The triple porosity model as a microsystem constraint to the joint petrophysical and seismic reservoir characterization of carbonate formations

Angelo Piasentin[1]

[1] GeoNeurale/Wavefields, Am Nymphenbad 8, 81245 Munich - Germany

angelo.piasentin@GeoNeurale.com

ABSTRACT

Several methods for the static reservoir characterization of reservoirs have been implemented in the last 20 years and also different commercial software applications have been developed based on different algorithms. A well accepted system consists of building a model departing from a 3D seismic impedance volume as a spatial background for the distribution of elastic properties and seismic attributes within this cube.

Most inverted volumes originate from post-stack inversion.

Quantitative interpretation methods are however still at the beginning of their evolution which is really promising and fully dependent on the advancement of future computing capabilities.

In this paper a new method for the quantitative analysis, distribution of microproperties with the triple porosity model for carbonate micro properties distribution in the 3D seismic volume is proposed.

With this model, one of the key elements for spatial analysis of carbonate is solved in a quantitative way.

Porosity partitioning spatial distribution can be regarded as a key theory to predict facies, micro and macro-properties.

Microsystems can be distributed through macrosystems in the 3D seismic cube within the pre-stack seismic inversion process.

These applications can be related to the sequential processing steps after the seismic inversion and before the implementation of a static model in order to maintain the development of interpretive models strictly quantitative and introduce new constraints to the calculation of micro and macrofield properties.

1. INTRODUCTION

For the petrophysical characterization of clastic formations the Archie equation is used to calculate porosity and water saturation. In pure sands we use the simplest Archie formulation. However when even a small saturation of clay is present, the additional clay conductivity brings a complication on the conductivity response of the effective rock and additional saturation equations are required to describe the petrophysical response in terms of saturation and porosity.

A similar phenomenon is present in carbonate, with critical complication due to the geochemical processes active in the carbonate transition to dolomites.

While the simple geometrical intercrystalline porosity can be often described with a simple Archie equation, the complex effective rock make this impossible. The most sensitive parameter to this complex behaviour is the cementation exponent. The high variability of this petrophysical property brings for the spatial facies distribution different characters then for clastic formations.

New equations taking into account the large **m** variability have to be introduced to describe the "flow lines" and the porosity partition as fundamental character in carbonate formations.

The petrophysical parameters specifying the simple equations are **a**, **m**, **n**.

a is often called tortuosity coefficient, however this parameters distinguish more the macroscopic porosity type. In fact the Tortuosity τ effect is also contained in **m** and **n** , therefore we will call **a** “Structural Porosity Constant” as **a** is a macroscopic attribute characterizing the porosity type into intercristalline, vuggy or fracture types in Carbonate formations (Lucia, Wang, Ballay, Aguilera).

Therefore we can affirm that **F** is a pure electrical attribute and ϕ a pure geometrical attribute.

a and **m** as empirical constants have the task to relate this pure electrical **F** with the pure geometrical attribute ϕ .

2. CONCEPTS OF THE PETROPHYSICAL / SEISMIC INTEGRATION

For scale description it is important to introduce new terminology and new concepts which also are indicative of the different equations and main phenomena acting at different scales.

These differences are related to different type of measurements available.
Seismic measurements for lower resolution but larger volume of investigation.

Petrophysical measurements for higher resolution and smaller volume of investigation.
Micro properties are the properties at the petrophysical scale, Macro properties are the properties at the seismic scale, Microsystems is the ensemble of micro properties and the physical processes relating them at the microscale.
Macrosystems is the ensemble of macro properties and the physical processes relating them at the macroscale.
The challenge is to relate micro and macrosystems.
Avseth and Johansen describe the transition process from micro to macroscale with following phases:
Elemental components interactions --> REV --> Sequential effective medium modeling --> Rock Physics --> AVO.
The Representative Elementary Volume (REV) varies from property to property.

3. FILLING THE DEFINITIONS GAP IN THE SEISMIC / PETROPHYSICAL INTEGRATION

Both in seismic and petrophysics we can distinguish between direct measurements and calculated attributes.

Related petrophysical properties **(RPP)** like : **a, R_w, R_t ,S_w, ρ_{ma}, ρ_f, m** represent direct or primary measurements or properies, which can be directly measured for instance by log measurements. ρ_{be}, τ_{be} , Z_e represent parameters that are calculated from these measurements and will be denominated primary attributes (**PA**).
Further attributes which can be calculated from primary attributes PA, will be called secondary attributes (**SA**).

4. CORRELATIONS BETWEEN ELECTRICAL AND ELASTIC PARAMETERS IN ROCK PHYSICS

Models in Rock Physics correlating elastic and elastic but also elastic and electrical properties
has been proposed by several authors both at the micro and macro-scale.
Theoretical models have been proposed by Gassman, Hertz-Mindlin, Voigt, Reuss, Hashin-Shtrickman, Kuster-Toksöz, Mavko, Dvorkin and others). Through the “Effective Rock” model they calculatefor instance the Effective Bulk Modulus K of the total composite rock related to the single component Bulk Moduli (grains , water , gas). Through specific models Avseth & Johansen extend the micro-theory to AVO attributes analysis.
Relations between elastic and electric parameters are better known as "Cross-Property Bounds".
Acknowledgement for scientists pioneering this field must be addressed to: Faust, Koesoemadinata, McMehan, Carcione, Bristow, Berriman, Milton, Gibiansky, Torquato, Raymer, Glover, Hermance, Brito Dos santos.
A question arise when considering all these theories.
Can we describe elastic models with electrical attributes ?
On this paper recent models will be reviewed and a new model considering the "Aguilera" triple porosity system will be proposed.

ELECTRICAL-WEIGHTED ELASTIC PROPERTIES: ELECTRO-DENSITY

For clean sands it is possible to integrate the bulk density with the Archie´s saturation equation (Piasentin 2013) :

$$\rho_b = \rho_{ma} + (\rho_f - \rho_{ma})\, e^{\left(\frac{\ln \frac{a\, R_w}{S_w^{\,n}\, R_t}}{m} \right)}$$

[1]

where:

F = Formation Factor
R_o = Formation Resistivity in a 100% saturated rock (Sw=1)
R_w = Formation Water Resistivity
a = Structural Porosity Constant
ϕ = Porosity
m = Cementation Exponent
S_w = Water Saturation
n = Saturation Exponent
ρ_b = Bulk density
ρ_{ma} = Matrix Density
ρ_f = Fluid Density

ρ_{be} has been called electro-density as it is a function of electrical Archie´s properties.

This equation relate the micro to macro properties for clean sands.

6. DUAL POROSITY MODEL

For carbonate and the complexity deriving in such formations the role of the cementation exponent becomes fundamental also due to its high sensitivity to changes in porosity.
The electro-density is therefore espressed by equation 2.
This is a parallel conductor equation with a_{ip} = 1 .

$$\rho_{be} = \rho_{ma} - (\rho_{ma} - \rho_f)\, e^{\left\{ \frac{Ln\left(\phi_{ip}^{m_{ip}} + \frac{\phi_v^{m_v}}{a_v} \right)}{m} \right\}}$$

[2]

Where new ρ_{be} RPP are:

ϕ_{ip} = Intercrystalline Porosity

ϕ_v = Vuggy Porosity

m_{ip} = Cementation exponent for intercrystalline Porosity

m_v = Cementation exponent for vuggy Porosity

m = Bulk Cementation exponent

a_v = Porosity structural factor for vuggy Porosity

7. INTEGRATED QUANTITATIVE ROCK PHYSICS CHARACTERIZATION IN CARBONATE

The spatial distribution of porosity type is fundamental in carbonate reservoir characterization. Connected and separated vuggy porosity play an important role in the parallel determination of elastic and electrical properties.

A new petrophysical analysis method can also be implemented as function of the intercrystalline to vuggy transform coefficients.

By setting : $m_v = \beta\ m_{ip}$

and : $\phi_v = \alpha\ \phi_{ip}$

$$\rho_{be} = \rho_{ma} - (\rho_m - \rho_f)\, e^{\left(\frac{Ln\left(\frac{a_v\, \phi_{ip}^{m_{ip}} + \alpha^{\beta\, m_{ip}}\, \phi_{ip}^{\beta\, m_{ip}}}{a_v} \right)}{m} \right)}$$

[3]

For fractured carbonate :

$$Ln\left(\phi_{ip}^{m_{ip}} + \frac{\phi_v^{m_v}}{a_v} \right) = Ln\left(\phi_{ip}^{m_{ip}} + \alpha^{\beta\, m_{ip}}\, \phi_{ip}^{\beta\, m_{ip}} \right)$$

[4]

The electro-Density equation simplifies into:

$$\rho_{be} = \rho_{ma} - (\rho_m - \rho_f)\, e^{\left(\frac{Ln\left(\phi_{ip}^{m_{ip}} + \alpha^{\beta\, m_{ip}}\, \phi_{ip}^{\beta\, m_{ip}} \right)}{m} \right)}$$

[5]

The porosity exponent for the dual porosity model (Dual Porosity Exponent) is DPexp.

$$DPexp = \left(\frac{Ln\left(\frac{a_v\, \phi_{ip}^{m_{ip}} + \alpha^{\beta\, m_{ip}}\, \phi_{ip}^{\beta\, m_{ip}}}{a_v} \right)}{m} \right)$$

[6]

8. TRIPLE-POROSITY MODEL: THE TPexp

The algorithm for elastic constraint in the macrosystem field has been developed starting from the Aguilera triple porosity model.

[7]

$$m = \frac{-\log\left[\phi_{nc} + \frac{(1-\phi_{nc})^2}{\phi_2 + (1-\phi_2-\phi_{nc})/\phi_b^{-m_b}} \right]}{\log \phi}$$

where:

ϕ_{nc} = Non connected Porosity relative to bulk volume

ϕ_2 = Fractures Porosity relative to bulk volume

ϕ_b = Matrix Porosity relative to matrix system

ϕ = Total Porosity

m_b = Cementation exponent for intercrystalline Porosity

The new electro-density equation is:

$$\rho_{be} = \rho_{ma} - (\rho_m - \rho_f)\ 10^{\left\{ \frac{-Log\left(\phi_{nc} + \frac{(1-\phi_{nc})^2}{\phi_2 + (1-\phi_2-\phi_{nc})/\phi_b^{-m_b}} \right)}{m} \right\}}$$

[8]

by setting:

$$\phi_{nc} = \eta\, \phi_b$$

$$\phi_2 = \iota\, \phi_b$$

$$m_b = \lambda\, m$$

(9)

$$\left\{ \frac{-\mathrm{Log}\left(\eta\, \phi_b + \dfrac{(1 - \eta\, \phi_b)^2}{\iota\, \phi_b + (1 - \iota\, \phi_b - \eta\, \phi_b) / \phi_b^{-\lambda m}} \right)}{m} \right\}$$

$\rho_{be} = \rho_{ma} - (\rho_m - \rho_f)$ 10

[9]

For the Triple Porosity exponent we can set :

$$TPexp = \left\{ \frac{-\mathrm{Log}\left(\eta\, \phi_b + \dfrac{(1 - \eta\, \phi_b)^2}{\iota\, \phi_b + (1 - \iota\, \phi_b - \eta\, \phi_b) / \phi_b^{-\lambda m}} \right)}{m} \right\}$$

[10]

9. THE INTEGRATION OF MICRO AND MACROSYSTEMS

Integrating micro and macrosystems requires the extension and validation of petrophysical equation at the seismic resolution domain. This is a different process from the "Upscaling" of petrophysical properties from the static to the dynamic simulation. In the micro / macrosystems integration the microsystem maintain its own resolution. Therefore increasing the resolution of the seismic domain.

It is useful to review the theory of seismic pre-stack inversion and the various linearization methods of the Zoeppritz equation. [11]

$$\begin{bmatrix} R_P(\theta_1) \\ R_S(\theta_1) \\ T_P(\theta_1) \\ T_S(\theta_1) \end{bmatrix} = \begin{bmatrix} -\sin\theta_1 & -\cos\phi_1 & \sin\theta_2 & \cos\phi_2 \\ \cos\theta_1 & -\sin\phi_1 & \cos\theta_2 & -\sin\phi_2 \\ \sin 2\theta_1 & \dfrac{V_{P1}}{V_{S1}}\cos 2\phi_1 & \dfrac{\rho_2 V_{S2}^2 V_{P1}}{\rho_1 V_{S1}^2 V_{P2}}\cos 2\phi_1 & \dfrac{\rho_2 V_{S2} V_{P1}}{\rho_1 V_{S1}^2}\cos 2\phi_2 \\ -\cos 2\phi_1 & \dfrac{V_{S1}}{V_{P1}}\sin 2\phi_1 & \dfrac{\rho_2 V_{P2}}{\rho_1 V_{P1}}\cos 2\phi_2 & -\dfrac{\rho_2 V_{S2}}{\rho_1 V_{P1}}\sin 2\phi_2 \end{bmatrix}^{-1} \begin{bmatrix} \sin\theta_1 \\ \cos\theta_1 \\ \sin 2\theta_1 \\ \cos 2\phi_1 \end{bmatrix}$$

Zoeppritz Equation in general form (Courtesy Brian Ru ssell, Robert Sheriff)

$$\begin{bmatrix} R_P(0^o) \\ R_S(0^o) \\ T_P(0^o) \\ T_S(0^o) \end{bmatrix} = \begin{bmatrix} R_{P0} \\ R_{S0} \\ T_{P0} \\ T_{S0} \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & \dfrac{V_{P1}}{V_{S1}} & 0 & \dfrac{\rho_2 V_{S2} V_{P1}}{\rho_1 V_{S1}^2} \\ -1 & 0 & \dfrac{\rho_2 V_{P2}}{\rho_1 V_{P1}} & 0 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 1 \\ 0 \\ 1 \end{bmatrix}$$

Zero Offset Zoeppritz Equation (Courtesy Brian Russell, Robert Sheriff)

$$Rp = \frac{A_r}{A_i}$$

[12]

For the pre-stack inversion and the distribution of elastic properties in the 3D seismic volume several linearization forms of the Zoeppritz equation are used. Aki-Richards derived the first important linearization algorithm.

Fatti derived the linearization method which is also used in the simultaneous inversion and describes the reflectivity as a function of zero offset reflectivity of P,S (theoretical)waves and a theoretical density reflectivity factor.

$$Rp(\theta) = c_1 Rp(0) + c_2 Rs(0) + c_3 Rd(0)$$

[13]

Wiggins extracted in the Aki-Richards equation the 3 components **A,B,C** thus also deriving from Zoeppritz (not zero-offset incidence equations). Where: **A** = linearized zero-offset reflection coefficient (Intercept), **B**= Gradient **C**= Curvature.

$$Rp(\theta) = A + B\sin^2\theta + C\tan^2\theta\,\sin^2\theta$$

Aki-Richards (Wiggins et al. modified version) [14]

Following this both Wiggins variant and Fatti variant contain the weighting coefficient $\dfrac{\Delta\rho}{\rho}$.

10. A SEISMIC INVERSION AND DISTRIBUTION OF MICRO AMD MACRO-PROPERTIES IN THE 3D SEISMIC VOLUME

Staring from the Triple Porosity model and applying the Wiggins variant of the Aki-Richards linearization equation it is possible to derive a model of the P and S waves Reflectivity as a function of related petrophysical properties defining the reservoir microsystems.

Considering the TPexp of equation 10 , it is possible to express the zero offset reflectivity as macrosystem as a function of microsystems and microproperties (RPP). (Piasentin 2015)

The weighting factor $\Delta\rho / \rho$ compares in all equations. We get this as a function of the Electrical-Weighted Density:

The TPexp is a function of: $\eta\ \iota\ \lambda\ \phi_b\ m$,

$\eta\ \iota\ \lambda$ normalizing $\phi_b\ m$.

We can express the TP exponent as :
$\mathbf{TPexp}\,(\eta\,,\iota\,,\lambda\,)$

$$\rho_b = \rho_{ma} + (\rho_f - \rho_{ma})\ 10^{\mathrm{TPexp}\,(\eta\,,\iota\,,\lambda\,)}$$

[15]

Resulting from this semplification we write the weighting coefficient $\Delta\rho/\rho$
of the Aki-Richards equation in form of Electrical-Weighted Density.
The Zero-Offset Reflectivity and Intecept A (Aki-Richards, Wiggins, Fatti) are equal to:

$$R_p(0) = \frac{1}{2}\left(\frac{\Delta V_p}{V_p} + \frac{\Delta\rho}{\rho}\right)$$

[16]

The following equation is a Seismic-Electrical (S-E) Attribute and expresses reflectivity as a function of an electrical-weighted Density / electrical-weighted slowness. The TPexp is the carbonate triple porosity exponent that defined above.
It is a background model that can be further developed into more complex attributes.
The Triple Porosity model takes into account the porosity partitioning in Carbonate .

$$R_p(0) = (1/2)\,*$$
$$\left\{\left(\frac{\dfrac{1}{\left[\tau_{ma} + (\tau_f - \tau_{ma})\ 10^{\mathrm{TPexp}(\eta,\iota,\lambda)}\right]_2} - \dfrac{1}{\left[\tau_{ma} + (\tau_f - \tau_{ma})\ 10^{\mathrm{TPexp}(\eta,\iota,\lambda)}\right]_1}}{\dfrac{\dfrac{1}{\left[\tau_{ma} + (\tau_f - \tau_{ma})\ 10^{\mathrm{TPexp}(\eta,\iota,\lambda)}\right]_2} + \dfrac{1}{\left[\tau_{ma} + (\tau_f - \tau_{ma})\ 10^{\mathrm{TPexp}(\eta,\iota,\lambda)}\right]_1}}{2}}\right) + \right.$$
$$\left. + \left(\frac{\left[\rho_{ma} + (\rho_f - \rho_{ma})\ 10^{\mathrm{TPexp}(\eta,\iota,\lambda)}\right]_2 - \left[\rho_{ma} + (\rho_f - \rho_{ma})\ 10^{\mathrm{TPexp}(\eta,\iota,\lambda)}\right]_1}{\dfrac{\left[\rho_{ma} + (\rho_f - \rho_{ma})\ 10^{\mathrm{TPexp}(\eta,\iota,\lambda)}\right]_2 + \left[\rho_{ma} + (\rho_f - \rho_{ma})\ 10^{\mathrm{TPexp}(\eta,\iota,\lambda)}\right]_1}{2}}\right)\right\}$$

[17]

This is a total Electro-Reflectivity where the electrical component appears both in the density and velocity term.
At the same time we can use the E-Density and E-slowness (ρ_e) $(\tau_e\ \ )$ to calculate the seismic Impedance and compare it with the conventional seismic impedance from from pre and post-stack inversion methods.

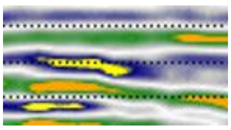
$$Z_{ep} = V_p\left[\rho_{ma} + (\rho_f - \rho_{ma})\ 10^{\mathrm{TPexp}}\right]$$

[18]

Parallel it is possible to calculate a partial (ρ_e) and a partial $(\tau_e\ )$ zero offeset
reflectivity and seismic impedance [Piasentin 2015].

11. APPLICATIONS

The described theory can be applied to clastic [Piasentin 2013] and carbonate with the Dual-Porosity model [Piasentin2015] and Triple-Porosity Model.
An example of increase of resolution with respect to conventional seismic inversion is represented in fig. 1 and 2 [Piasentin 2015 - Dual-Porosity model].



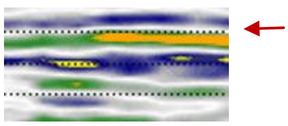


Fig. 1 Baseline Model Δ-Poisson Fig. 2 e- Model Δ-Poisson

12. CONCLUSIONS

This is a fully deterministic method to distribute micro-attibutes, showing their relation with macro-attributes /elastic properties and increase the 3D static model resolution. The model can be extended also a stochastic application by introducing specific correlations with seismic attributes.

REFERENCES

Aguilera, R., Al-Ghamdi, A., Chen, B., Behmanesh, A., Quanbari, F. 2010, An Improved
Triple Porosity Model for Evaluation of Naturally Fractured Reservoirs, SPE 132879
Aki, K., and P. G. Richards, 1980, Quantitative seismology, 2nd ed.: W. H.
Freeman and Co.
Avseth, P. and Johansen, T.A., 2011, Exploration Rock Physics and Seismic
Reservoir Prediction.
Europeas Associaton of Geoscientists and Engineers
Ballay, R.E., 2012. The "m" Exponent in Carbonate Petrophysics.
GeoNeurale Review. 2012
Ballay R.E., Mathurin, G.,Piasentin, A. 2007. Petrophysical characterization of
carbonate formations for geothermal reservoir analysis. Proceedings European
Geothermal Congress 2007. BvG
Ballay, R.E., 2000. Multidimensional Petrophysical Analysis in the Reservoir
Description Division. Saudi Aramco Journal of Technology
Bassiouni, Z., 1994. Theory, Measurement and Interpretation of Well Logs.
SPE Textbook Series , Vol.4
Biot, M.A., 1956. Theory of propagation of elastic waves in a fluid saturated porous solid.
I. Low frequency range and II. Higher-frequency range. J. Acoust. Soc. Am., 28, 168–191.
Carcione, J.M., Ursin, B., and Nordskag, J.I., 2007. Cross-property relations between electrical
conductivity and the seismic velocity of rocks. Geophysics, 72, E193–E204.
Castagna, J.P., Batzle, M.L., and Kan, T.K., 1993. Rock physics – The link between rock properties
and AVO response. In Offset-Dependent Reflectivity – Theory and Practice of AVO Analysis.
Chiles, J-P., Delfiner, P., 1999. Geostatistics: Modeling Spatial Uncertainty.
Wiley Series in Probability and Statistics
Chopra, S., Marfurt K.J., 2007. Seismic Attributes for Prospect Identification and Reservoir
Characterization. Society of Exploration Geophysicists and the European Association of Geoscientists & Engineers.
Dubrule, O., 2003. Geostatistics for seismic data integration in earth models. Distinguished
Instructor Series, No.6., Tulsa, USA, Sponsored by the Society of Exploration Geophysicists
and the European Assocation of Geoscientists & Engineers.
Dvorkin, and A. Nur, 1996, Elasticity of high-porosity sandstones: Theory for two North Sea data sets:
Geophysics, 61, no. 5, 1363-1370,doi:1().1190/1.1444059. "
Fanchi, R.J.,2001. Principles of Applied Reservoir Simulation. Gulf Professional Publishing
Garotta, R., 2013. Wave Polarization in Anisotropic Media GeoNeurale Review, 2013
Geldart, L.P. and Sheriff R.E., 2004, Problems in Exploration Seismology and their Solutions.
Society of Exploration Geophysicists , Tulsa
Hilterman, F., 1989. Is AVO the seismic signature of rock properties?
Expanded Abstracts, Soc. Expl. Geophys., 59th Annual International Meeting.
Tulsa, OK: Society of Exploration Geophysicists, p. 559.
Ikelle, L.T. and Amundsen, L., 2005. Introduction to Petroleum Seismology.
Society of Exploration Geophysicists
Mavko, G., T. Mukerji, and J. Dvorkin, 2009, The rock physics handbook:
Cambridge University Press.
Mindlin, R.D., 1949. Compliance of elastic bodies in contact. J. Appl. Mech., 16, 259–268.
Piasentin, A.: Basic Wireline Logs Principles and lnterpretations, „Schlumberger SFE Review" (1991)
Piasentin, A.: The Seismic Dimension of Archie´s Equation „ FKPE Conference" (Celle 2013)
Piasentin, A.: "Microsystems and macrosystems attributes integration in the petrophysical and seismic domain "
FKPE Conference" (Sedimentary Basin Jena 2015)
Piasentin, A. : "A new Multiscale Model for Reservoir Characterization of Carbonate Formations" Geothermiekongress
Proceedings - Essen 2015.
Schön, J.H., 1996. Physical Properties of Rocks. Oxford: Elsevier.
Sheriff, R.E., 1991. Encyclopedic Dictionary of Exploration Geophysics, 3rd edn. Tulsa, OK:
Society of Exploration Geophysics.
Russell, B. H., K. Hedlin, F. J . Hilterman, and L. R. Lines, 2003, Fluid-prop-
erty discrimination with AVO: A Biot-Gassmann perspective: Geophys-
ics, 68, 29-39, doi: 10.1190/1.1543192.
Wiggins, R., Kenny, G.S., and McClure, C.D., 1983. A method for determining and
displaying the shear-velocity reflectivities of a geologic formation.
European Patent Application 0113944.
Yilmaz O., Seismic Data Analysis: Processing, Inversion, and Interpretation of Seismic Data.
Tulsa: Society of Exploration Geophysicists; 2001.