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

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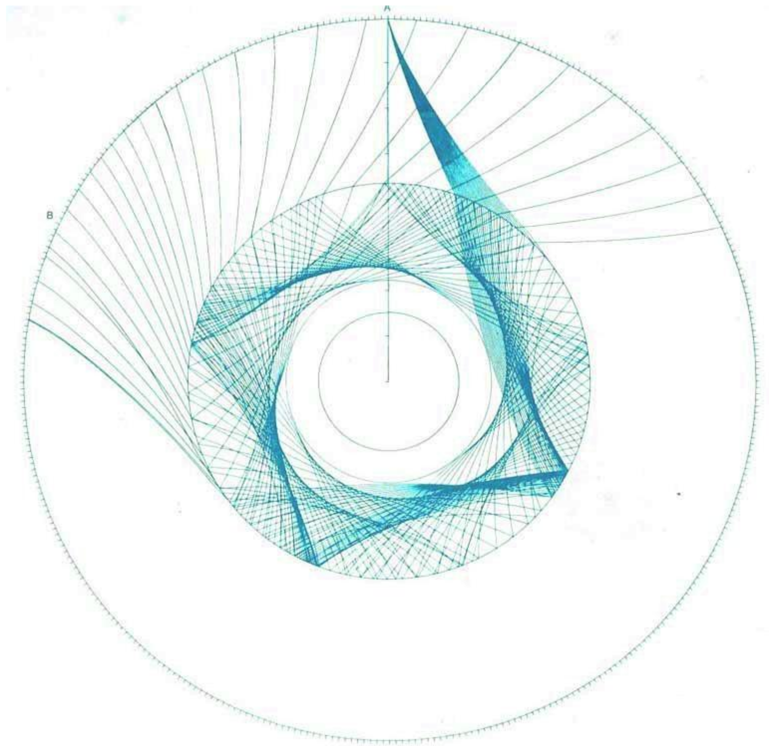

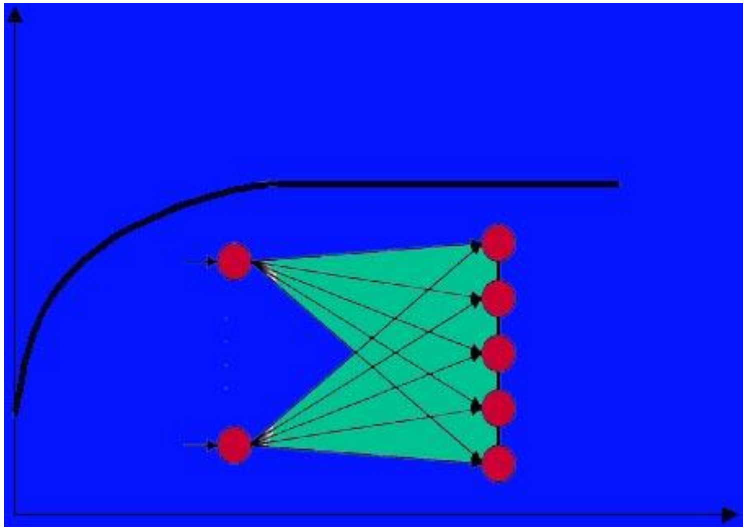

Petrophysic-Consultants

Geosystems Engineering

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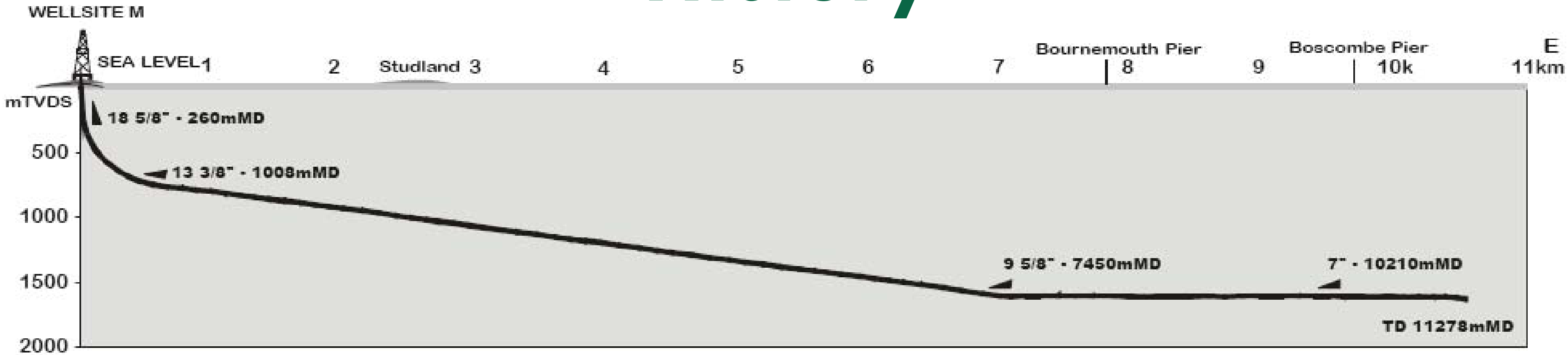
HIGHLIGHTS

MORE THAN 70 PROJECTS

BP Brent Bruce – North Sea

History



M16 Well Trajectory

WYTCH FARM

The longest "Extended-Reach Drilling" well worldwide MD > 11 Km

-Active Member of the SEG " Society of Exploration Geophysicists "

-Participation to over 70 projects in 4 continents

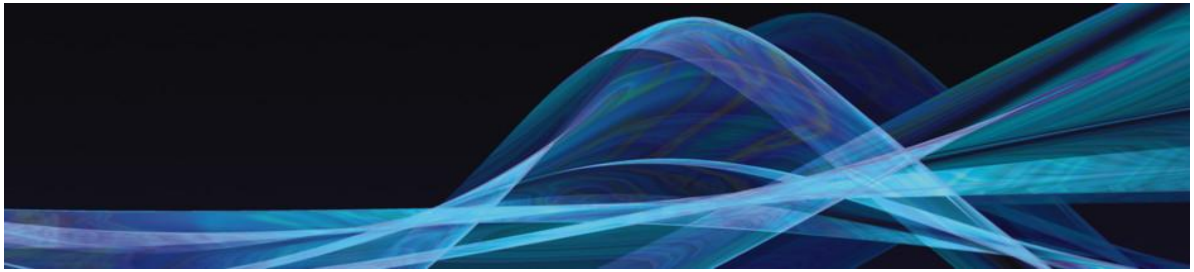
-Participation to the longest extended reach worldwide: "Wytch Farm Project" U.K. 11278 meters depth MD , (horizontal drilling)

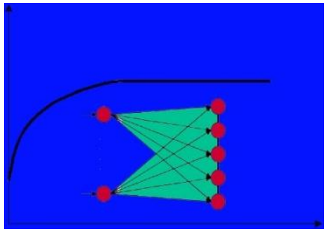
-Feasibility study for the deepest geothermal project in Germany: "Koenigsdorf", up to 5400 meters MD. (Also the first feasibility study with log analysis and seismic integration in geothermal projects in Germany)

-Participation to the first Geosteering project in Germany: "Soltau-Z5" using inverse modelling interpretation programs of LWD electromagnetic resistivity for trajectory prediction

-Development of the fundamentals for the microsystems to macrosystems scale theory in sesimic inversion

-More than 80 Certificates for Post-University Specialization Courses / training in the oil industry





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Angelo Piasentin

- Archie developed his equation for describing the measurements of resistivity in clean sands.

F = Formation Factor
R_o = Formation Resistivity in a 100% saturated rock (Sw=1)
R_w = Formation Water Resistivity
a = Structural Porosity Constant
f = Porosity
m = Cementation Exponent
S_w = Water Saturation
n = Saturation Exponent

$$F = \frac{R_o}{R_w}$$

$$S_w^n = \frac{R_o}{R_t}$$

$$S_w^n = \frac{a}{\phi^m} \frac{R_w}{R_t}$$

$$F = \frac{a}{\phi^m}$$

As the equation is empirical it is not easy to classify the parameters into pure electrical and pure geometrical. There is a multitude of interpretations which would relate the main sensitivity of the formation factor to Permeability or Porosity. However laboratory studies verified that the Formation factor / Porosity Correlation Coefficient is mostly much higher than the Formation Factor / Permeability one. Therefore the Formation factor characterize the Electrical Tortuosity not the Hydraulic Tortuosity and the Porosity must be considered
not an Effective Porosity but as Effective plus Electrically Connected Porosity in saturated or partially saturated formations. There is also a variety of nomenclature regarding the coefficients **a, m, n. a** is often called tortuosity coefficient, however this can be somewhat confusing, in fact the Tortuosity **t** 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)

INTRODUCING THE ELECTRICAL COMPONENT INTO ROCK PHYSICS

In Rock Physics we make reference to models each time that we wish to compare the measurements to the theoretical rocks internal Structure, Texture, Saturation etc. With this goal we refer to theoretical models like Gassman, Hertz-Mindlin, Voigt, Reuss, Hashin-Shtrickman, Kuster-Toksöz Dvorkin and others to construct the "Effective Rock" and calculate Effective Bulk Modulus K of the total composite rock related to the single component Bulk Moduli (grains , water , gas).

These however are mechanical models. Can we describe mechanical models with electrical attributes ?

For this scope we need at this point to simplify the model and consider a clean Archie sand equation and consider the anomalies and deviations from the model as an attribute for seismic characterization.

This way we could make a model of the "electrical complexity" that could be called Seismic Electrical Characterization and further Seismic Electrical Inversion and introduce the micro-field attributes into the macro-field.

In the simple model, Porosity from Density and Resistivity measurements will be the same.

Rest the fact that out of the model, only non-conducting water or isolated water will introduce a difference in the Porosity evaluation between Density logs and Resistivity logs. In this case we will have an anomaly that could serve as a diagnostic attribute in the interpretation process.

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

FURTHER COMPLICATIONS IN CARBONATE BETWEEN INTX AND VUGGI PHI

FURTHER COMPLICATIONS IN CARBONATE BETWEEN INTX AND VUGGI PHI
We have to do some considerations about the Archie ´s equations parameters.
Considering an example of the specific case of the Wang & Lucia Type I Dual Porosity Model in carbonate formations, a_v is dependent from the type of Porosity (Lucia, Wang, Ballay, Meyers et al.) where we have:

$a_{(v)} > 100$ for separate vugs
$a_{(v)} < 20$ for touching vugs
$a_{(v)} = 1$ for connected planar fractures

$$m = \frac{Ln\left(\frac{\phi_{ip}^{m(ip)}}{a_{(ip)}} + \frac{\phi^{m(v)}}{a_{(v)}}\right)}{Ln\ \phi_t}$$

Gene Ballay observed that local, calibrated m estimations may be possible but the following is not a routine nor certain way of deducing ‘m’. Some companies believes that their new Dielectric Scanner can yield foot-by-foot ‘m’.
Further efforts are directed with the purpose to clear the following relationships:
1. NMR derived Capillary Pressure Curve (modal distribution and parametrization).
2. m from direct test on Hg injection pressure and results of capillary pressure curve parametrization.

A TRANSITION TO A SEISMIC DIMENSION

To this point the petrophysical world and the micro-field. Introducing the petrophysical Electrical Density into a seismic equation and trying to clear as much as possible at least at the beginning, uncertainty components we can try to create our model of seismic-electrical attributes.

Recalling the methods of seismic pre-stack inversion and the various linearization methods of the Zoeppritz equation is a first step in the petrophysical input in the elastic attributes.

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

Zoeppritz Equation in general form (Courtesy Dan Hampson Robert Sheriff)

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

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

The Aki-Richards linearized Zoeppritz equation has the form (Fatti):

$$R_p(\theta) = p\,\frac{\Delta V_p}{2V_p} + q\,\frac{\Delta V_s}{2V_s} + r\,\frac{\Delta V_\rho}{2\rho}$$

Where: **p,q,r** are the weights function of the incidence angle **q** which multiply the elastic Parameters.

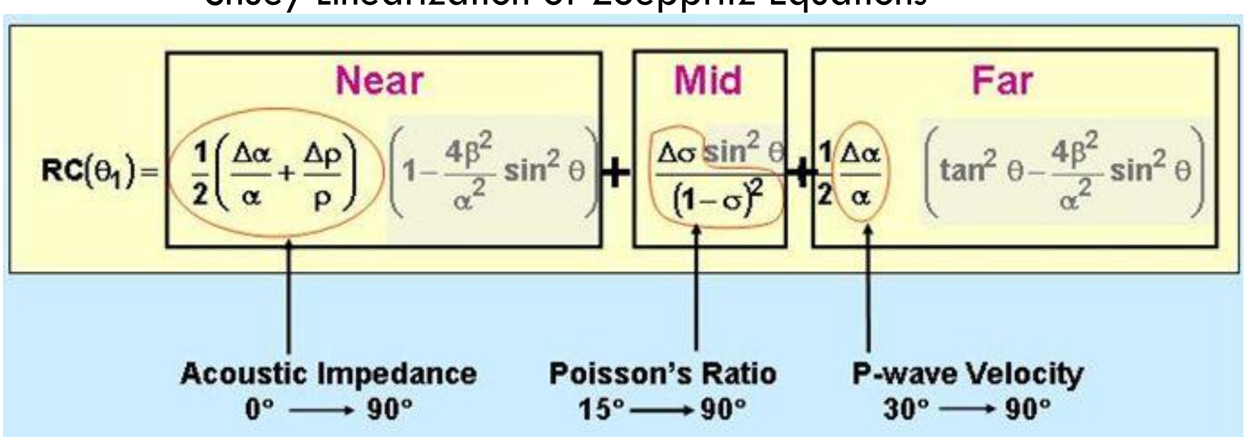
Wiggins extracted in the Aki-Richards equation the 3 components **A,B,C** thus also deriving from Zoeppritz (not zero-offset incidence equations). Where: **A** = linearized zero-offset reflection coefficient (Intercept), **B**= Gradient **C**= Curvature.

$$R_p(\theta) = A + B\sin^2\theta + C\tan^2\theta\,\sin^2\theta$$ Aki-Richards (Wiggins et al. modified version)

Further, Fatti derived a linearization where the elastic parameters are expressed as Zero-Offset Reflections coefficients: **Rp(0), Rs(0), Rd**.

Following this both Wiggins variant and Fatti variant contain the weighting Coefficient

Shuey Linearization of Zoeppritz Equations



Courtesy Fred Hilterman Geokinetics

Seismic Inversion

- Intercept / Gradient
- Offset or angle limited range stack (Near-Far)
- Elastic impedance inversion $f(\theta)$ (Connolly – Fatti)
- Extended Elastic impedance inversion (Whitcombe)
- Independent inversion Rp-Rs Reflectivity and Post-Stack Inversion (Fatti)
- Zp and Zs from Rp/Rs reflectivity
- Lambda-Mu-Rho analysis of Zp and Zs
- Simultaneous inversion for Zp, Zs and Rho (CGG, Hampson-Russell linear iterative mod.)
  Fatti equation, NMO $f(\theta)$-dependent wavelet
- FWI (Misfit vector, objective function minim. , Grad, Hessian)
- Stochastic inversion (CGG – Compagnie Generale de Geophisique)
- Inversion in the Attributes domain (Multiattributes Analysis, Neural Networks)
  probabilistic neural-networks, radial basis function neural networks)

A BASELINE MODEL FOR ANOMALY INDENTIFICATION AND SEISMIC ATTRIBUTES CORRELATION

Following the Aki-Richards linearization we introduce the Electrical-Weighted Density into the Acoustic Impedance expression and into the Wiggins et al. variant equation for the Reflectivity.
Considering that the weighting factor $\Delta\rho$ compares in all equations we get :

$$\rho = \frac{\left[\rho_{ma} + (\rho_f - \rho_{ma})\ e^{[Ar\_Mod]} \right]_2 + \left[\rho_{ma} + (\rho_f - \rho_{ma})\ e^{[Ar\_Mod]} \right]_1}{2}$$

$$\Delta\rho = \left[\rho_{ma} + (\rho_f - \rho_{ma})\ e^{[Ar\_Mod]} \right]_2 - \left[\rho_{ma} + (\rho_f - \rho_{ma})\ e^{[Ar\_Mod]} \right]_1$$

Reflectivity Aki-Richards (Wiggins)

$$R_P(\theta) = A + B\sin^2\theta + C\tan^2\theta\sin^2\theta, \ \text{where:}$$

$$A = \frac{1}{2}\left[\frac{\Delta V_P}{V_p} + \frac{\Delta\rho}{\rho}\right], B = \frac{1}{2}\frac{\Delta V_P}{V_p} - 4\left[\frac{V_S}{V_P}\right]^2 \frac{\Delta V_S}{V_S} - 2\left[\frac{V_S}{V_P}\right]^2 \frac{\Delta\rho}{\rho}, C = \frac{1}{2}\frac{\Delta V_P}{V_p}.$$

We express then twice the Zero-Offset Reflectivity as:

$$R_p(0) = \frac{\Delta V_p}{V_p} + \frac{\left[\rho_{ma} + (\rho_f - \rho_{ma})\, e^{[Ar\_Mod]}\right]_2 - \left[\rho_{ma} + (\rho_f - \rho_{ma})\, e^{[Ar\_Mod]}\right]_1}{\dfrac{\left[\rho_{ma} + (\rho_f - \rho_{ma})\, e^{[Ar\_Mod]}\right]_2 + \left[\rho_{ma} + (\rho_f - \rho_{ma})\, e^{[Ar\_Mod]}\right]_1}{2}}$$

Add properties + increase detail = decrease uncertainty

From elemental electro-density (clean sands) add properties (carbonate)

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 expressed by the equation below.

$$\left(\frac{\ln \left(\phi_{ip}^{m_{ip}} + \alpha^{\beta m_{ip}} \phi_{ip}^{\beta m_{ip}} \right)}{m} \right)$$

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

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

$$m_v = \beta \; m_{ip}$$
$$\phi_v = \alpha \; \phi_{ip}$$

TRIPLE-POROSITY MODEL: THE TPexp

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

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

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:

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

$$\phi_{nc} = \eta\,\phi_b$$
$$\phi_2 = \iota\,\phi_b$$
$$m_b = \lambda\,m$$

Specific Electro-density

$$\left\{ \frac{-\operatorname{Log}\left(\eta\,\phi_b + \dfrac{(1 - \eta\,\phi_b)^2}{\iota\,\phi_b + (1 - \iota\,\phi_b - \eta\,\phi_b) \,/\, \phi_b^{-\lambda m}} \right)}{m} \right\} \quad (9)$$

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

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.

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

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

We can express the TP exponent as :

$TPexp(\eta, \iota, \lambda)$

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

Starting from the Triple Porosity model and applying the Wiggins and Fatti 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)

Reflectivity Aki-Richards (Fatti)

$$R_P(\theta) = c_1 R_P(0^\circ) + c_2 R_S(0^\circ) + c_3 R_D, \text{ where:}$$

$$c_1 = 1 + \tan^2\theta,\ c_2 = -8(V_S/V_P)^2 \sin^2\theta,\ c_3 = 4(V_S/V_P)^2 \sin^2\theta - \tan^2\theta,$$

$$R_P(0^\circ) = \frac{1}{2}\left[\frac{\Delta V_P}{V_P} + \frac{\Delta\rho}{\rho}\right],\ R_S(0^\circ) = \frac{1}{2}\left[\frac{\Delta V_S}{V_S} + \frac{\Delta\rho}{\rho}\right], \text{ and } R_D = \frac{\Delta\rho}{\rho}.$$

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

The following equation is a Seismic-Electrical (S-E) Attribute and expresses 0-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.

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

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 (r_e) (t_e) to calculate the seismic Impedance and compare it with the conventional seismic impedance from from pre and post-stack inversion methods.

$$Z_{er} = V_p \, [\, \rho_{ma} + (\, \rho_f \; - \; \rho_{ma}) \;\; 10^{\,TPexp} \,]$$

Parallel it is possible to calculate a partial (**r_e**) and a partial (**t_e**) zero offset reflectivity and seismic impedance.

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].

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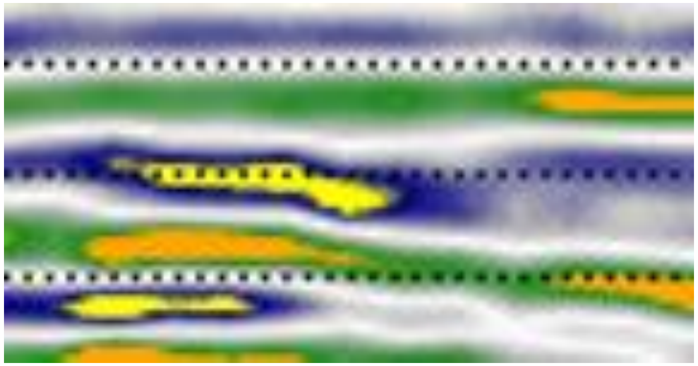

Fig. 1 Baseline Model Δ-Poisson

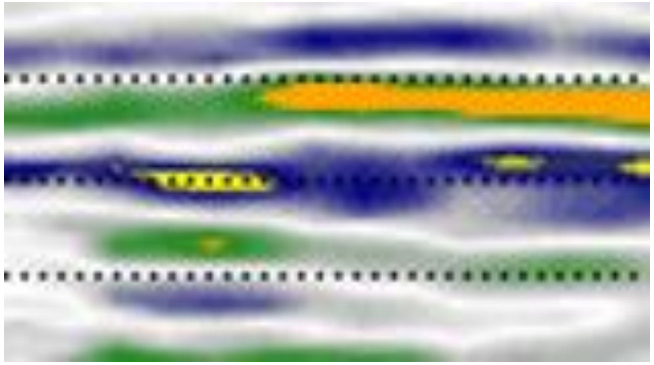

Fig. 2 e- Model Δ-Poisson

CGG , Hampson-Russell

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.

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WAVEFIELDS RESEARCH TEAM (MICRO-MACROSYSTEMS INTEGRATION, SEISMIC ATTRIBUTES ANALYSIS, FREQUENCY ATTRIBUTES)

PATENTS, PAPERS, PUBLICATIONS

Thank you for your attention

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