Integrating Geological Attributes with a Multiple Linear Regression of Geophysical Well Logs to Estimate the Permeability of Carbonate Reservoirs in Campos Basin, Southeastern Brazil*

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Abstract

The knowledge of petrophysical properties of hydrocarbon reservoirs is essential for the development of an oil field. Among the main petrophysical properties, the permeability is one of the most complex to be determined, because it is not a direct measure. Its estimate can be done in different ways some of which are: formation test, empirical models with data obtained from basic or nuclear magnetic resonance (NMR) well logs or laboratory analysis of core samples or plugs. The distribution of petrophysical properties in carbonate rocks, when compared to siliciclastic, tends to be more heterogeneous due to diagenetic processes that they suffer and, therefore, the more complex is its determination. Thus, a more accurate analysis can be performed by combining the contributions of different sources to estimate the permeability. The well logs and the laboratory data from two wells (A3 and A10) drilled in a carbonate reservoir of Campos Basin were used in this work to asses the permeability using different approaches, such as multiple linear regression (MLR), rock types and empirical models, integrating available geological attributes in order to validate the study in a qualitative way. Campos is a sedimentary basin located along the continental margin of Southeastern Brazil, which has several oil fields. The basin covers an area of approximately 100,000 km^2, corresponds to the main oil province of Brazil, comprising approximately 80% of the country's oil reserves. Hydrocarbon reservoirs occur throughout almost the entire stratigraphic column of this basin, being that the main sequences consist of fractured basalts, coquinas, turbidites, and carbonate rocks. Therefore, the results of the study of this carbonate reservoir indicate that the permeability estimated by MLR method associated with reservoir zoning based on environmental energy zones is one that comes closest of laboratory data.

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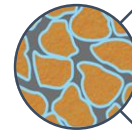
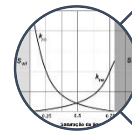
SUMMARY

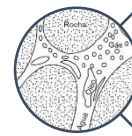
- Introduction
- Goals & Motivation
- Review of Concepts
- Methodology
- Results and Analysis
- Conclusions
- References

INTRODUCTION

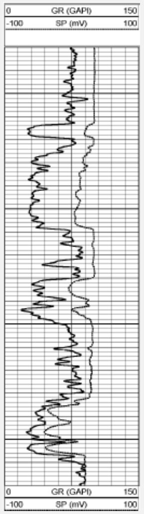
Reservoir Characterization → Determination of petrophysical properties


Porosity

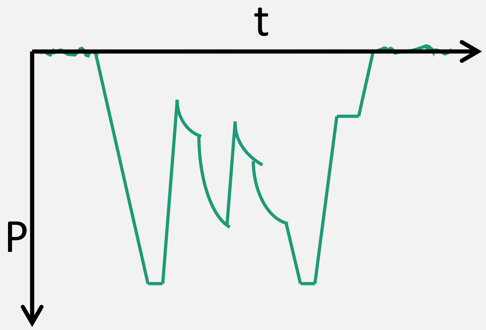

Permeability


Fluids Saturation

Cores and Plugs



Logs



Formation Tests

GOALS

- Study the various ways of determining permeability using well logs.

MOTIVATION

- Inability to extract cores and plugs in all the wells of an oil field.

GEOLOGICAL CONTEXT

Oilfield A

Oilfield A is located in the Campos Basin, in a water depth of approximately 105 meters. It comprises carbonate reservoirs of the Albian age, belonging to the Macae Group of the Quissama Formation, formed approximately 110 million years ago. These reservoirs are predominantly oncolytic grainstones formed in high energy banks of carbonate platforms.

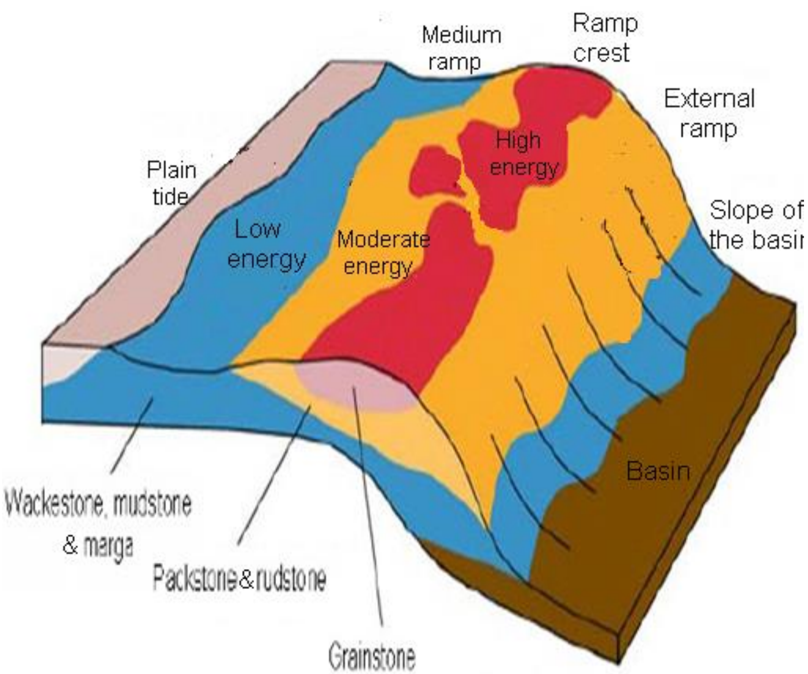


Figure 1. Scheme of a carbonate ramp with structural high. Adapted from LUCIA (2007).

REVIEW OF CONCEPTS

Well Logs

Table 1. Relationship between the parameters measured by the profiles and their derived properties (adapted from Rider, 2000).

Log	Measured Parameter	Derivative Property/Information
Gamma rays	Total U, Th, and K content of formations	Lithology/argilosity/hydrocarbon generation
Resistivity	Resistivity of areas furthest from well walls	Resistivity of large volumes of rock
Microrresistivity	Resistivity of regions closer to well walls	Resistivity of small volumes of rock
Density	Quantity of electron per unit volume of rock	Porosity / density of rocks
Sonic	Time an elastic wave takes to travel 1 foot of well wall	Porosity / velocity / elastic constants of rocks
Neutronic	Quantity of hydrogen element per unit volume of rock	Porosity / presence of light hydrocarbons in rocks

REVIEW OF CONCEPTS

Resistivity Log

- It measures the resistivity of a rock volume through the induction of electric current in the porous medium.

$$R = \frac{U}{I}$$

- Water Saturation (ARCHIE, 1942):

$$S_w = \left(\frac{a}{\boldsymbol{\phi}^m}\frac{R_w}{R_t}\right)^{\frac{1}{n}}$$

- It assists in determining the geometry of the reservoir: hydrocarbon top and oil-water contact.

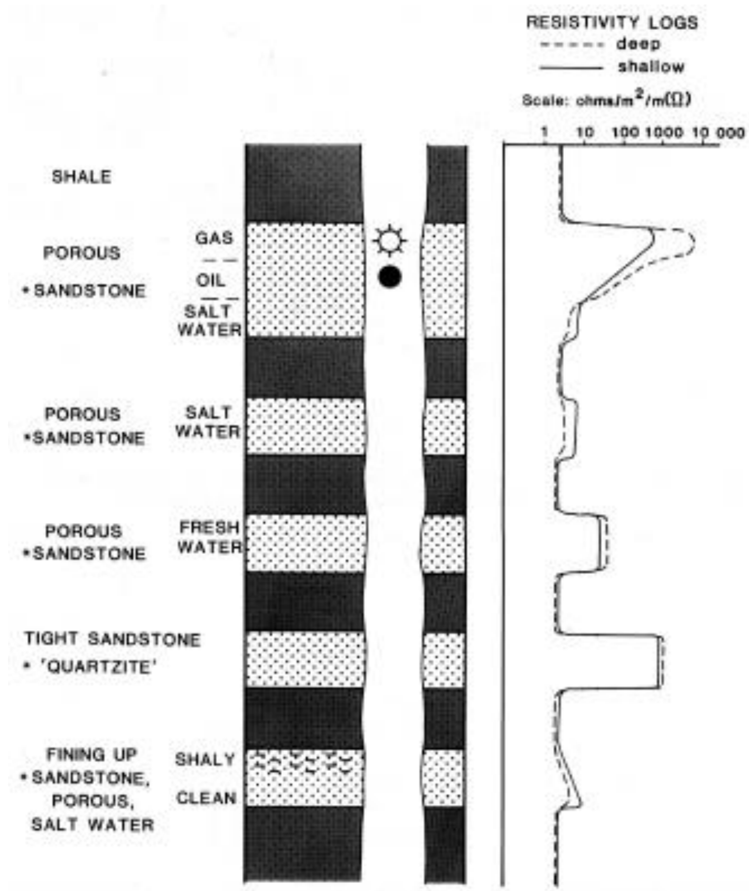


Figura 2. Perfil de resistividade sintético. (Adaptado de RIDER, 2000).

REVIEW OF CONCEPTS

Gamma Rays Log

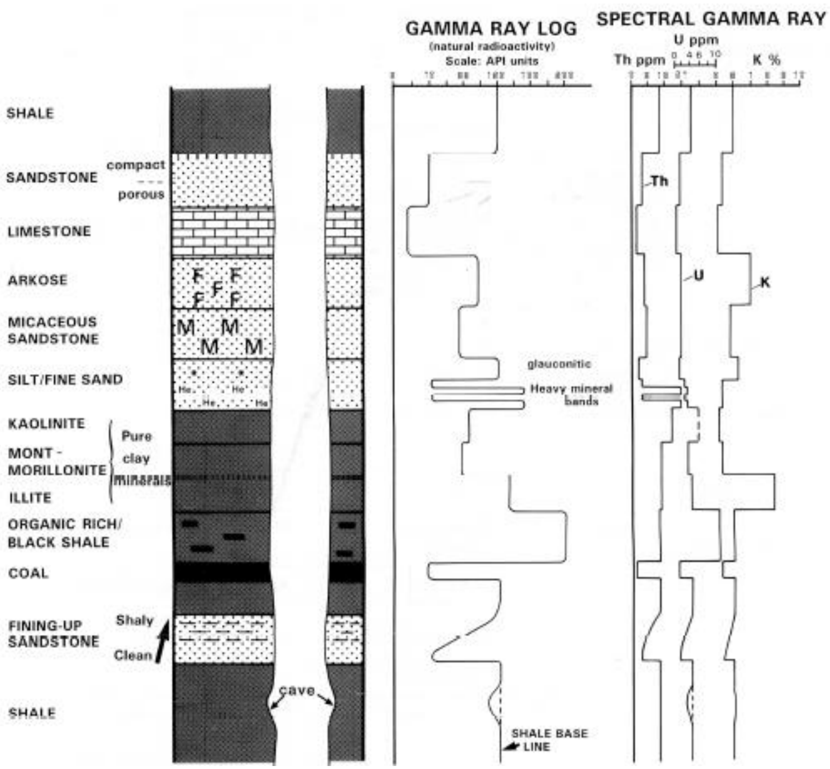


Figure 3. Granulometric variation according to the gamma ray loge (adapted from RIDER, 2000).

- It measures the total U, Th and K content of the formations and is used to measure the clay content of the rocks.
- Qualitative distinction between facies, sequences and types of lithology (RIDER, 2000).

REVIEW OF CONCEPTS

Porosity Logs

Sonic: measures the time that an elastic wave takes to travel a unit length in the medium in which it propagates.

$$\boldsymbol{\phi}_s = \frac{\Delta t_{perfil} - \Delta t_{ma}}{\Delta t_{fluido} - \Delta t_{ma}}$$

Neutron: measures the amount of hydrogen element per unit volume of rock. Usually, the profile response is directly considered to be the porosity value.

Density: measures the amount of electron per unit volume of rock.

$$\boldsymbol{\phi}_D = \frac{\rho_{perfil} - \rho_{ma}}{\rho_{fluido} - \rho_{ma}}$$

METHODOLOGY

Regression models for determination of permeability

Simple linear regression :

$$\log(k) = a\phi + b$$

Exponential regression :

$$\log(k) = ae^{b\phi}$$

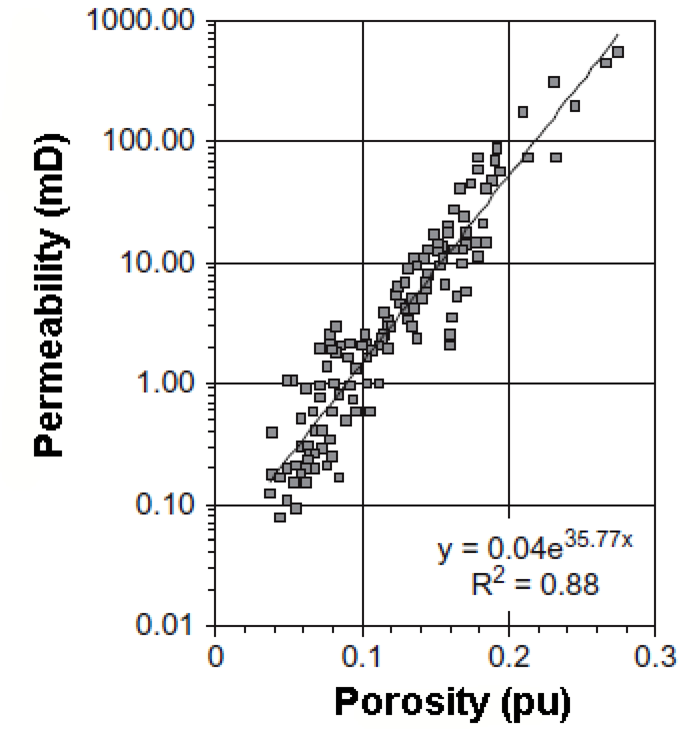


Figure 4. Porosity versus permeability (sandstone, Rotliegend). Adapted from SCHÖN (2015).

METHODOLOGY

Empirical models for determination of permeability

Kozeny-Carmen Equation: **Kozeny (1927)** **Carmen (1937)**	$k = \frac{1}{K_T S_{V_{gr}}^2} \frac{\phi^3}{(1-\phi)^2}$	K_T: constant of Kozeny that depends on the tortuosity. $S_{V_{gr}}$: specific surface area ϕ: porosity
Tixier (1949)	$k^a = c \frac{\phi^b}{S_{w_{irr}}}$	$S_{w_{irr}}$: irreducible saturation of water a, b e c: parameters dependent on grain size, saturation distribution and rock diagenesis.

METHODOLOGY

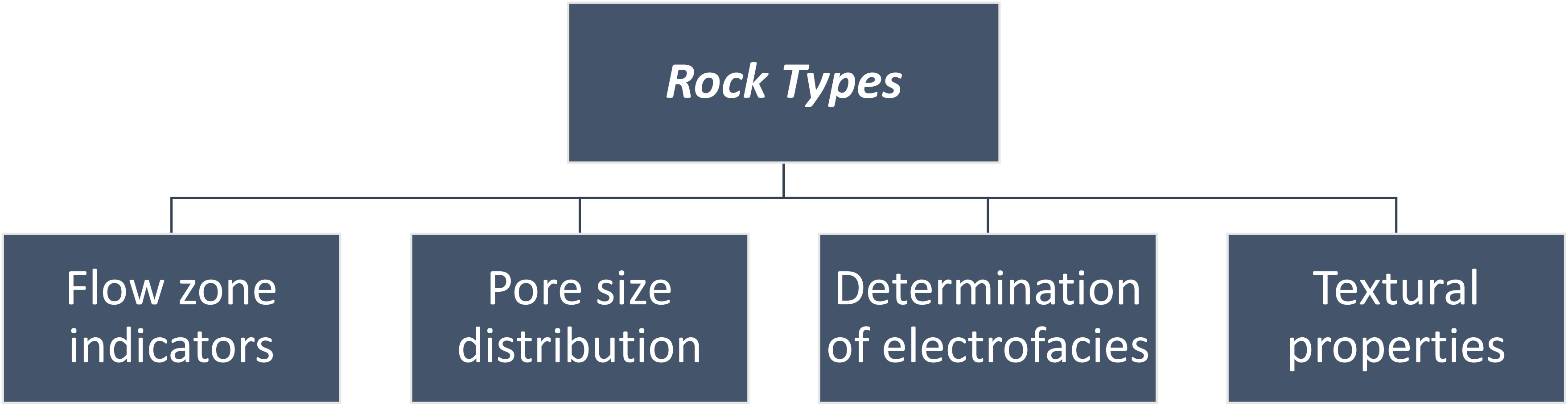
Empirical models for determination of permeability

Timur (1968)	$k^{0,5} = 93\,\frac{\phi^{2,2}}{S_{w_{irr}}}$	$S_{w_{irr}}$: irreducible saturation of water ϕ: porosity
Coates & Dumanoir (1974)	$k^{0,5} = \frac{300}{w^4}\frac{\phi^w}{S_{w_{irr}}^w}$ $w^2 = (3{,}75 - \phi) + \frac{1}{2}\left[log_{10}\left(\frac{R_w}{R_{ti}}\right) + 2{,}2\right]$	R_w: water formation resistivity R_t: formation resistivity
Coates & Denoo (1981)	$k^{0,5} = \frac{100(1 - S_{w_{irr}})\phi^2}{S_{w_{irr}}}$	$S_{w_{irr}}$: irreducible saturation of water ϕ: porosity

METHODOLOGY

Rock Types

It is a classification that allows to group categories of reservoir rocks that have similar petrophysical characteristics..



METHODOLOGY

Flow Zone Indicators (FZI)

Flow zone: continuous body along the volume of a reservoir that exhibits similar petrophysical and fluid properties (Amaefule *et al,* 1988).

From the Kozeny-Carmen equation, Amaefule et l. (1988) defined the concept of reservoir quality index (RQI).

$$k = \frac{1}{K_T S_{V_{gr}}^2} \frac{\phi^3}{(1-\phi)^2} \quad \Rightarrow \quad k = \frac{1}{K_T S_{V_{gr}}^2} \frac{\phi^2 \phi}{(1-\phi)^2}$$

Eq. Kozeny-Carman

METHODOLOGY

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$$k = \frac{1}{K_T S_{V_{gr}}^2} \frac{\phi^3}{(1-\phi)^2} \quad \Longrightarrow \quad \frac{k}{\phi} = \frac{1}{K_T S_{V_{gr}}^2} \frac{\phi^2}{(1-\phi)^2}$$

Eq. Kozeny-Carman

METHODOLOGY

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Eq. Kozeny-Carman

METODOLOGIA

Flow Zone Indicators (FZI)

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$$k = \frac{1}{K_T S_{V_{gr}}^2} \frac{\phi^3}{(1-\phi)^2}$$

Eq. Kozeny-Carman

$$\underbrace{\sqrt{\frac{k}{\phi}}}_{RQI} = \underbrace{\frac{1}{\sqrt{K_T} S_{V_{gr}}}}_{FZI} \underbrace{\frac{\phi}{(1-\phi)}}_{\phi_Z}$$

RQI$= FZI \times \phi_z$

METHODOLOGY

Flow Zone Indicators (FZI)

$$RQI = \phi_z \times FZI$$

$$\log(RQI) = \log(\phi_z) + \log(FZI)$$

$$y = ax + b$$

$$a = 1 = tg45°$$

According to Tiab (2000), the FZI is a unique parameter that includes geological attributes of texture and mineralogy in the structure of facies.

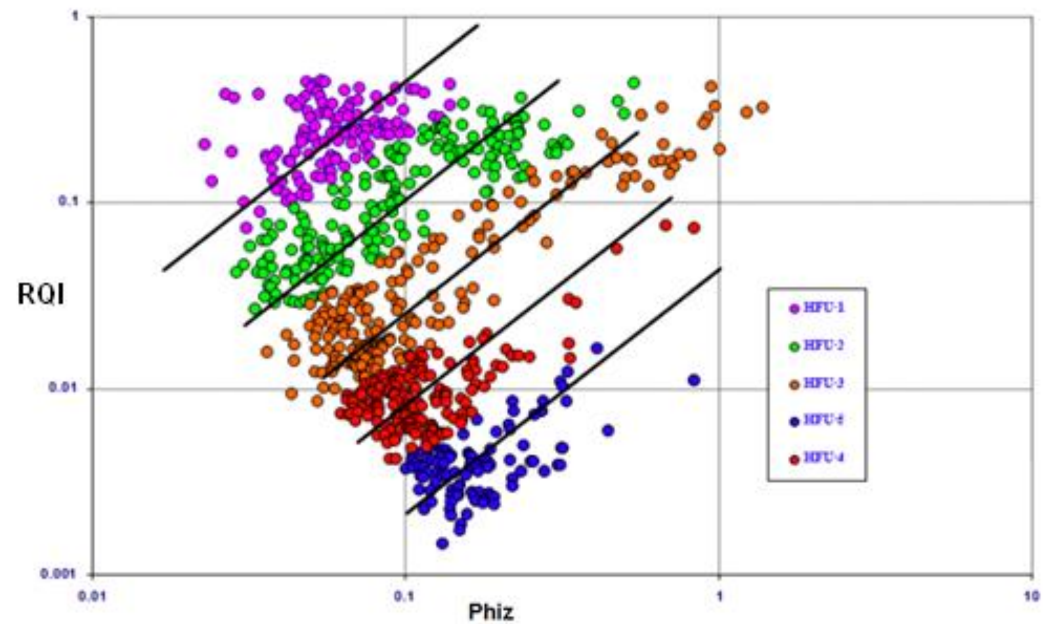


Figure 5. Log-log graph of reservoir quality index (RQI) versus normalized porosity (Phiz). Adapted from BORHANI (2011).

METHODOLOGY

	Wells	
Data	**A3**	**A10**
Density log	√	√
Sonic log	√	√
Gamma rays log	√	√
Resistivity log	√	√
Neutronic log	√	√
Caliper	√	√
Permeability from plugs	√	√
Porosity from plugs	√	√
Gradient temperature	√	√
Core pictures	√	X
Facies description	√	√

Figure 6. List of available data.

Data Set

Data provided by PETROBRAS from two wells, A3 and A10, drilled in a carbonate reservoir located in Field A in the Campos Basin.

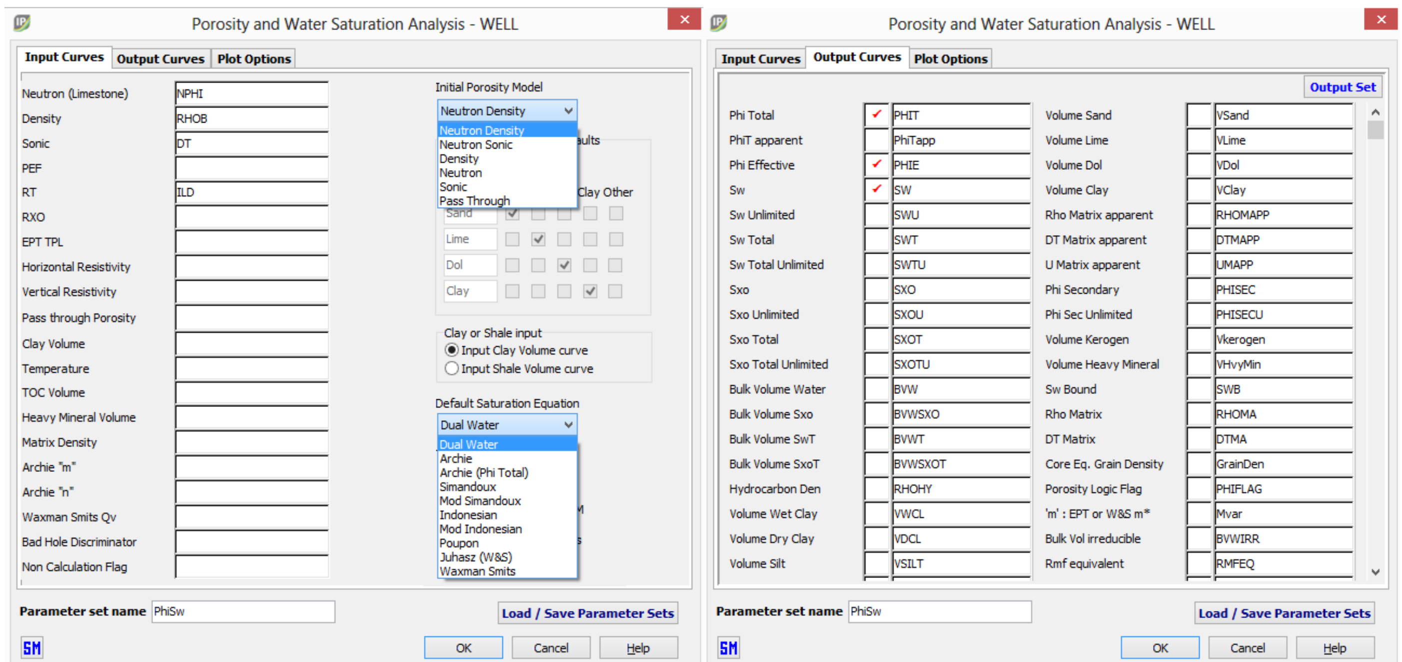
METHODOLOGY

Interactive Petrophysics®

Interactive Petrophysics is Senergy's commercial software used for various applications in the fields of petrophysics, geology and reservoir engineering. The version used was the 4.2 granted in the form of an academic license to LENEP / UENF.

(a)

(b)



(a) (b)

Figure 7. Interface of the porosity and water saturation module of the Interactive Petrophysics software: (a) Input curves and models. (b) output curves.

METHODOLOGY

Data Processing

- Data processing:
  - Adjusting log with laboratory data.
  - Disposal of permeability data obtained in the laboratory with values equal to or less than 0.1 mD.

- Calculation of porosity and water saturation logs.

- Analysis and interpretation of the logs in the limits of the reservoir.

Table 2. Data used to interpret the logs. Source: ICCR / SCTC - Petrobras Covenant (2014)

Data	Well A3	Well A10
Water formation resistivity - Rw	0,0437 $ohm.m$	0,0437 $ohm.m$
Sea water blade	104,5 m	105 m
Gradient temperature	47 $°F/Km$	49,2 $°F/Km$
Sea bottom temperature	59,4 $°F$	59,4 $°F$
Matrix density (reservoir)	2,71 g/cm^3	2,71 g/cm^3
Fluid density	0,85 g/cm^3	0,85 g/cm^3
Saturation exponent, n	2	2
Cementing exponent, m	2	2
Matrix transient time	46,7 $\mu s/pé$	46,7 $\mu s/pé$
Fluid transient time	189 $\mu s/pé$	189 $\mu s/pé$
Salinity of the reservoir	90000 ppm	90000 ppm

RESULTS

Logs interpretation Well A3

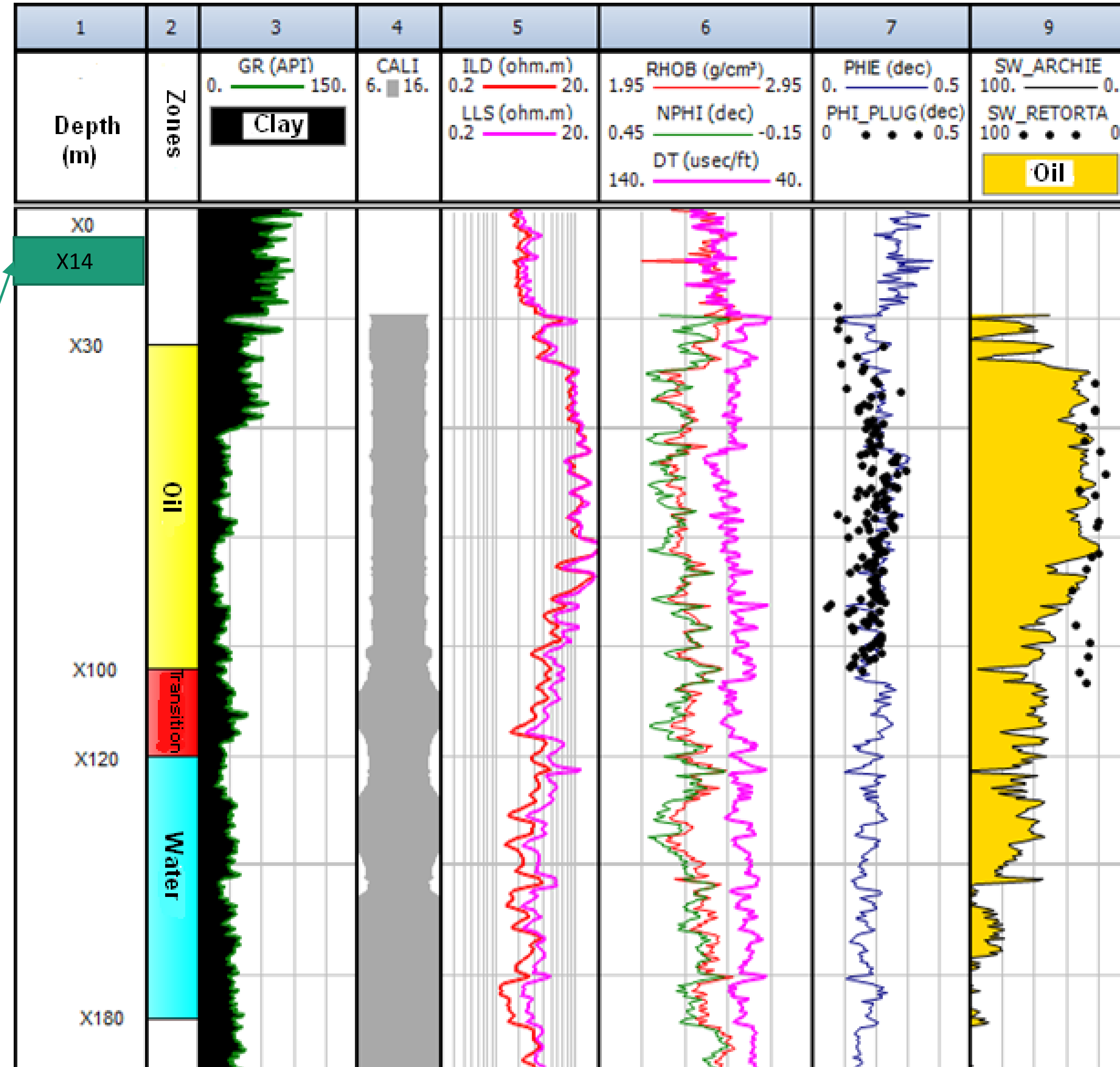


Figure 8. Logs interpretation – Well A3.

RESULTS

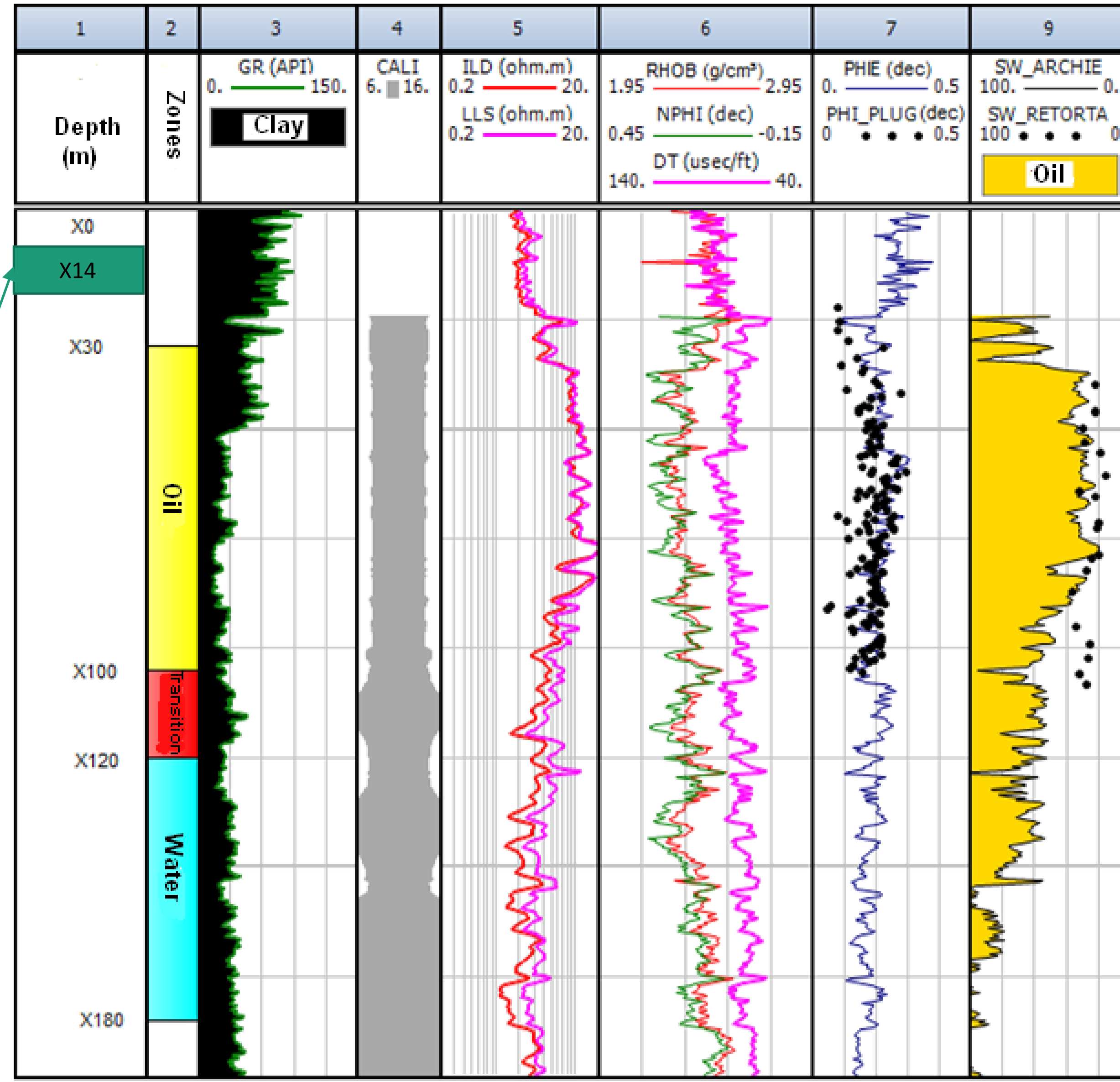


Figure 8. Logs interpretation – Well A3.

RESULTS

Permeability estimation

1. Simple linear regression

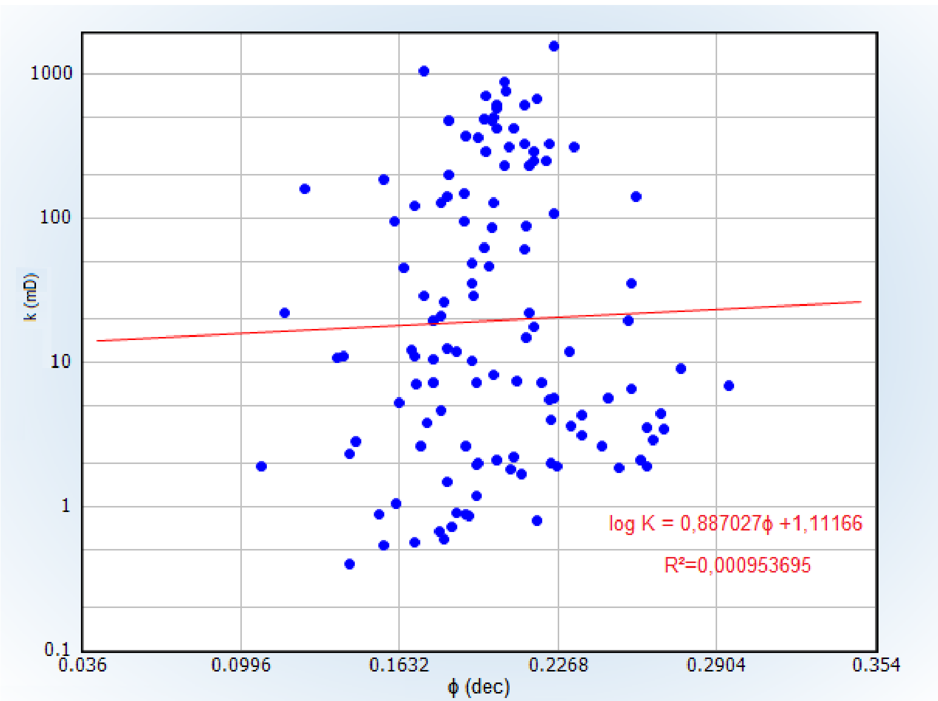


Figure 9. Simple regression between porosity and permeability - Well A3.

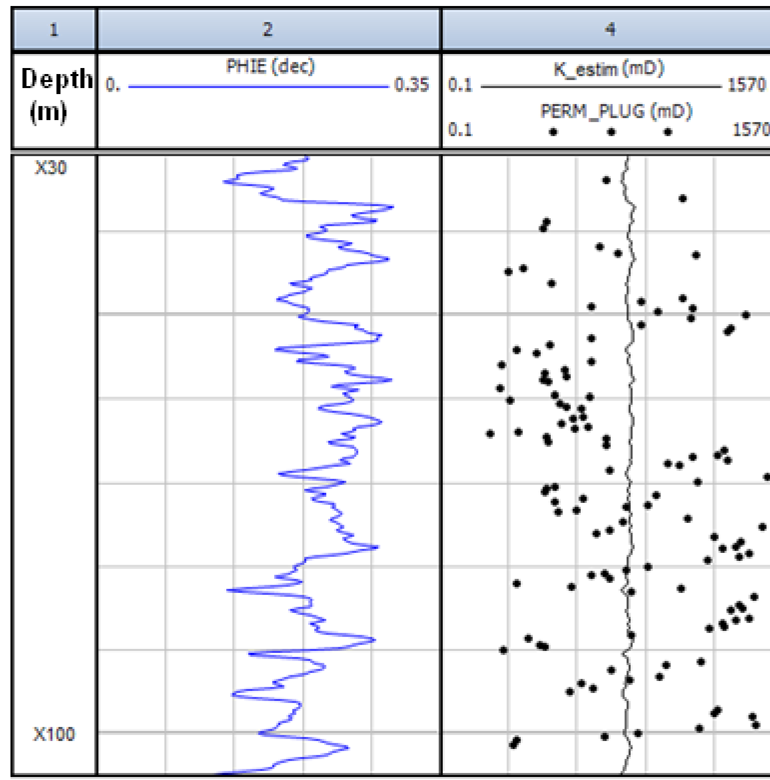


Figure 10. Permeability log estimated by simple regression - Well A3.

RESULTS

Permeability estimation

2. Empirical models

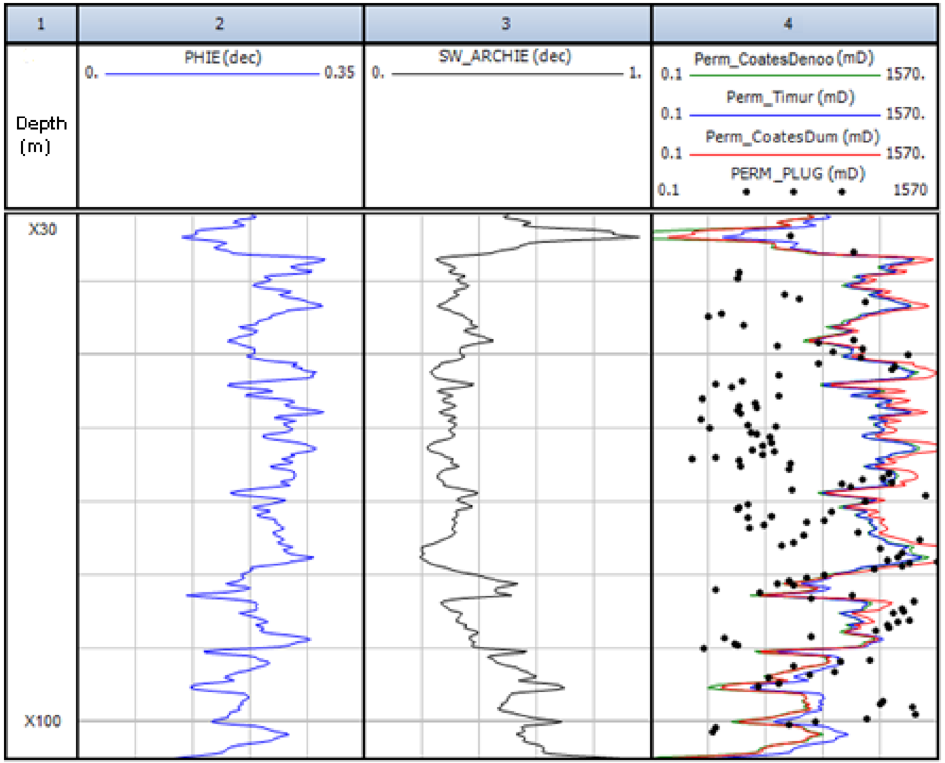


Figure 11. Permeabilities estimated by empirical models.

AUTHOR	MODEL	CORRELATION
Timur (1968)	$k^{0,5} = 93\frac{\phi^{2,2}}{S_{w_{irr}}}$	R^2 =0,00365
Coates & Dumanoir (1974)	$k^{0,5} = \frac{300}{w^4}\frac{\phi^w}{S_{w_{irr}}^w}$	R^2 =0,01884
Coates & Denoo (1981)	$k^{0,5} = \frac{100(1-S_{w_{irr}})\phi^2}{S_{w_{irr}}}$	R^2 =0,00799

RESULTS

Permeability estimation

3. Multiple linear regression from logs

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \varepsilon$$

Y: dependent variable
X_i: independent variables
β_i: regression coefficients
ε: error

Table 3. Correlation matrix between the logs available for Well A3.

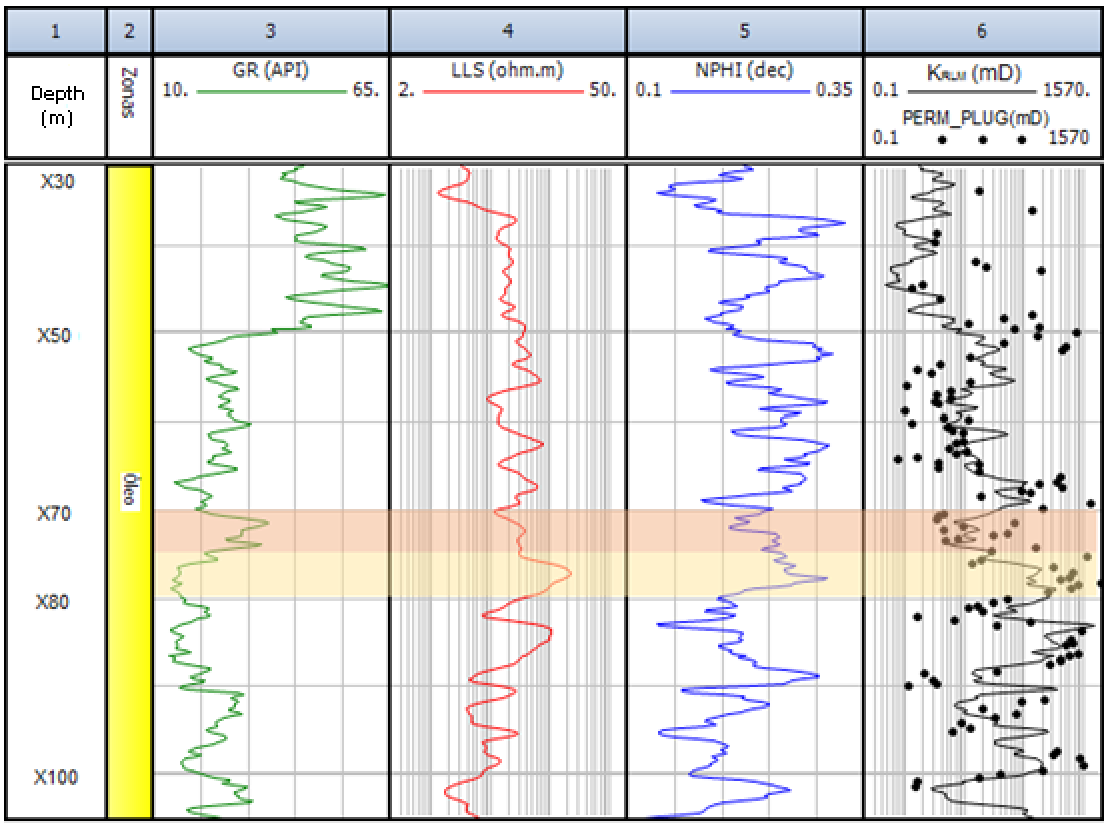
	DT	GR	ILD	NPHI	RHOB	LLS
DT	1					
GR	0,013484	1				
ILD	0,150604	0,082908	1			
NPHI	0,364891	1,96E-05	0,128766	1		
RHOB	0,514586	0,002702	0,143919	0,710218	1	
LLS	0,07198	0,132784	0,91022	0,064259	0,086757	1

RESULTS

Permeability estimation

3. Multiple linear regression from logs

$$Log(K_{RLM}) = 3{,}307 + 1{,}019 \times Log(LLS) - 3{,}919 \times Log(GR) - 3{,}699 \times Log(NPHI)$$



$R^2 = 0{,}245243$

Figure 12. Permeability log estimated by multiple linear regression - Well A3.

RESULTS

Permeability estimation

4. Flow Zone Indicators

$$RQI = \sqrt{\frac{k}{\phi}}$$

$$Phiz = \frac{\phi}{(1-\phi)}$$

$$FZI = \frac{RQI}{Phiz}$$

The FZI values found ranged from 0 to 8.

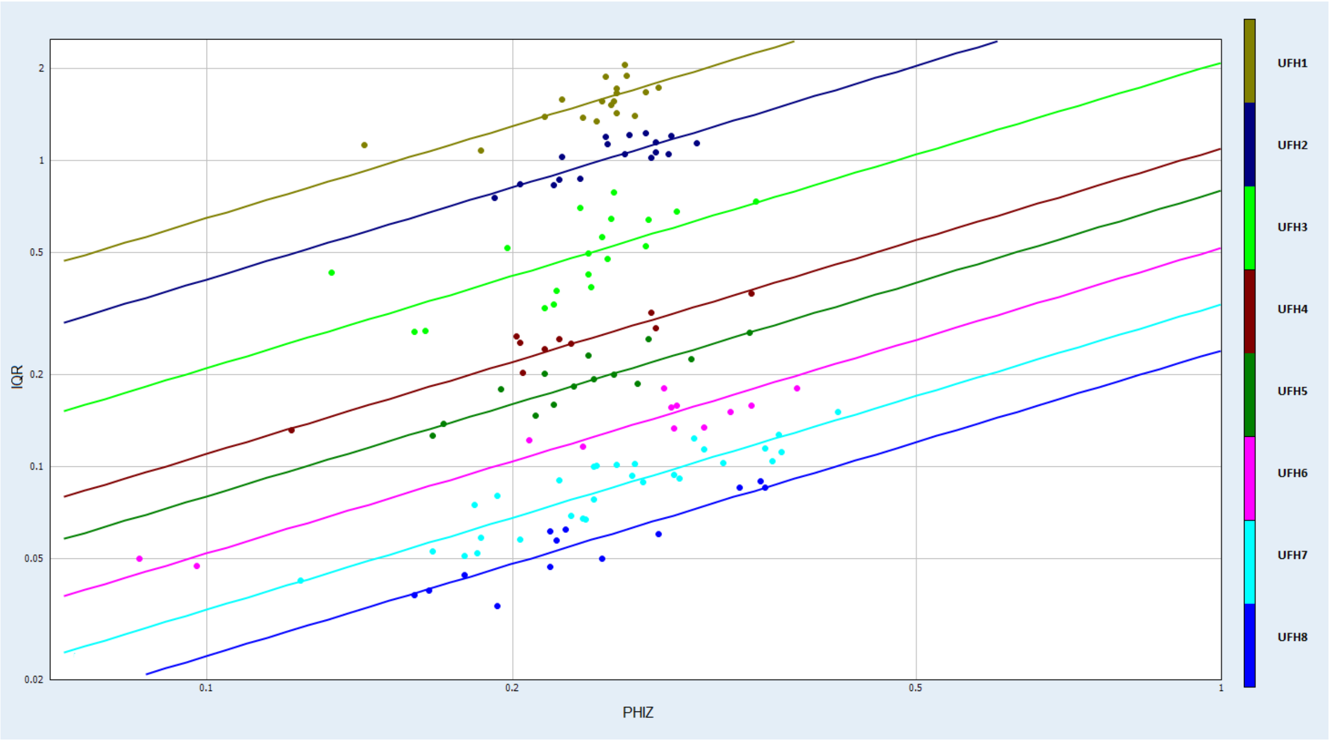


Figure 13. Division of FZI values into eight intervals, or eight hydraulic flow units - well A3.

RESULTS

Permeability estimation

4. Flow Zone Indicators

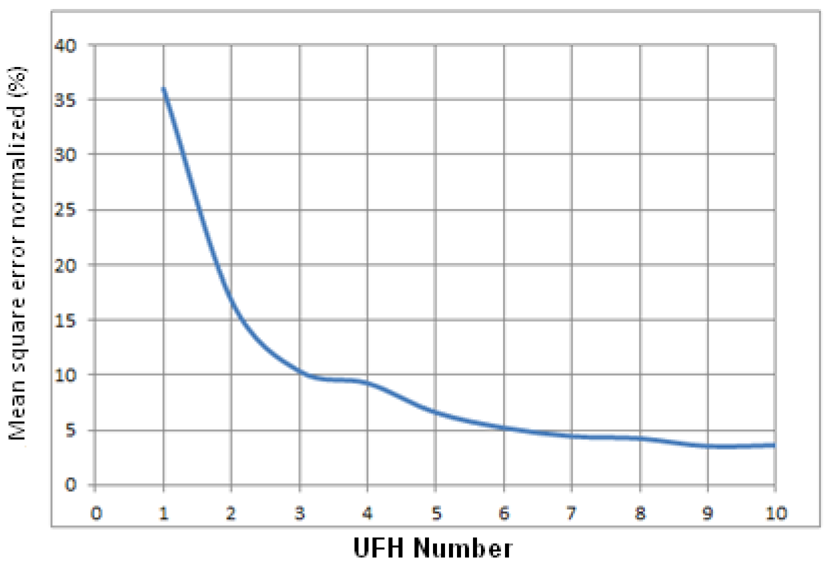


Figure 14. Mean square error normalized according to the number of UFH.

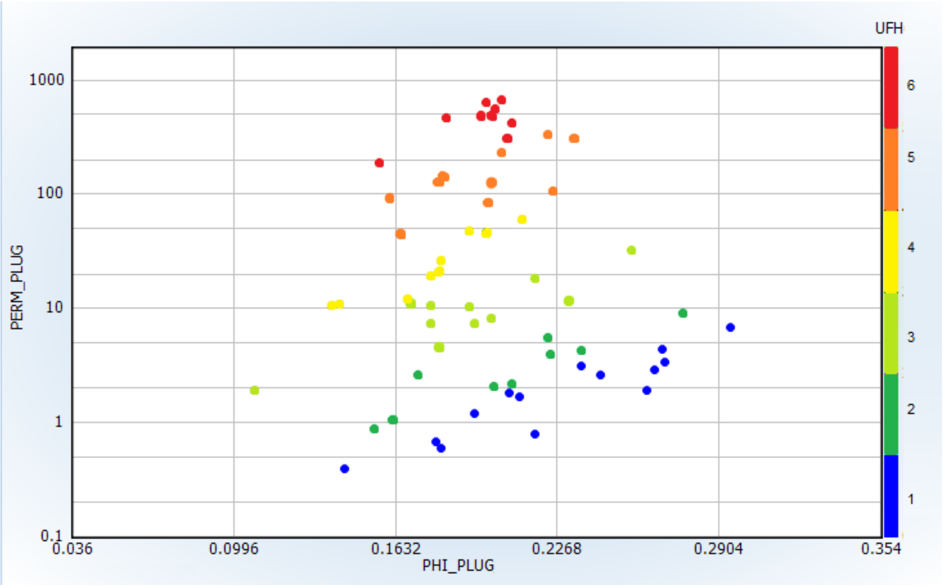


Figure 15. Laboratory porosity versus permeability - Well A3. Data were classified according to each of the six zones found.

RESULTS

Permeability estimation

4. Flow Zone Indicators

Table 4. Reservoir divided into rock types - Well A3.

Flow zones	FZI	Relationship k - ϕ	Correlation R^2	Predominant facies
UFH1	0-0,371	$Log(k) = -1{,}5002 + 7{,}67175\phi$	0,857665	Mudstones ans marls, oncolytic wackestones with partial cement, cimented rocks
UFH2	0,371-0,648	$Log(k) = -1{,}17003 + 7{,}80773\phi$	0,854953	Brescia and pebbles with cemented fractures
UFH3	0,648-1,292	$Log(k) = -0{,}461503 + 7{,}41864\phi$	0,780209	Oncolytic and peloid packstones
UFH4	1,292-2,214	$Log(k) = -0{,}551592 + 10{,}8653\phi$	0,872405	Oncolytic grainstones with peloids and moderate to high cimentation
UFH5	2,214-4,379	$Log(k) = -0{,}650861 + 7{,}49462\phi$	0,498868	Medium to coarse oncolytic grainstones with small cimentation
UFH6	4,379-8	$Log(k) = 1{,}16024 + 7{,}70159\phi$	0,444213	Oncolytic grainstones with few vugs and rare to partial cimentation

$$Log(IZF) = 3{,}261 + 0{,}217 \times Log(LLS) - 1{,}694 \times Log(GR) - 4{,}356 \times NPHI$$

RESULTS

Permeability estimation

4. Flow Zone Indicators

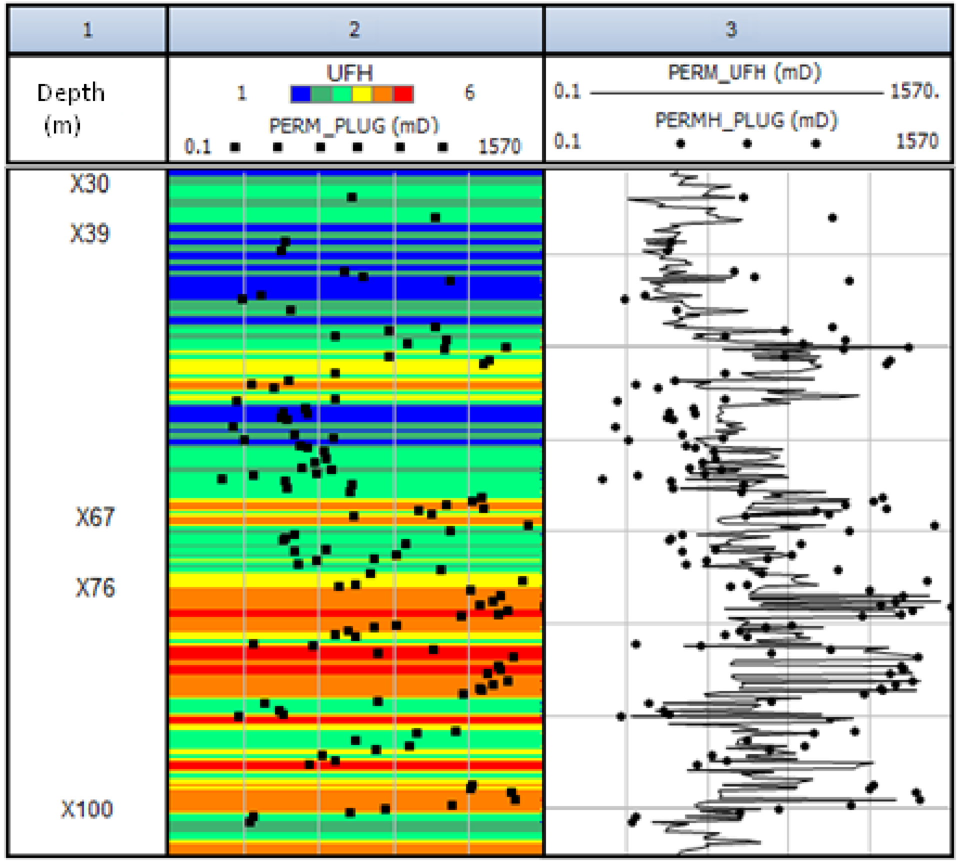


Figure 16. Permeability log estimated by IZF and flow zones - Well A3.

Figure 17. Core in X67. Bioturbated oolytic grainstone belonging to UFH 5 - Well A3.

RESULTS

Permeability estimation

4. Flow Zone Indicators

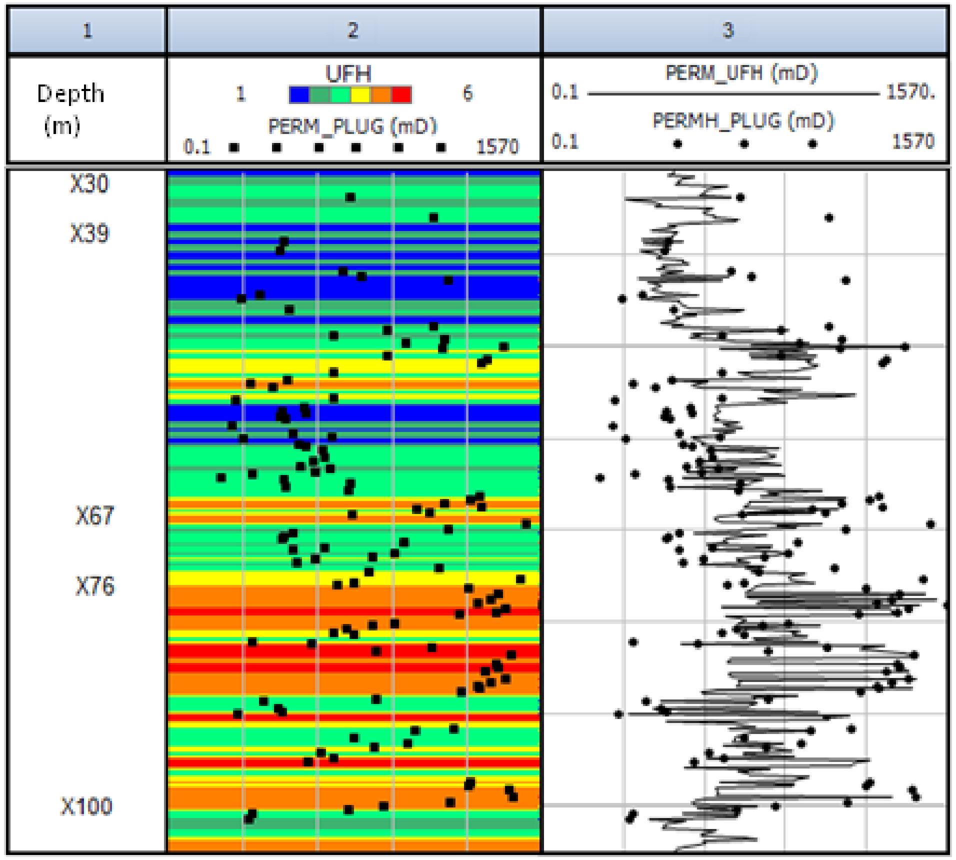


Figure 16. Permeability log estimated by IZF and flow zones - Well A3.

Figure 18. Core in X39. Packstone oncolytic with vertical vugs and cemented fractures - Well A3.

RESULTS

Permeability estimation

4. Flow Zone Indicators

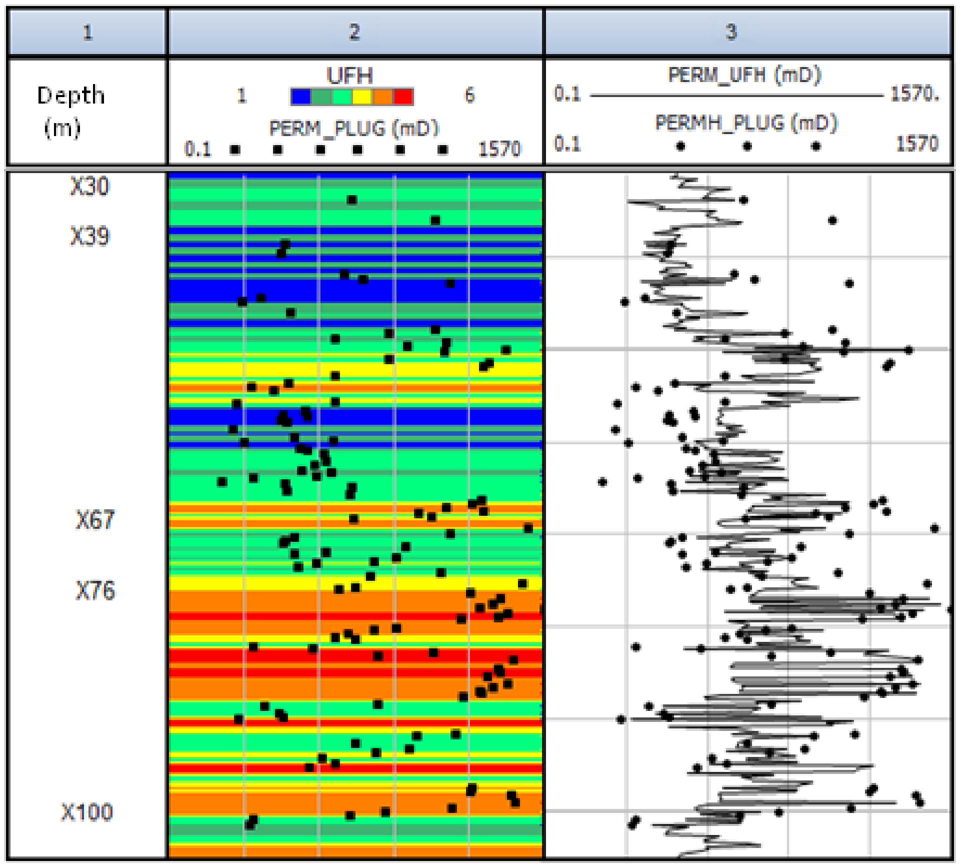


Figure 16. Permeability log estimated by IZF and flow zones - Well A3.

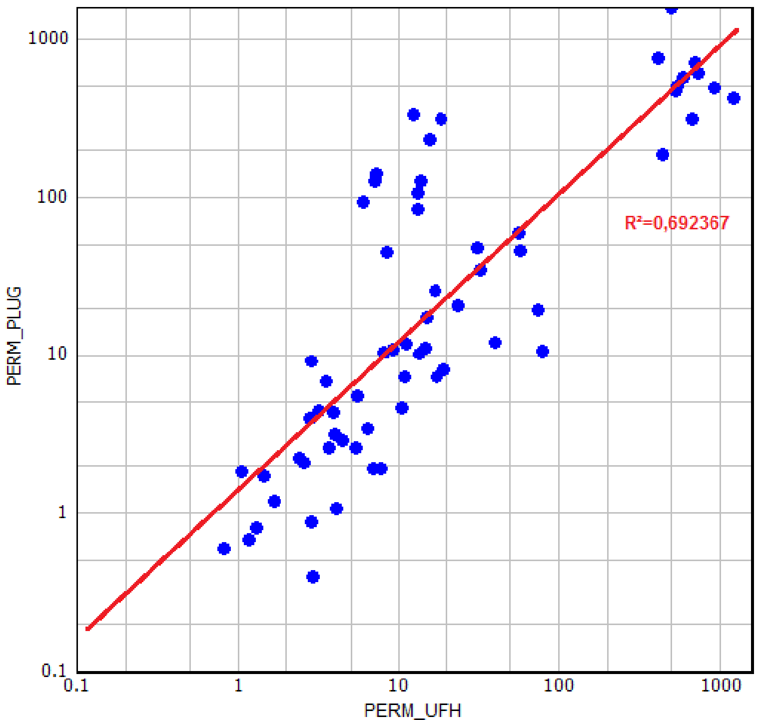


Figure 19. Correlation between estimated permeability and laboratory permeability - Well A3.

RESULTS

Permeability estimation

5. New Approach

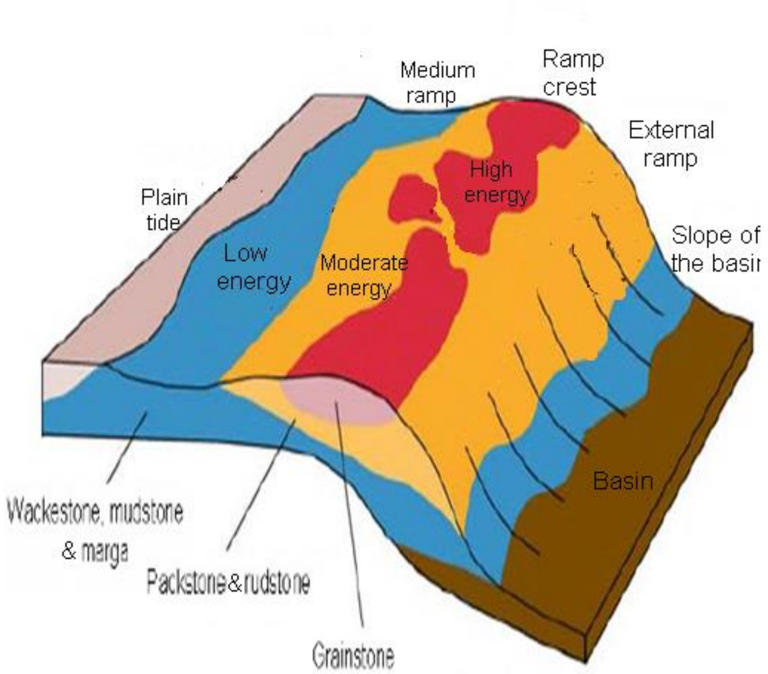


Figure 1. Scheme of a carbonate ramp with structural high. Adapted from LUCIA (2007).

High energy	*Grainstones*
Moderate energy	*Packstones*
Low energy	*Mudstones, wackestones and cimented rocks*

RESULTS

Permeability estimation

5. New Approach

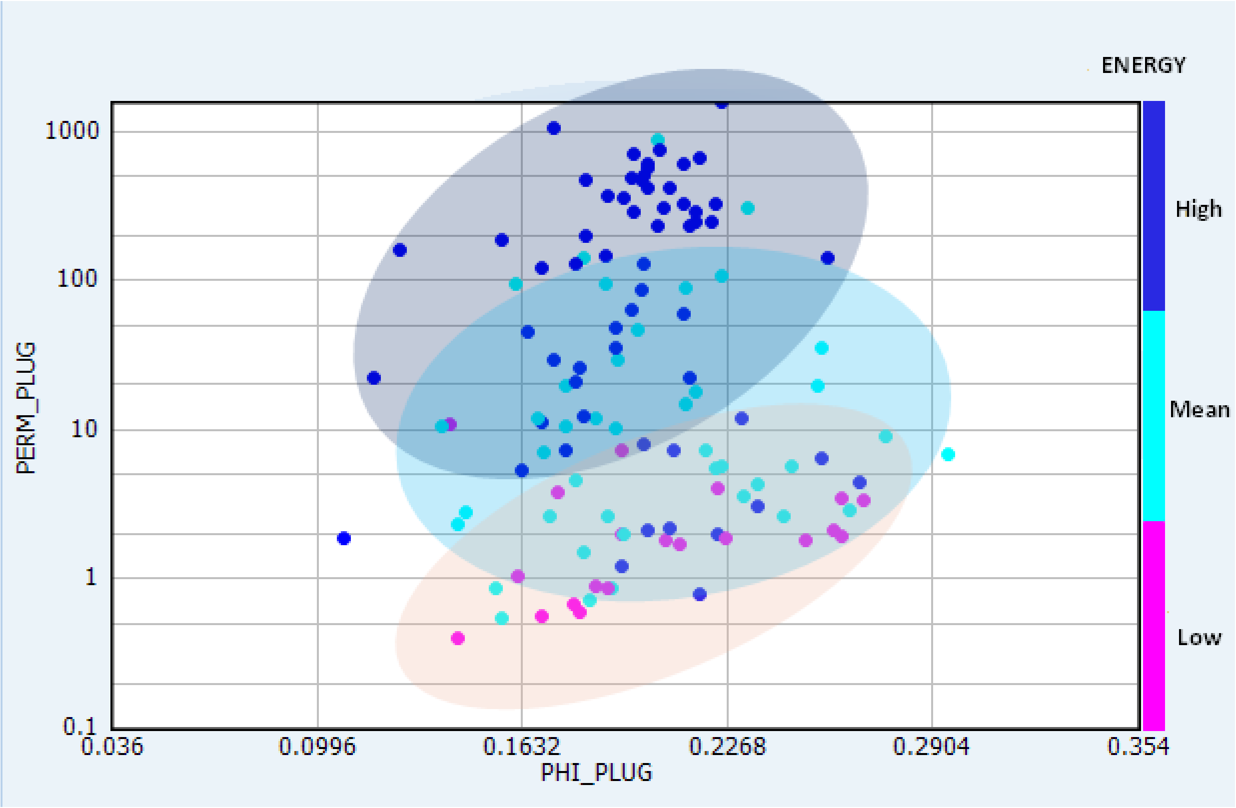


Figure 20. Plug porosity versus permeability, according to ambient energy - Well A3.

RESULTS

Permeability estimation

5. New Approach

Tabela 5. Energia do ambiente baseada nos perfis de raios gama– poço A3.

Zone	Gamma ray log values	Environmental energy	Permeability estimated by MLR from logs
1	GR <= 22	High	$Log(k) = 1,954 - 0,9Log(ILD) + 3,724Log(LLS) - 0,181GR$
2	22 < GR < 45	Medium	$Log(k) = -20,742 - 2,208.10^{-5}ILD + 1,913Log(LLS) + 8,458RHOB$
3	GR > 45	Low	$Log(k) = 1201,345 + 12,556Log(ILD) - 117,394Log(LLS) - 339,876Log(GR) - 264,434RHOB + 2,067DT$

RESULTS

Permeability estimation

5. New Approach

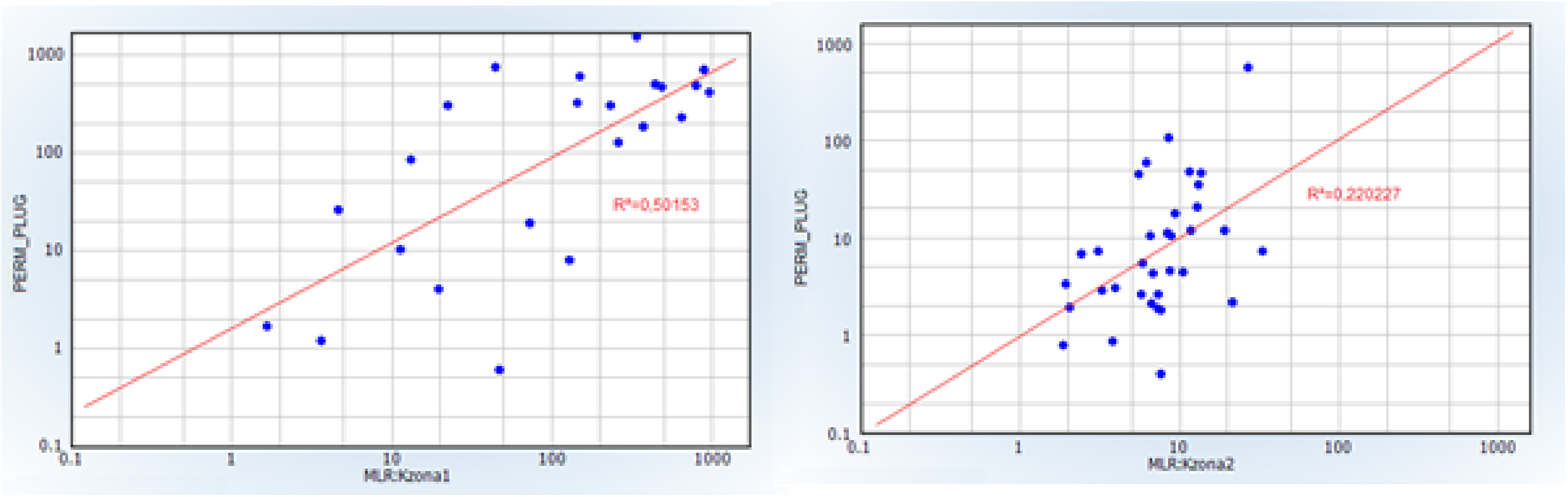


Figure 21. Correlations between the estimated and the laboratory permeability for zones 1 and 2 - Well A3.

RESULTS

Permeability estimation

5. New Approach

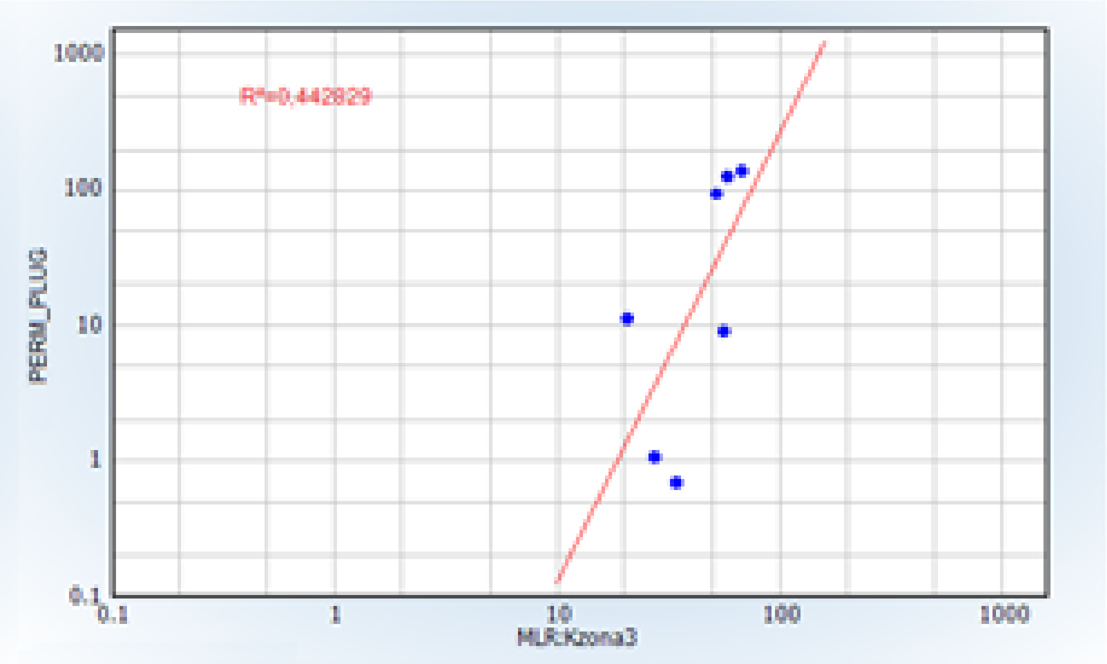


Figure 22. Correlations between the estimated and the laboratory permeability for zone 3 - well A3.

RESULTS

Permeability estimation

5. New Approach

$Z1\text{: } R^2 = 0{,}501530$
$Z2\text{: } R^2 = 0{,}220227$
$Z3\text{: } R^2 = 0{,}442829$

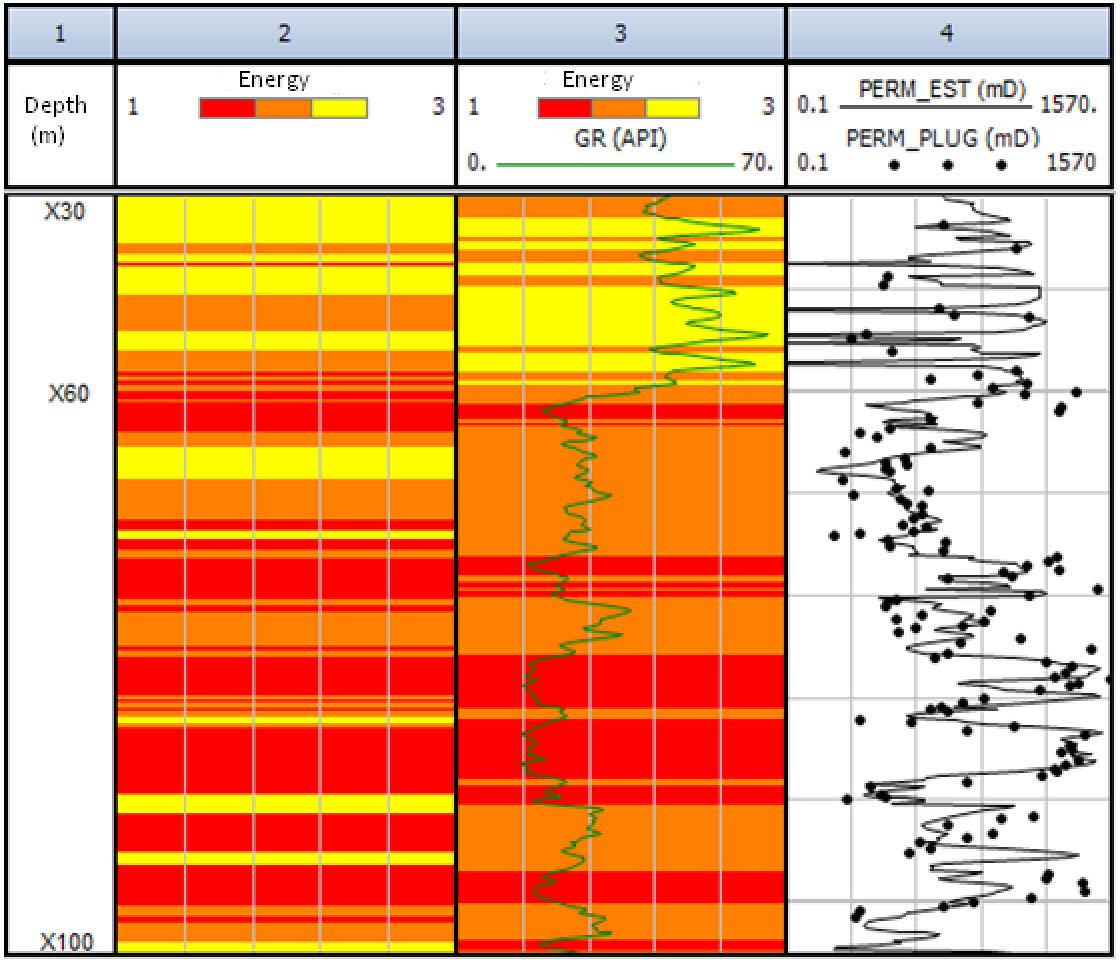


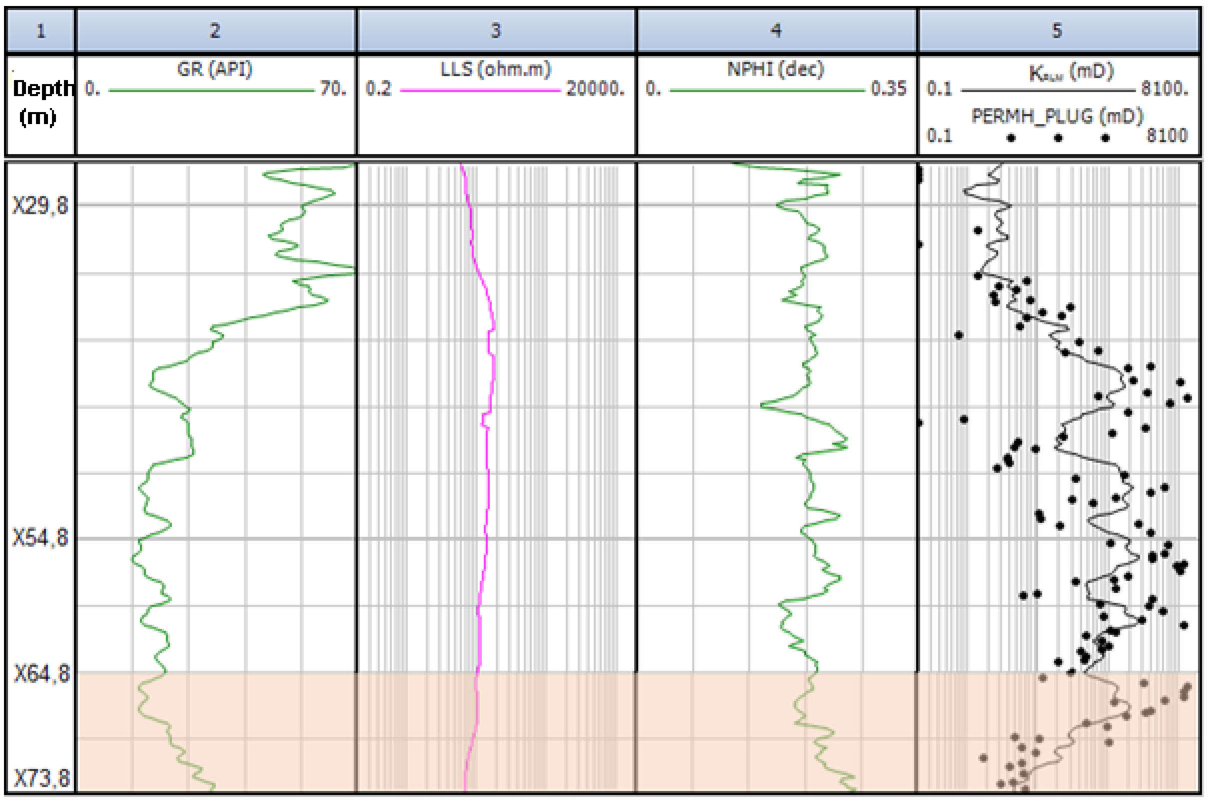
Figure 23. Estimated permeability profile based on the energy of the environment defined by the gamma ray log - well A3.

RESULTS

Application of estimated permeability

1. Multiple linear regression from logs - Well A10

$$Log(K_{MLR}) = 3{,}307 + 1{,}019 \times Log(LLS) - 3{,}919 \times Log(GR) - 3{,}699 \times Log(NPHI)$$



$$R^2 = 0{,}594051$$

Figure 24. Permeability log estimated by multiple linear regression - well A10.

RESULTS

Application of estimated permeability

2. Flow Zone Indicators - Well A10

$$Log(\,FZI\,) = 3{,}261 + 0{,}217 \times Log(\,LLS\,) - 1{,}694 \times Log(\,GR\,) - 4{,}356 \times NPHI$$

Table 4. Reservoir divided into rock types - well A3.

Flow zones	IZF	Relationship $k - \phi$
UFH1	0-0,371	$Log(k) = -1{,}5002 + 7{,}67175\phi$
UFH2	0,371-0,648	$Log(k) = -1{,}17003 + 7{,}80773\phi$
UFH3	0,648-1,292	$Log(k) = -0{,}461503 + 7{,}41864\phi$
UFH4	1,292-2,214	$Log(k) = -0{,}551592 + 10{,}8653\phi$
UFH5	2,214-4,379	$Log(k) = -0{,}650861 + 7{,}49462\phi$
UFH6	4,379-8	$Log(k) = 1{,}16024 + 7{,}70159\phi$

$R^2 = 0{,}0478838$

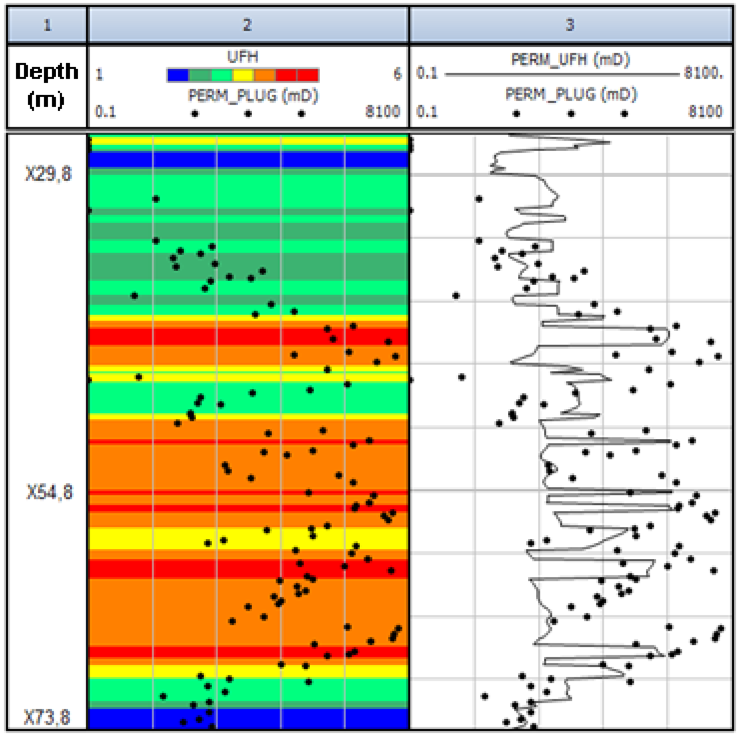


Figure 25. Estimation of permeability by rock types.

RESULTS

Application of estimated permeability

2. Flow Zone Indicators - Well A10

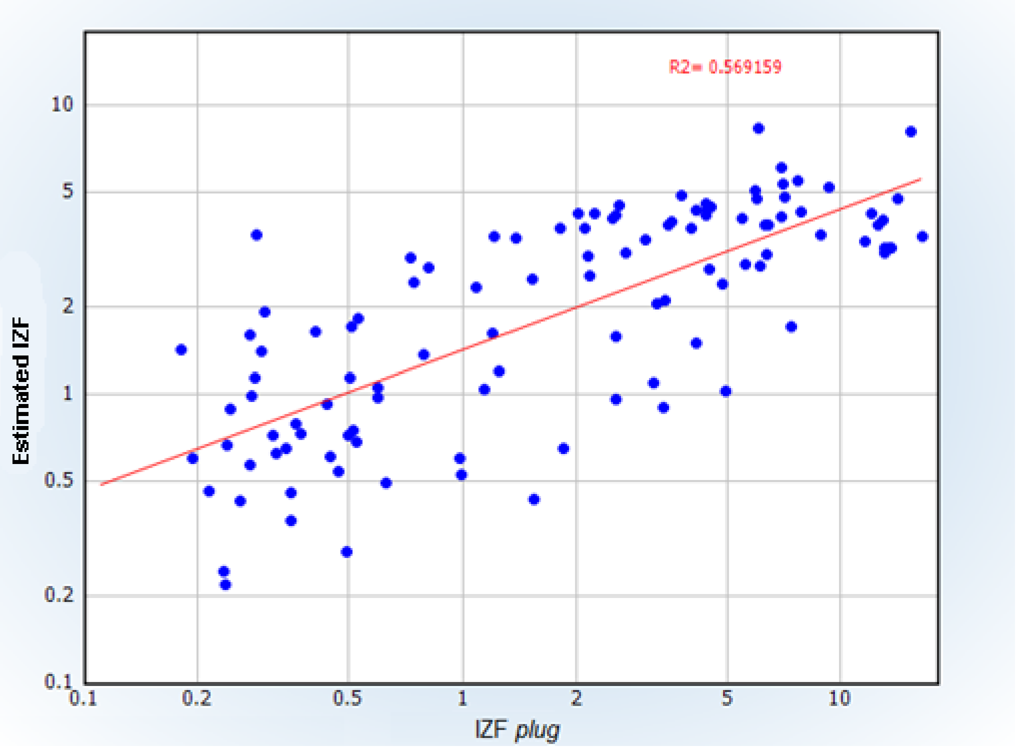


Figure 26. Correlation between the FZI plug and the estimated FZI.

RESULTS

Application of estimated permeability

3. New approach – Well A10

$$Z1:\ R^2 = 0{,}353290$$
$$Z2:\ R^2 = 0{,}387911$$
$$Z3:\ R^2 = 0{,}372745$$

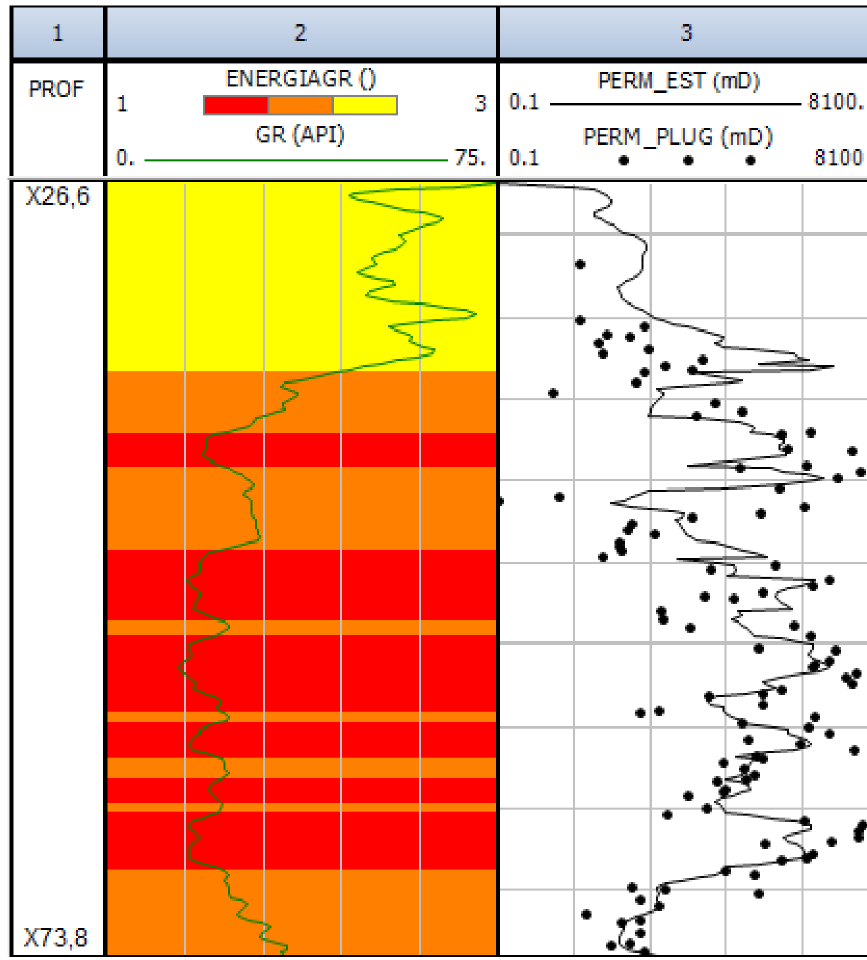


Figure 27. Estimated permeability loge based on the energy of the environment defined by the gamma-log - Well A10.

CONCLUSIONS

This work has estimated permeability through logs using simple (SLR) and multiple linear regression (MLR) approaches, empirical models and rock types, integrating available geological attributes.

The MLR approach used the logs as input curves for estimation and presented good trends for both wells.

Another method to estimate permeability was to divide the reservoir into six hydraulic flow units with good qualitative results. However, the correlations found for well A10 are poor.

The division of the reservoir based on the gamma ray curve showed good results both qualitatively and quantitatively, in agreement with the description of facies of the samples. The permeability estimation was performed with MLR and showed good correlations.

It is concluded that among the approaches tested the division of the reservoir into flow zones provided good qualitative interpretations of the permeability. However, this method is time-consuming and requires a detailed study of the interval according to the description of facies, attributing point-to-point data to each zone in order to minimize fit errors. The MLR based on the logs presented good qualitative estimates and reasonable quantitative estimates, being a fast and simple method, when compared to the division of the reservoir into zones. The latter approach attempted, however, has yielded even better results, since in some ways it is a combination of the two above.

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