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Petrophysical characterization of carbonate formations for geothermal reservoir analysis

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ABSTRACT

As of today most of geothermal projects and the related feasibility studies have been realized on the basis of geological, 2D-seismic and hydrogeological data interpretation without considering the petro-physical and geomechanical properties at the micro scale.
In this paper we want to point out the primary role of petrophysics in the reservoir analysis for a right identification of the structural lineaments and flow lines, to optimize the thermal efficiency of a geo-thermal project finalized to decrease the risk and the costs.

1. INTRODUCTION

As far as the application of Archie´ s law is concerned, petrophysicists discriminate between Sand-Shale or Clastic and Complex Lithology or Carbonate formations.
While for pure homogeneous sands the simple Archie´s law for standard values of the cementation exponent m and the constant a is often verified, complex lithologies with high heterogeneity need a detailed study for a detailed function description and parameters determination.

This paper describes a methodology for the petrophysical characterization of geothermal carbonate reservoirs.
The study has two main purposes.

- To analyze the type of porosity-permeability transforms, the porosity types and their spatial distribution as a first phase of the petrophysical characterization.
- To develop a system to apply carbonate classification for the identification of structural heterogeneities and main permeability features, identification of connectivity type, compartimentalization of petrophysical properties for possible correlation to other geophysical and seismic attributes.

2. BACKGROUND

A method was applied by Lucia for the Mansfield Field 1. We adapted some solutions to solve specific problems related to geothermal projects.

The most important aspect of these techniques concerns the application of the touching vugs porosity, permeabilty and fracture analysis. An extremely important factor for carbonate characterization is the determination of the separate vuggy porosity (Phi-SV). Through the comparison of different methods we can establish the amount of separate and connected vuggy porosity. This permits to access a second step where we can calculate the cementation exponent that further characterizes the petrophysical and mechanical properties of the formation allowing further possibilities of correlation with other geophysical attributes.

3. THE PROCEDURE

Seven models are considered for the calculation of secondary porosity including separate vuggy porosity and total vuggy porosity ratio (VPR) from acoustic and resistivity logs with the neutron porosity plot and core measurements used as reference criteria.
The following models are considered: Secondary Porosity Index (SPI), Nurmi, Quadratic, Power law, Lucia, Phi-Acoustic ϕv^{ac} , Phi-Resistivity ϕv^{ei} .
From these models a few guidelines for the interpretation of geothermal associated problems are derived.
For the SPI Model the P waves of the sonic tool bypass the vuggy porosity therefore we can represent the secondary porosity with the equation 1:

$$\phi 2 = \phi t - \phi s \qquad (1)$$

where: $\phi 2$ is the secondary vuggy porosity , ϕt is the total porosity and ϕs is the porosity from the sonic tool.
The Nurmi Model considers that the acoustic waves bypass only half of the vuggy porosity and this can be represented by the following equation. Eq. 2 :

$$\phi 2 = 2 (\phi t - \phi s) \qquad (2)$$

This model however was applied in formations where most of the secondary porosity was separate-vuggy porosity.
The Quadratic Model unify the previous methods with the introduction of an empirical constant p and a quadratic dependence. Eq. 3 :

$$\phi 2 = (\phi t - \phi s) + p(\phi t - \phi s)^2 \qquad (3)$$

The Power Law Model uses a scaling factor α as exponent of the ratio between the total porosity and the sonic porosity calculated from the Wyllie time-average equation. Eq. 4 :

$$\phi_2 = \left[\frac{\phi_t}{\phi_s}\right]^{\text{ϹƷ}} (\phi_t - \phi_s) \qquad (4)$$

Lucia and Conti calibrated the effect of separate-vug porosity on acoustic and resistivity logs using thin-section data in an upward-shoaling oomoldic sequence and used the point count method to measure ϕ_{sv} .
The equation that expresses such calibration is the following Eq. 5 :

$$\phi_{sv} = 10^{4.09 - 0.1298\ (\Delta t - 141.5\ \phi t)} \qquad (5)$$

After comparison of the results produced by the application of each method for the calculation of the separate vuggy porosity it was stated that the SPI method agrees with values derived from core data (point count analysis) for low vuggy porosity and can be applied in areas of low vuggy porosity representing the lower limit of the secondary porosity , while the Nurmi, Power Law and Quadratic models can represent a good approximation of the vuggy porosity in high vuggy porosity areas, representing therefore the upper limit of the secondary porosity. SPI is often similar to the resistivity porosity and the comparison of these methods can be often used as a diagnostoc for the heterogeneity type.
Fig. 1
Two more models were considered for the calculation of the vuggy porosity from acoustic logs ϕv^{ac} and resistivity logs ϕv^{ei} and the corresponding cementation exponent was derived with the equations of Brie, Johnson and Nurmi .
In this new example the vuggy porosities were calculated with five equations: SPI, Nurmi, Quadratic, ϕv^{ac} and ϕv^{ei} .
The results are exposed in Fig. 2 and show that the comparison of different methods and expecially the difference between ϕv^{ac} and ϕv^{ei} can evidence the presence of fractures and structural discontinuity.

4. THE ARCHIE EQUATION APPLIED TO CARBONATIC FORMATIONS

The determination of the secondary vuggy porosity is fundamental for the characterization of carbonate formations. This influences the static, dymamic and mechanical properties.
This is the first step on the way to find a convenient form of the Archie equation and consequently to derive a realistic cementation exponent.
On the way to derive a generic Archie equation which takes into account the porosity type we refer to the Generalized Parallel Conductor Model (Lucia, Wang, Ballay).
We consider various forms of the Formation Factor F and Archie equation and refer to the end of the paper for the the parameter list. Eq. 6, 7, 8 :

The one conductor model will have the form of Eq. 9 :

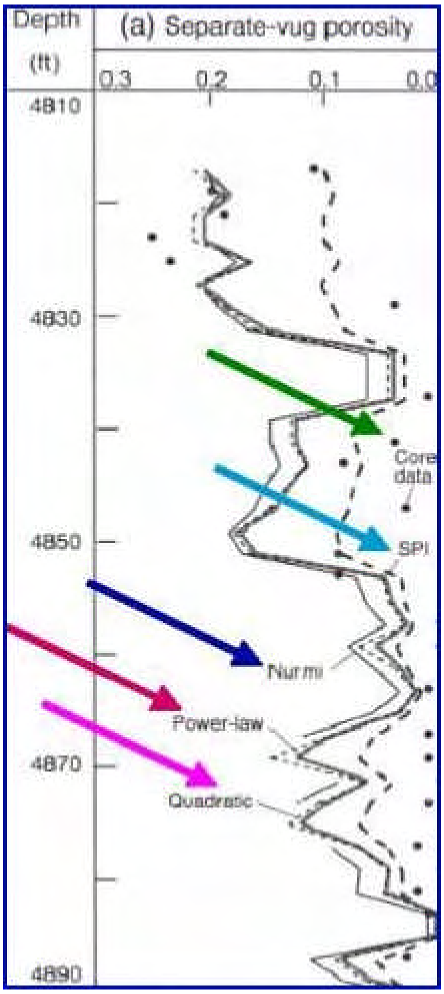

Fig. 1: Comparison of different models for the calculation of the vuggy porosity (Courtesy of F. Jerry Lucia, Rev. Robert E . Ballay)

Quadratic, Power-Law,

Nurmi, SPI, Core Data

$$F = \frac{a}{\phi^m} \qquad (6)$$

$$F = \frac{R_o}{R_w} \qquad (7)$$

$$F = \frac{C_w}{C_o} \qquad (8)$$

$$\phi^m$$

$$Co = \frac{}{a} Cw \qquad (9)$$

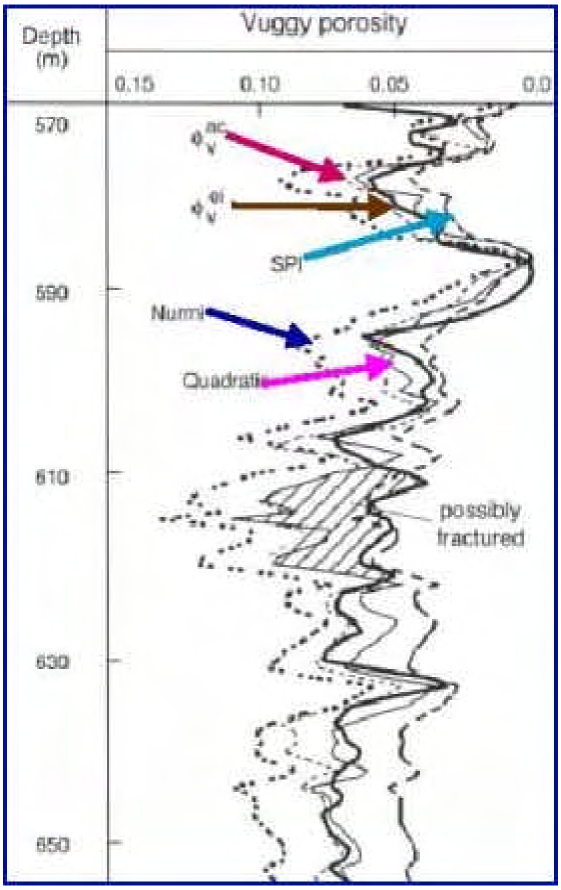

Fig. 2. Heterogeneity and structural interpretation from vuggy porosity models (Courtesy of F. Jerry Lucia, Rev. Robert E. Ballay)

Quadratic, Nurmi, SPI,

ϕ_v^{ei} , ϕ_v^{ac}

The i conductors model has the form of Eq. 10 :

$$Co = Cw \boxtimes \frac{1}{F_i} \qquad (10)$$

The Parallel Conductior Model is derived from the review of various models for separate vug systems, touching-vug systems and fractured systems (Wang, Lucia, Ballay) and assumes that conductivities related to different pore types are linearly additive.
Linearly additive in the conductivity domain means that also the factor $1 / F_i$ and its components are lineary additive. For this reason we can consider a model where Co accounts for the intercrystalline porosity and the vuggy porosity components. Eq. 11:

$$\left[\quad ^{m_{ip}} \qquad ^{m_v} \quad \right]$$

$$Co = Cw \frac{\phi}{a_{ip}} + \frac{\phi}{a_v} \qquad (11)$$

a_v characterizes the vuggy porosity type and is a fundamental parameter for the classification of carbonatic formations. This parameter could be used as an aid for facies characterization purposes as source of correlation with seismic attributes to identifiy the spatial porosity and facies distribution.

In practical log analysis the Dual-Porosity model finds a more flexible application and can be applied for vuggy and fractured reservoirs. The Dual-Porosity Model is derived from the Parallel Conductor Model.

We can set $a_{ip} = 1$ for well connected intercrystalline porosity.
Therefore the Dual-Porosity Model can be expressed from the following equation. Eq.12 :

$$Co = Cw \left[\phi^{m_{ip}} + \frac{\phi^{m_v}}{a_v} \right] \qquad (12)$$

The parameter a_v describes the characterization of the porosity type and its connectivity.
The sensitivity of the the cementation exponent m is dependent upon the value of a_v Fig. 3 .

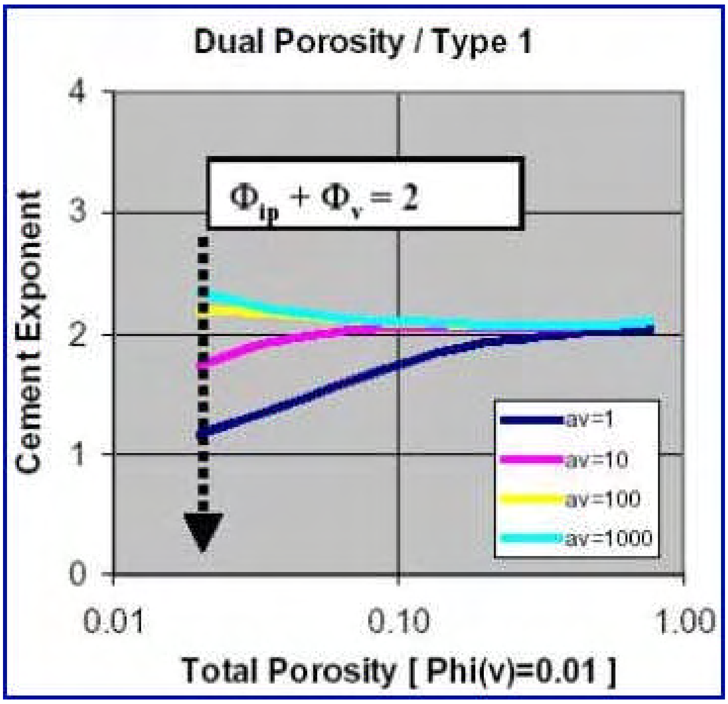

Fig. 3. Dependence of the cementation exponent m from a_v

If we consider the Dual Porosity model we can characterize the Phi-SV on the basis of the parameter a_v **.**

For $a_v > 100$: we can recognize separate vugs.

For $a_v < 20$: touching vugs porosity and

for $a_v = 1$: well connected planar fractures.

This is a very important result for the target identification in the geothermal exploration.

5. DERIVATION OF THE CEMENTATION EXPONENT m

The calculation of m represents a critical phase of the petrophysical analysis.
The modeling of the cementation exponent m takes into account the above performed porosity analysis.
For this new interpretation step we consider six models for the calculation of m from acoustic and resistivity measurements. The models differ as a function of the weight given to the VPR for such calculation.
The following models are considered: SPI/Nugent, Lucia, Nurmi/Asquith, Modified Myers, Dual Porosity, Archie.

For the One-Conductor model where the a effect is already contained in the conductivity equation, m can be calculated as Eq. 13 and 14 :

$$C_o = \phi^{m} C_w \tag{13}$$

$$m \operatorname{Log} \phi = \operatorname{Log}\left(\frac{C_o}{C_w}\right) \tag{14}$$

Here we introduce the parallel conductor model, Eq. 15, 16:

$$m \operatorname{Log} \phi = \operatorname{Log}\left(\frac{\phi_{ip}^{m_{ip}}}{a_{ip}} + \frac{\phi_{v}^{m_{v}}}{a_{v}}\right) \tag{15}$$

The parameter m if a fundamental property for the carbonate petrophysical evaluation:

$$\operatorname{Log}\left(\frac{\phi_{ip}^{m_{ip}}}{a_{ip}} + \frac{\phi_{v}^{m_{v}}}{a_{v}}\right)$$

$$m = \frac{\quad}{\operatorname{Log} \phi} \tag{16}$$

We state that for high values of the cementation exponent the SPI/Nugent method sets a lower limit of m while Nurmi/Asquith sets the upper limit. The Archie and Lucia equations set a benchmark. The Dual Porosity model also matches Archie´s m for high m values but overestimates m for lower m values.
Fig. 4 .

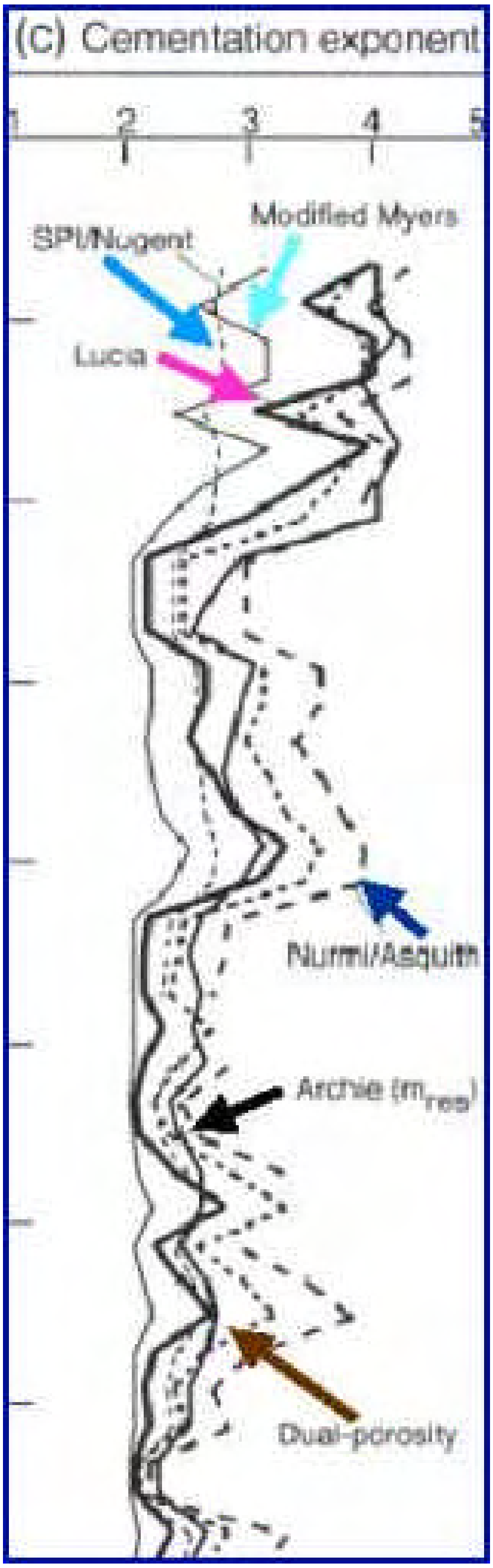

Fig. 4. Variability of m as a function of the model used which shows the dependence from the vuggy porosity type (Courtesy of F. Jerry Lucia, Rev. Robert E. Ballay)

Dual –Porosity, Archie mres, M. Myers
Nurmi/Asquith, Lucia, SPI/Nugent

For reservoirs with well connected planar fractures the coefficient of the vuggy porosity coefficients reduce to ϕ_f (fracture porosity). Eq. 17 :

$$m = \frac{\mathrm{Log}\left(\dfrac{\phi_{ip}^{\,m_{ip}}}{a_{ip}} + \phi_f \right)}{\mathrm{Log}\ \phi} \qquad (17)$$

6. CONCLUSIONS

With these models we can also characterize carbonates on the base of permeability and can use the parameters m and a_v as mapping attributes to verify geostatistical cross-covariance relations with other petrophysical,geomechanical and/or complex, amplitude or time seismic attributes.
This technique is a remarkable step to be integrated with other disciplines for a detailed reservoir analysis on the way to construct a static geological model with enhancement of the most important reservoir architecture´s structural features that help to identify the right target for the optimization of the geothermal project efficiency.

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NOMENCLATURE

m = cementation exponent
a = structural constant
VPR = vuggy porosity ratio = ϕ_{sv} / ϕ_t
ϕ = effective porosity
ϕ_t = total porosity from Neutron-Density logs
ϕ_{sv} = Phi-SV = separate vuggy porosity
ϕ_2 = secondary porosity (separate and connected)
ϕ_s = sonic porosity (Wyllie time-average equation)
p = quadratic model constant
Δt = p wave sonic arrival time
ϕ_v^{ac} = vuggy porosity from sonic logs
ϕ_v^{ei} = vuggy porosity from resistivity logs
ϕ_{ip} = intercristalline (interparticle) porosity
α = power low model scaling factor
F = formation factor
R_o = resistivity of the brine saturated formation
R_w = formation water (brine) resistivity

C_o = conductivity of the brine saturated formation
C_w = formation water (brine) conductivity
F_i = formation factor of the conductor I
m_{ip} = cementation exponent of the intercrystalline porosity
m_v = cementation exponent of the vuggy porosity
a_v = structural constant of the vuggy porosity component
a_{ip} = structural constant of the intercrystalline porosity component

Subscripts

t = total
sv = separate vuggy
2 = secondary
s = sonic
v = vuggy
ip = intercrystalline (interparticle)
o = 100 % brine saturated formation
w = formation water (brine)
i = conductor i

Superscripts

ac = acoustic (sonic)
ei = resistivity (electrical)

REFERENCES

Aguilera, R., 1976, Analysis ofnaturally fractured reservoirs from conventionai weil bgs: *Journal of Petroleum Technology,* vol. XXVIII, no. 7, p. 764 772.

Aguilera, R., 1995, Naturally fractured reservoirs: PennWell Books, Tulsa, Oklahoma, 521 p.

Aguilera, R., 1999, Recovery factors and reserves in naturally fractured reservoirs: *Journal of Canadian Petroleum Technology,* vol. 38, no. 7, p. 15—18.

Archie, G. E., 1952, Classification of carbonate reservoir rocks and petrophysical considerations: *AÄPG Bulletin,* vol. 36, no. 2, p.272—298.

Ballay R.E. , Hussein A. , Scott A. , Dennis B., 2002, In the driver´s seat with LWD Azimuthal Density Images: Saudi Aramco Journal of Technology, Summer-2002

Ballay R.E. , Roy R. , Cox E. , 2005, Formation Evaluation : Carbonate versus Sandstone, 2005 Robert Ballay LLC

Ballay R.E. , 2001 , Multidimensional Petrophysical Analysis in the Reservoir Description Division, Saudi Aramco Journal of Technology, Winter 2000/2001

Ballay R.E. , Al-Behair M. , 2005 , Up versus Down: Pipe-conveyed Wireline Data Quality

Carothers, J.W.: "A Statisticai Study of the Formation Factor Relationship," *The Log Analyst,* (Sept.-Oct. 1968) 14-20.

Coalson, E. B., Hartmann, D. J., and Thomas, J. B., *1985,* Productive characteristics of common reservoir porosity types: *Bulletin of the South Texas Geological Society,* vol. 25, no. 6, p. 35—5 1.

Coates, G.R. and Dumnnoir, J.L.: "A New Approach to Improved Log Derived Permeability," *Trans.,* SPWLA (May 1973) paper R.

Choquette, P. W. and Pray, L. C., 1970, Geologic nomenclature and classification of porosity in sedimentary carbonates: *AAPG Bullettin,* vol. 54, no. 2, p. 207-250

Focke & Munn´s classic work,
Cementation Exponent ranges from 2 to 5, dependant upon Vuggy / Total Porosity Ratio Laboratory data interpreted within context of pore geometry illustrations

Focke, J. W., and Munn, D., 1987, Cementation exponents in middle eastern carbonate reservoirs: *SPE Formation Evaluation,* vol. 2, 110. 2, p. *155—167.*

Hartmann, D. J., and Beaumont, E. A., 1999, Predicting reservoir System quality and performance, Edward A. Beaumont and Norman H. Foster (eds.), *Exploring for Oil and Gas Traps, AAPG Treatise of Petroleum Geology,* Chapter 9, p. 9-10

Lucia, F. J., 1983, Petrophysical parameters estimated from visual descriptions of carbonate rocks: a field classification of carbonate pore space: *Journal of Petroleum Technology,* vol. *35,* p. 629—637.

Lucia, F. Jerry, 1995, Rock-fabric/petrophysical classification of carbonate pore space for reservoir characterization: *ÄAPG Bulletin,* vol. 79, 110. 9, p. 1275—1300.

Martin, A. J., Solomon, 5. T., and Hartmann, D. J., 1999, Characterization of petrophysical flow units in carbonate reservoirs:*AAPG Bulletin,* vol. 83,110. 7, p. 1164—1173.

Piasentin, A.: Basic Wireline Logs Principles and lnterpretations, „Schlumberger SFE Review" *(1991)*

Piasentin, A.: „The new Strategy for Geothermy" Geothermische Energie (2005) No 46, 26 World Geothermal Congress 2005, Antalia, Turkey

Piasentin, A. Godail, L. , Neff, P. : Komplexe Herausforderungen in der geothermischen ReservoirAnalyse. Beispiel der Analyse der Fließeinheiten eines geklüfteten Reservoirs, 9. Geothermische Fachtagung 2006, 15-17 Nov. 2006 Karlsruhe, Tagungsband

Pickett G R "A Review of Techniques for Water Saturation from Logs Roberto Aguilera, incorporating .. and Winland r35 values on Pickett plots

Serra, 0., 1989, Formation MicroScanner image interpretation: Schlumberger Educational Service, Houston, SMP-7028, 117p.

Towle, G., 1962, An Analysis of the formation resistivity factor-porosity relationship of some assumed pore geometries, paper 3, *in* 3rd Annual Logging Symposium Transactions, Society of Professional Well Log Analysts.

White, K. E., 1995, A petrophysical evaluation of the slave point formation, Cranberry Field, Alberta, *in* 1st Joint Symposium of the Canadian Society of Petroleum Geologists and the Canadian Well Logging Society, Calgary, Alberta.

Wang & Lucia classic review, including theory and applications to actual data, Estimation ot vuggy Porosity Fraction, Secondary Porosity Index (Generalized, Sonic vs Total Porosity). Nurmis Model (Originally developed for oomoldic grainstones in the Smackover), Quadratic Model (Combination of SPI & Nurmi), Power Law (Cornbination of SPI & Nurmi), Estimation of Cementation Exponent, Lucia Model, Nugent Model, Asquith Model