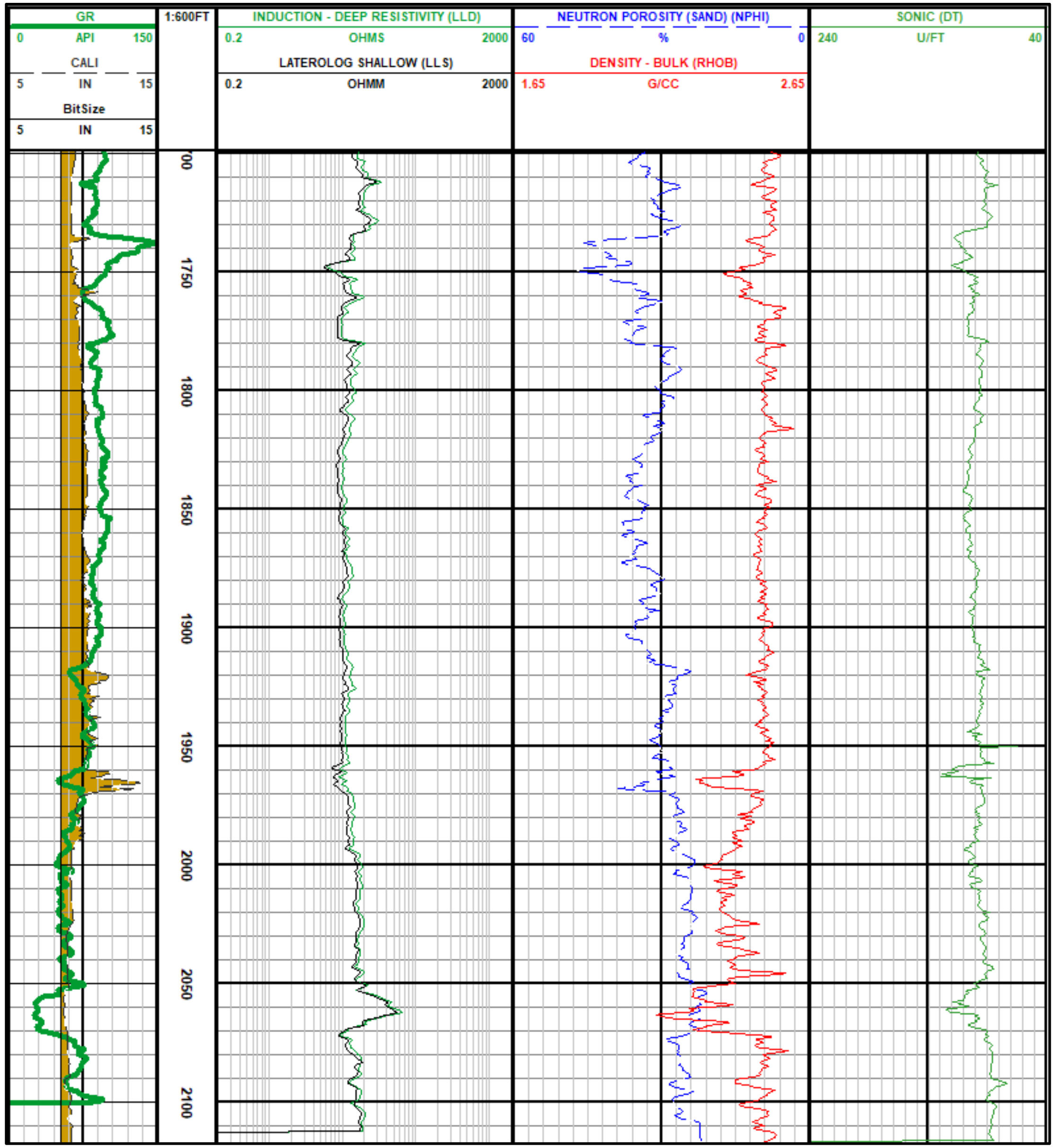
Well Log Data



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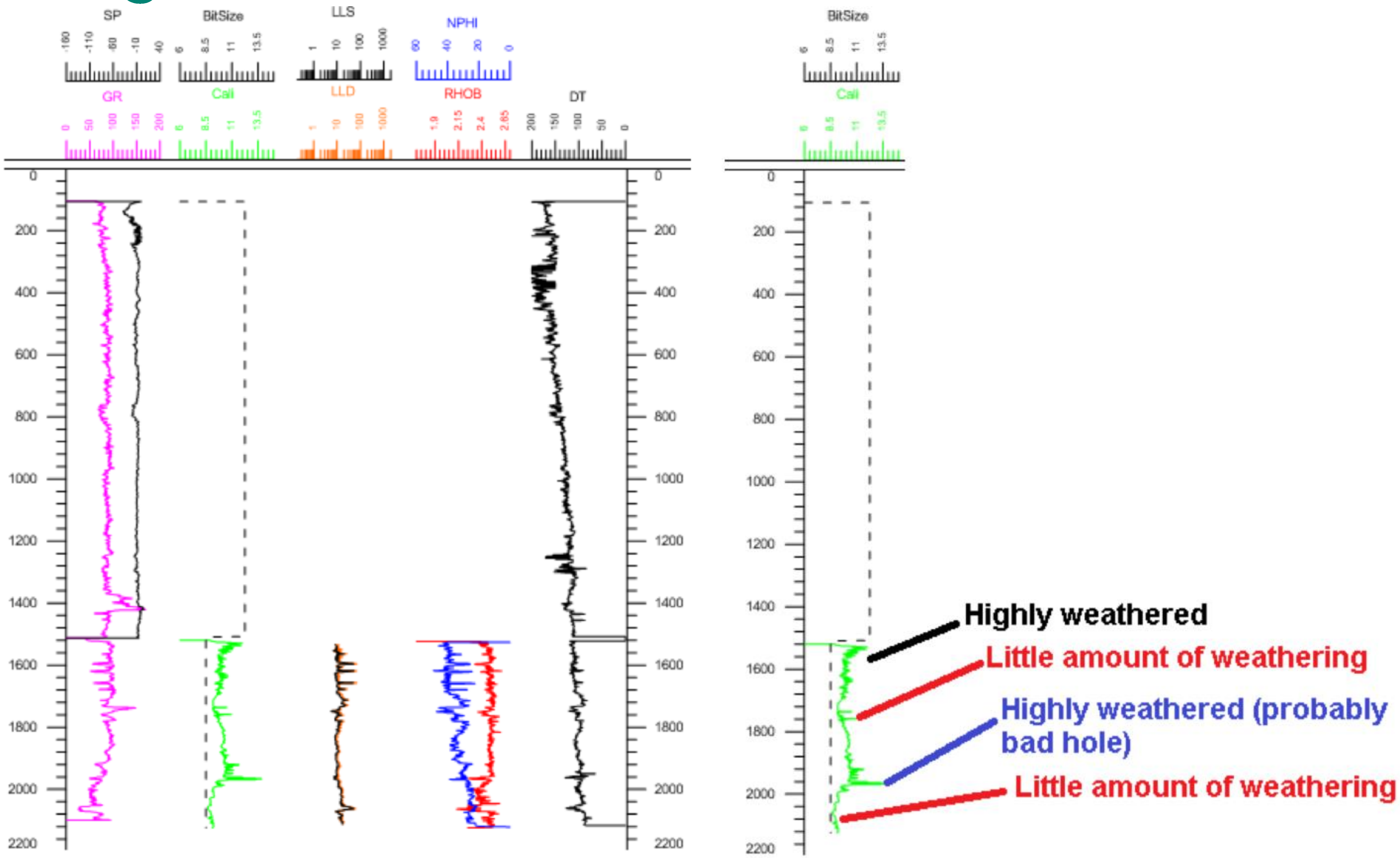
Well Log Data QC



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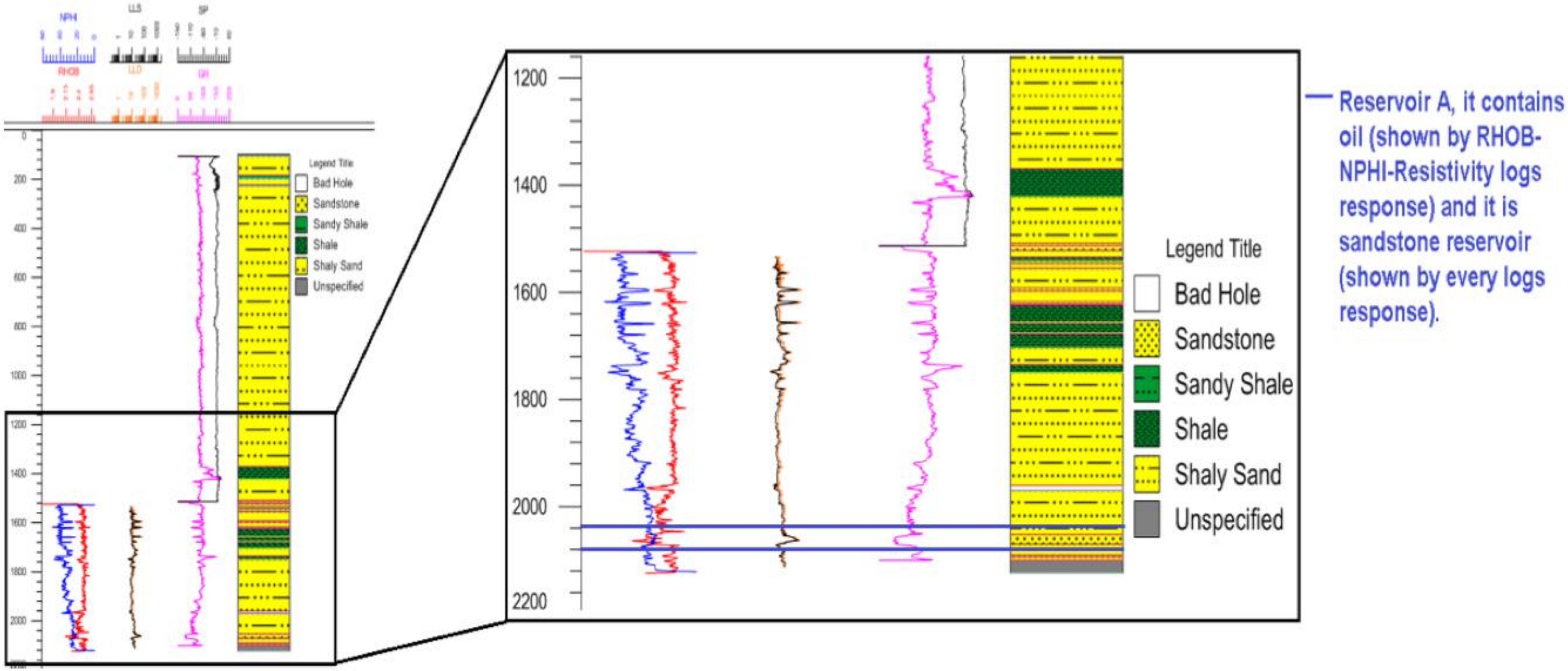
Lithology



- A combination of GR, SP, resistivity (LLD and LLS), and density log (RHOB) was used to interpret the lithology
- Four lithologies namely are sandstone, shaly sandstone, sandy shale, and shale was interpreted.

Lithology

- GR was used to differentiate shale (or shaly sand) from non-shale.
- SP was used to validate the interpretation of GR.
  - Shale has positive SP reading, while clean formation (sand) have very negative SP log reading.
- Resistivity log was also used to validate the lithology because sandstone or carbonates have high resistivity while marine shales have low resistivity.
- Formations with high resistivity can be classified as:
  - Sandstone, if the gamma ray value is low to medium
  - Carbonates, if the gamma ray value is very low
- The density log (RHOB) was used to determine the formation tightness.
  - Very high density log reading denotes a "tight" formation.
  - High RHOB with GR of 30-50 API is most likely a "tight sandstone" formation.
  - High RHOB with GR below 15 API is probably an anhydrite, which is a good cap rock.

Lithology

Petrophysical properties of some sedimentary rocks.

Lithology	Gamma Ray (API)	Spontaneous Potential (mV)	Resistivity (Ωm) [If shale resistivity is 8]	Density (gr/cm3)
Sandstone	30 – 50	Varies, very negative	10+	2.4 – 2.8
Shaly-sandstone	50 – 75	Varies, negative	8 < Resistivity < 10	Around 2.4
Sandy-shale	75 – 90	Varies, negative	Around 8	Around 2.3
Shale	Higher than 90	Higher than 0	8	Around 2.3
Anhydrite	Below 15	-	Very high, up to 100+	Up to 2.9
Coal	Varies	-	Varies	Varies, could be 1.7 – 2.2
Crystalline	Below 30	-	Very high, up to 150+	Up to 2.9
Limestone	20 – 30	-	Very high, up to 100+	2.3 – 2.7

Petrophysical Properties

- Reservoirs have lower density, lower gamma ray, and higher resistivity responses than the shoulder bed.
- A formation with low density usually has high porosity.
- The usual reservoirs such as sandstone and carbonates have very low gamma ray.
- A high gamma ray response will indicate the presence of shale, which will block the interconnected pores and thus reduce the effective porosity and permeability of the reservoirs.
- Radioactive sandstones are an exception.
- Oil and gas bearing reservoirs have higher resistivity than salt water bearing reservoirs.

Petrophysical Properties

- On a well log data, a zone of high resistivity is a good place to start the search for hydrocarbon.
- This interval should also have a good crossover between the density and neutron logs.
- Not all high resistivity readings indicate the presence of hydrocarbon; low resistivity hydrocarbon bearing reservoirs exists.
- The computed petrophysical properties are Volume of Shale (Vsh), Water Saturation (Sw), Porosity (φ), and Permeability (k)
- From the petrophysical data, the reservoir in the study well has lower shale volume content and higher permeability than the non-reservoirs.
- The reservoir also has low water saturation and high porosity.

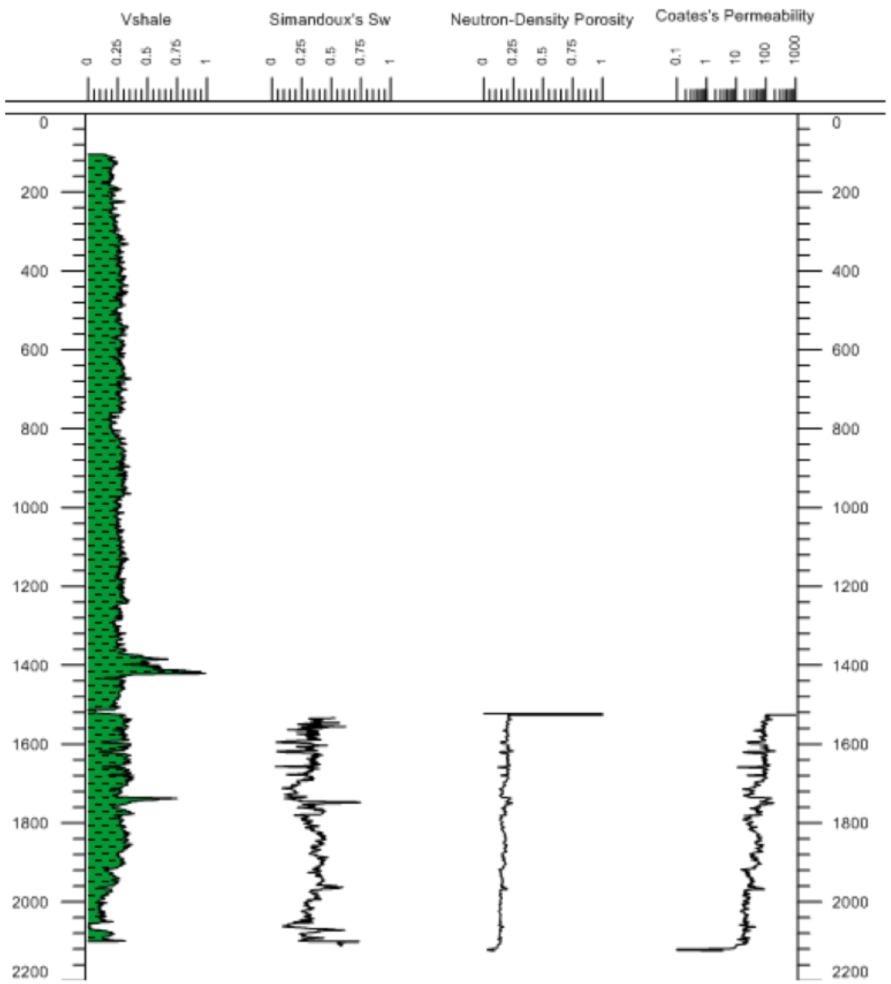
Geomechanical Properties

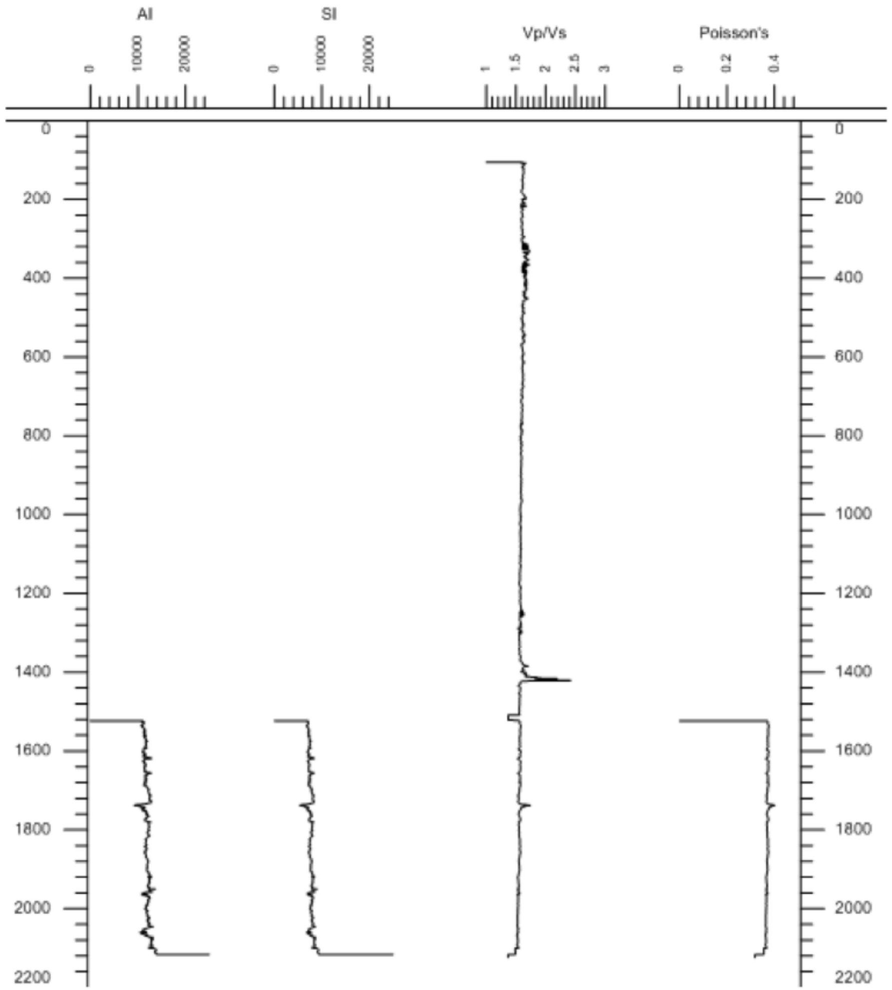
- The computed geomechanical properties are Acoustic Impedance (AI), Shear Impedance (SI), P-wave to S-wave Velocity Ratio (Vp/Vs), and Poisson's Ration (*v*).
- Hydrocarbon bearing sands exhibit a decrease in Vp (due to significant reduction of bulk modulus and a moderate reduction of density), but a little increase in Vs (due to a reduction of bulk density).
- Consequently, the combined effect is considerably lower Vp/Vs ratio in the hydrocarbon bearing sands.
- From the geomechanical data, the reservoir has low Vp/Vs ratio.
- There is also an Acoustic Impedance anomaly.

Geomechanical Properties

- Theoretically, Acoustic Impedance of a rock increases with depth.
- Acoustic Impedance anomalies are zones of interest that could contain hydrocarbon.
- They should, however, not be used in isolation but compared with other data to get accurate results.
- Reflectivity is also a hydrocarbon indicator.
- The formation has very negative and very positive reflectivity indicating large density and wave velocity differences between the reservoir and non-reservoir.
- Though, reflectivity can be used as a direct hydrocarbon indicator, it should be interpreted alongside the gamma ray, resistivity, and caliper logs.

Geomechanical Properties





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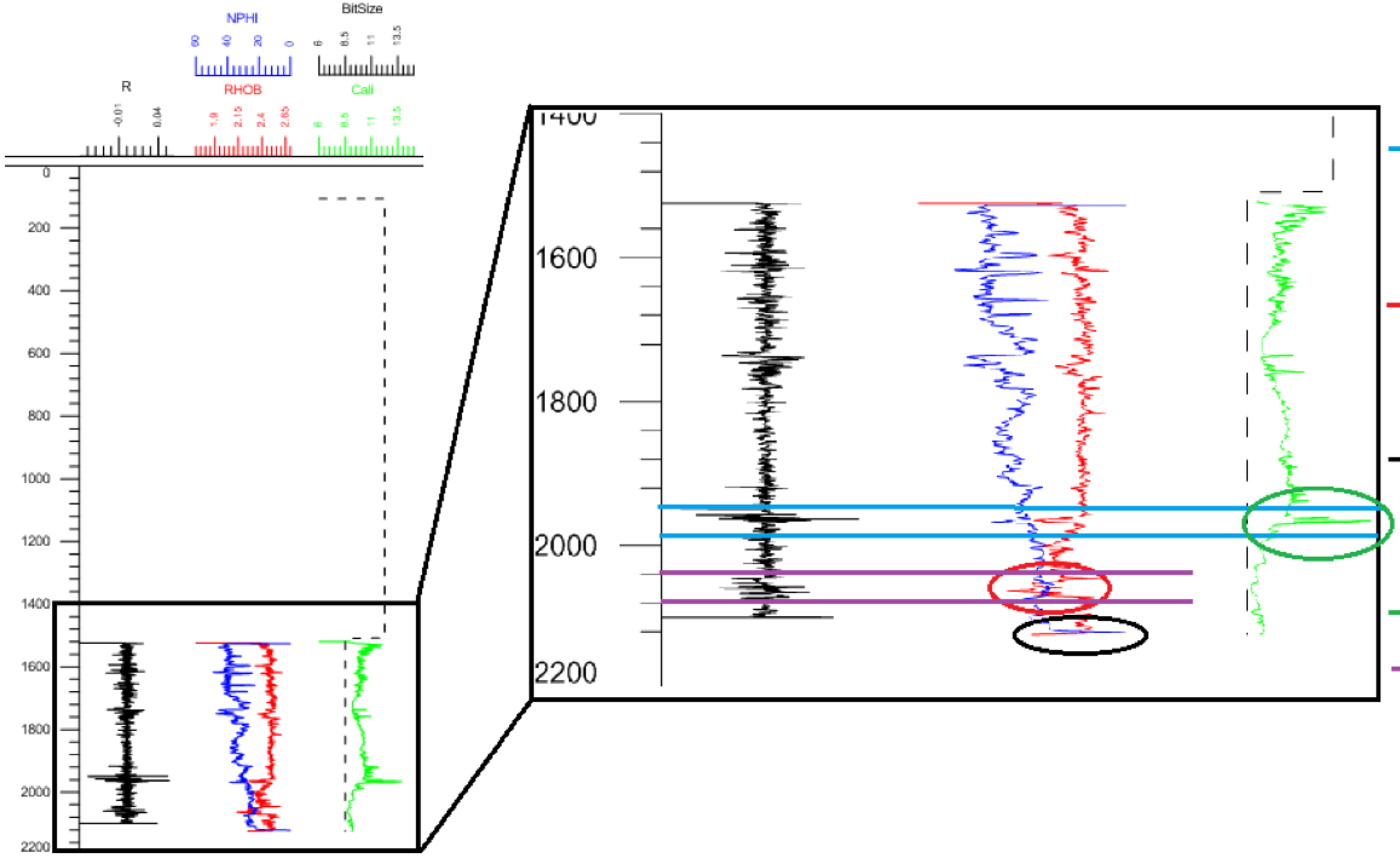
Result Interpretation



Not a Bright spot, it is an error which is caused by the bad hole.

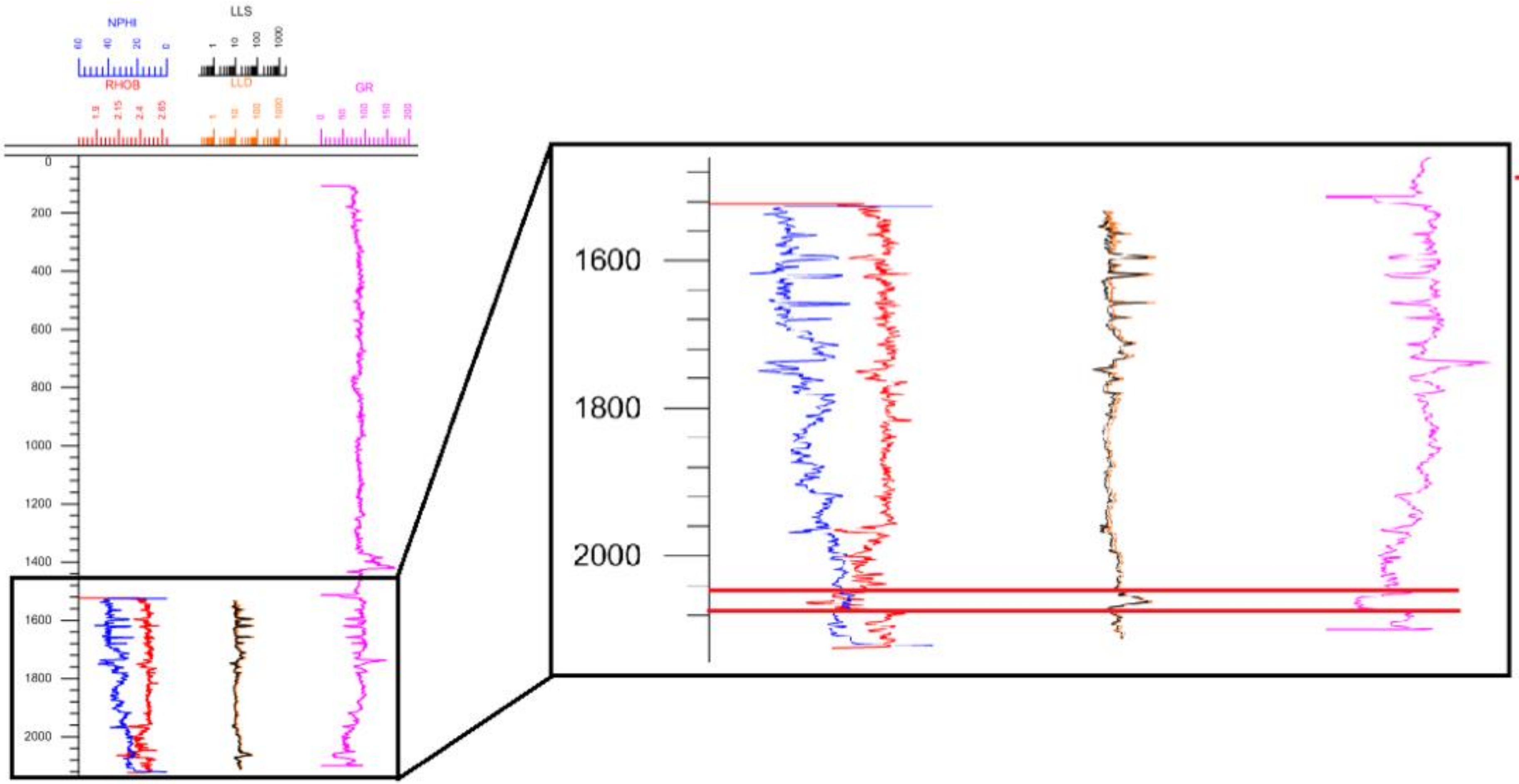
RHOB-NPHI cross over (small), an indication of hydrocarbon (oil)

RHOB-NPHI cross over (big), an indication of hydrocarbon (gas).

Bad hole.

Medium-sized reflectivity coefficient, an indication of hydrocarbon (oil).

Result Interpretation



A sandstone reservoir, indicated by low gamma ray, RHOB-NPHI cross over, and high resistivity value. This is an oil reservoir (NPHI not too low).

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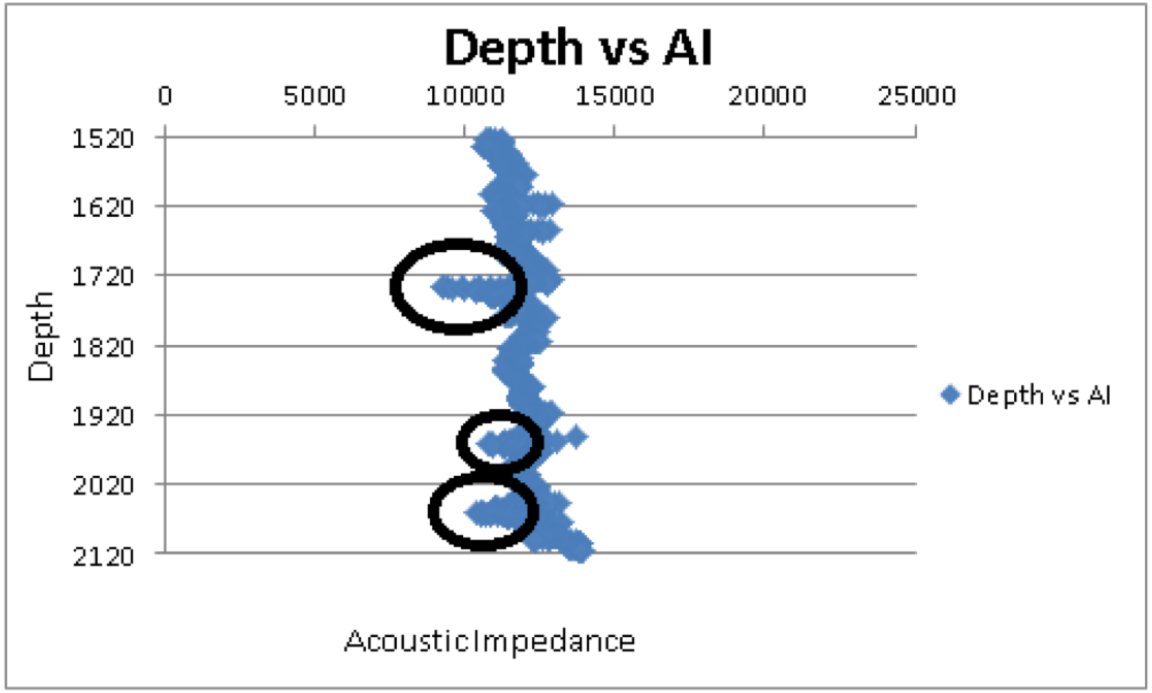
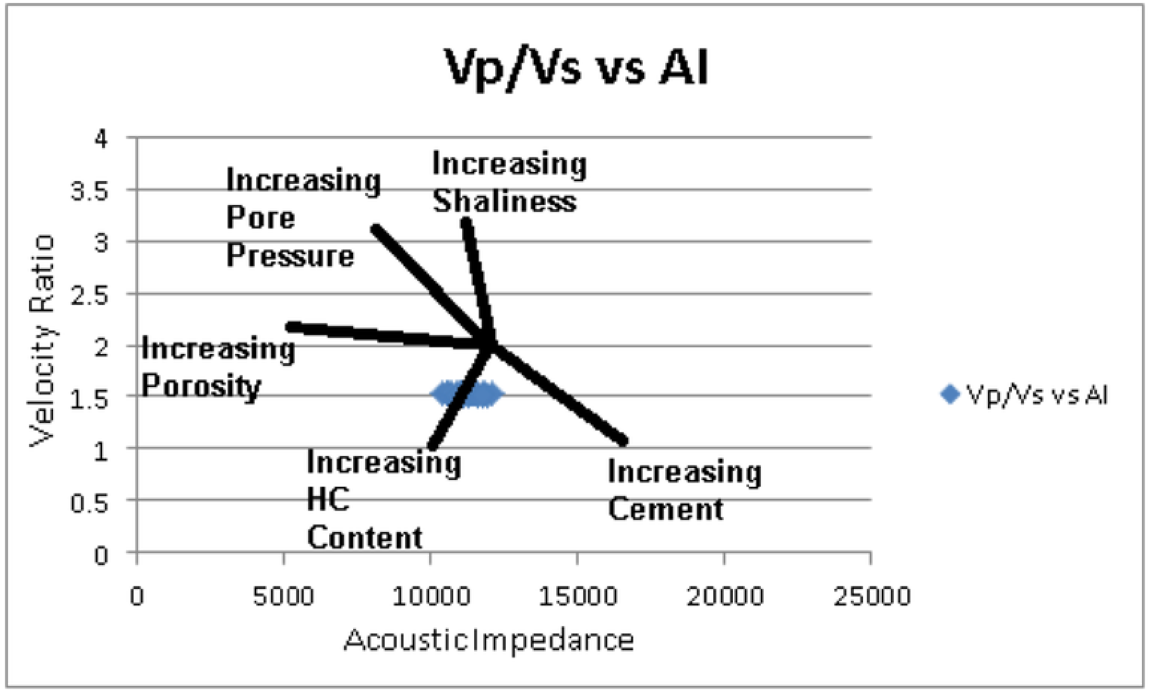
Acoustic Impedance Anomaly





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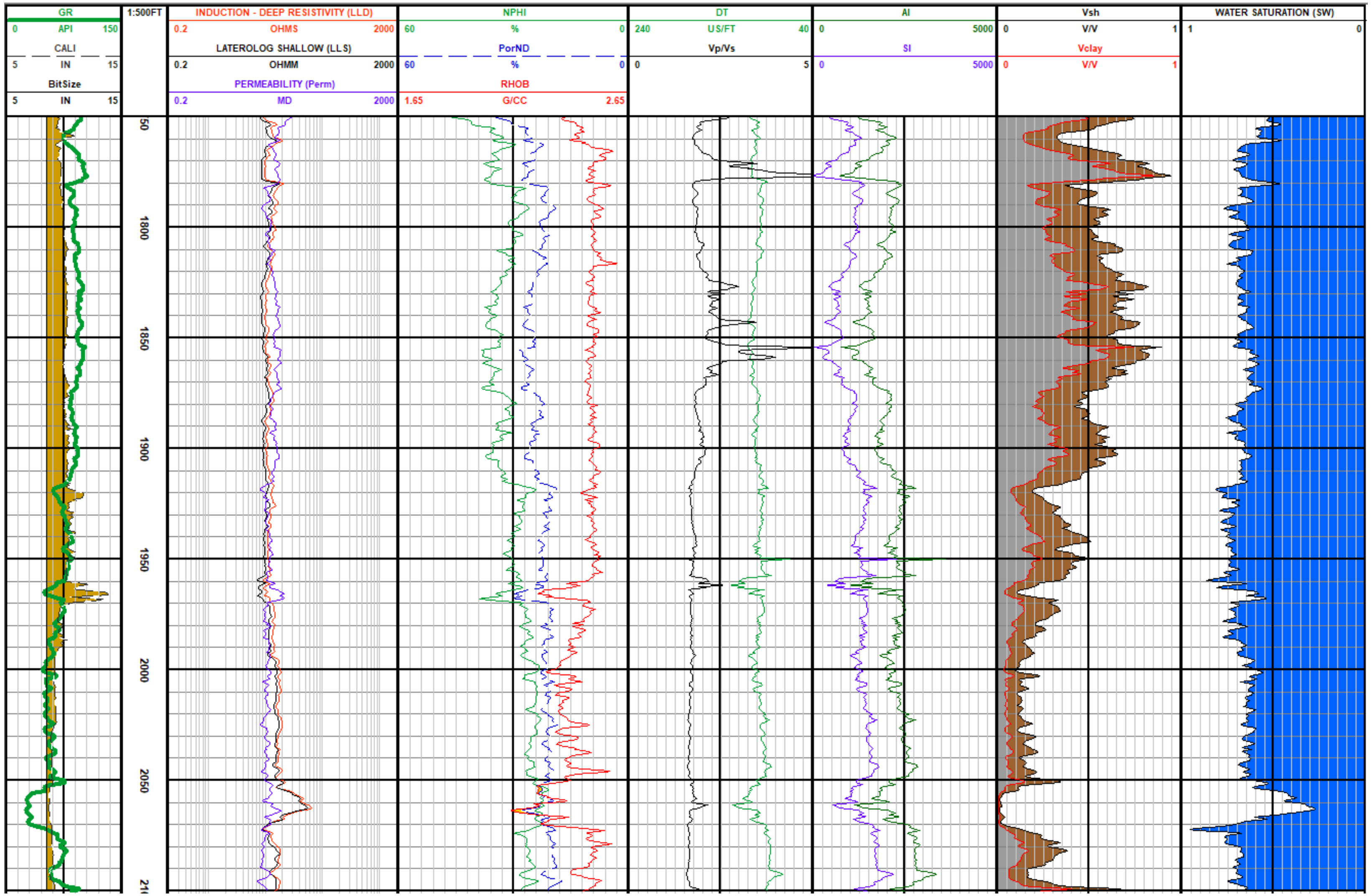
Integrated Result



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