

## The Seismic Dimension of the Archie 's Equation

Angelo Piasentin (Petrophysic-Consultants)

### ABSTRACT

Petrophysics and Seismic have often been considered as separate fields without many common points other than the calculation of synthetic seismograms. This paper could give an example, how the two disciplines can be dynamically integrated and how respective properties depend one from another much strongly as previously supposed.

Starting from the concept that the origin of macro complexity lies in the micro complexity, we can develop a model for the consideration of the Archie's equations parameters into Seismic Attributes relations on the attempt to outline electric-elastic driven anomalies and develop models which help and discover fluid and lithological anomalies in the seismic interpretation.

Constraining seismic attributes with micro petrophysical properties is not new, however introducing electric properties through micro elastic properties opens new perspectives in the seismic interpretation methods.

In this paper petrophysical considerations are approached to parallel seismic considerations. The author would consider a very good goal if this paper could create new arguments of discussion creating new questions and new answers.

### INTRODUCTION

Archie developed his equation for describing the measurements of resistivity in clean sands (A). 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 characterizes the Electrical Tortuosity rather than the Hydraulic Tortuosity and the Archie Porosity must be considered not an Effective Porosity but as Effective and Electrically Connected Tortuosity-Porosity plus conductive mineralogical intrusions in saturated or partially saturated formations. To this point reference should be made to Dual Water model (B) or Triple Porosity models in carbonate (Aguilera, Serra et al.) to understand the complexity of the phenomenon. How the conductivity can be translated into "mechanical" effect in terms of "cementation" is also an uncertainty issue.

For more complex formation than the basic clean sands case, we should think of a "weighted" effect of various types of brine conductivity related to the mechanical support of the rock because the  $C_{wb}$  and  $C_w$  contribute to  $C_t$  can be proportional to the Aspect Ratio, Curvature, Coordination Number, of the grain components and inclusions plus Non-Brine Conductivity of other mineral components, and These properties are the basis of the effective rocks theory for seismic wave elastic parameters calculations.

Further complexity related to the electric-elastic relationship is introduced by the fact that the maximal sensitivity on elastic parameters is related to  $V_p$ ,  $V_s$  and not to  $\rho$  (Fig.1), that  $C_t$  can also be a non-linear function of  $C_w$ . Further rock physics models should consider the effect of the Coordination Number, Aspect Ratio, Curvature on  $V_p$ ,  $V_s$ . In this model I will consider the effect of Archie-Density in producing anomalies. In the seismic domain, as the density effect increases in

the angle range, AVO angle stack effects must be considered. On the zero offset reflection  $V_p, V_s$  are actually the main parameters discriminating between lithology and fluid (Fig.1).

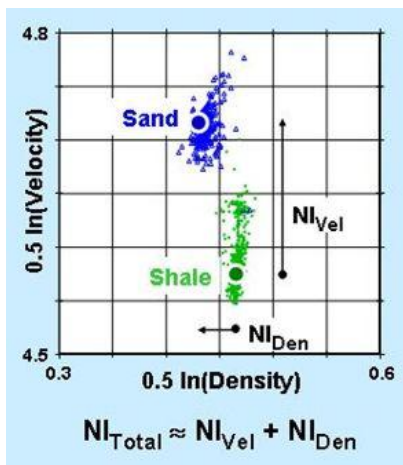


Fig. 1 Variability of velocity and density for NI calculation.  
Courtesy F. Hilterman

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  $\tau$  effect is also contained in **m** and **n** since the conductivity complexity requires both linear and non linear coefficients. These two parameters respectively represent the tortuosity of the current path in absence of non-wetting phase and in presence of non-wetting phase. The parameter **a** introduces a linear element in the equation for macro-characterization of the porosity type.

Therefore we will call **a** "Structural Porosity Constant" as **a** in Carbonate formations serves as macroscopic attribute characterizing the porosity type into intercrystalline, vuggy or fracture types (Lucia, Wang, Serra, Aguilera, Berg, Ballay)

- F** = Formation Factor
- R<sub>o</sub>** = Formation Resistivity in a 100% saturated rock ( $S_w=1$ )
- R<sub>w</sub>** = Formation Water Resistivity
- a** = Structural Porosity Constant
- $\phi$  = Porosity
- m** = Cementation Exponent
- S<sub>w</sub>** = Water Saturation
- n** = Saturation Exponent

(A)  
For the Archie Equation we have the following relationships:

$$F = \frac{R_o}{R_w} \quad (1)$$

$$S_w^n = \frac{R_o}{R_t} \quad (2)$$

$$F = \frac{a}{\phi^m} \quad (3)$$

$$S_w^n = \frac{a}{\phi^m} \frac{R_w}{R_t} \quad (4)$$

Following the above discussion further issues related to uncertainty must be considered during the calculation of Porosity with the Archie Equation.

The uncertainty is normally calculated with a Monte Carlo simulation algorithm and represents the uncertainty (instrument and environment error) which is propagated from the specific log measurements into the Porosity Parameter.

Porosity even in clean sandstones, calculated from the Archie equation and derived from resistivity logging tools not only has a higher uncertainty compared with Porosity from Density measurements, but also, due to the dependence on the parameters  $m$ ,  $n$  and  $a$  further sources of uncertainty structural dependence is introduced.

## INTRODUCING THE ELECTRICAL COMPONENT INTO ROCK PHYSICS

In Rock Physics we make reference to models each time we wish to compare the measurements to the theoretical rocks internal Structure, Texture, Matrix, Porosity, Saturation etc.

In this context we refer to theoretical models like Gassmann, Hertz-Mindlin, Voigt, Reuss, Hill, 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 models only deal with elastic parameters. For instance the Gassmann equation considers  $K$ ,  $\mu$ ,  $V_p$ ,  $V_s$  on the dry and saturated condition.

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

For this scope we need at the first impact to simplify the model and consider a simple theoretical model which can be described with a relative simple algorithm. This could be a clean "Archie" sand for clastic formations or a "Lucia" intercrystalline porosity limestone for carbonate formations.

As far as the clean Archie sand equation we can consider the anomalies and deviations from the "baseline clean sand" model as an attribute for seismic interpretation and reservoir characterization.

This way we could create 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. This attribute contains the fluid effect and eventually we could extend the model further in complex rocks by modifying the Saturation equation.

In the reference model, Porosity from Density and Resistivity measurements can be equalized and considered as baseline for interpretation. Further variations can be regarded as anomalies.

One procedure could be:

A. In a first step we can calculate the difference between a constant baseline minimum resistivity clean wet sand Archie theoretical model and the measured clean sand Archie model at different depths and up to the oil levels on the water table and then transfer the difference on the seismic volume.

B. On a second step we can do the same process for another property, for instance  $S_w$  and propagate again in the volume.

We can choose different models (Dual Water, Indonesian etc.) or the local representative equation. There can be different propagation mechanisms, statistic or deterministic.

We could think that these procedures are similar to the  $R_w$ \_apparent in log analysis where we can also talk about baseline and anomaly, ( we can remember that it is possible to simulate  $R_o$  with  $R_{ho}$  on logs compatible scales) the procedure in this case is transferred in the domain of the 3D seismic volume.

The saturation or the mapping parameter equation can vary in clean sands, clay sands and different porosity type carbonate, choosing the equation that better describes the petrophysical interpretation model. We can use a simple Archie (4) to a complex Archie up to Dual Water (5), Indonesian, Dual Porosity, Triple Porosity equation etc. and for each calculate the corresponding model to transfer into the seismic volume.

In more complex models further parameters have to be introduced as we can see for instance in the Dual Water model (5):

$$C_t = \frac{\phi^m S_{wt}^n}{a} \left\{ C_w + \frac{S_{wb}}{S_{wt}} \left( C_{wb} - C_w \right) \right\} \quad (5)$$

In all these equations we associate electrical components  $R_w, R_t$ , to geometrical/mechanical components  $S_w, \phi$ , the parameters and weights relating electrical and spatial/elastic components are  $m, n, a$ .

These could be also mapped in terms of variations from the baseline and also compared with other elastic seismic attributes.

Following all former considerations, the links between Rock Physics, Petrophysics and further scaling to the seismic domain can be found if we consider various models and expressions for Porosity-Density as spatial-elastic intermediate entity of the scaling process between petrophysical and seismic realizations. In this logic we can introduce a Density-Porosity concept into the Resistivity-Porosity concept.

## INTRODUCING THE ELECTRICAL-WEIGHTED DENSITY

The algebraic solution will be to extract the expression for Density in the Archie's equation and in the end consider some simple elemental models as first approximation of the seismic-electrical characterization workflow. In this context the petrophysical notation  $\rho_b$  which is referred to the density measured from the density tool is substituted from  $\rho_{be}$  which means density calculated from the Archie equation and therefore resistivity tool dependent:

$$\rho_{be} = \rho_{ma} + \left( \rho_f - \rho_{ma} \right) e^{\left( \frac{\ln \left( \frac{a R_w}{S_w^n R_t} \right)}{m} \right)} \quad (6)$$

## UNCERTAINTY ASPECTS IN THE MODELING WORKFLOW

To this point we should again consider some intensive works of Chen and Fang, as discussed by Ballay on the uncertainty levels of the components  $a$ ,  $m$ ,  $\phi$ , revealing the overwhelming weight of  $m$  in the uncertainty calculations.

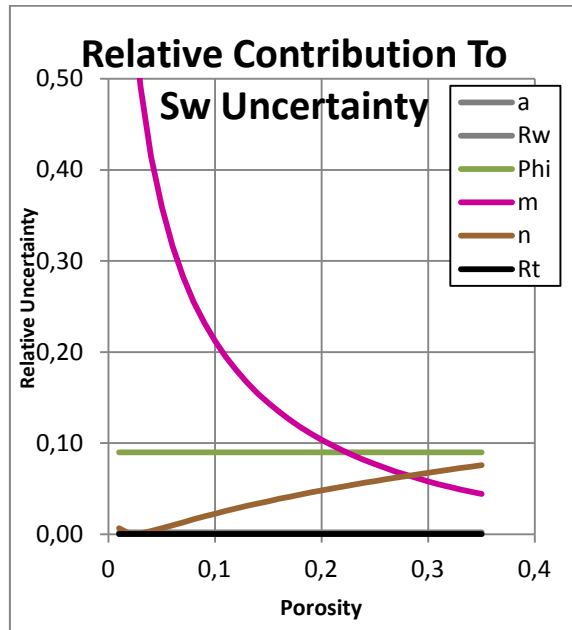


Fig. 2 Courtesy H.C. Chen and J.H. Fang , Robert E. Ballay

From this diagram it is evident that for low Porosity values the  $m$  variability is very high. In modeling and upscaling problems this issue must be taken into account and accordingly the right Statistical model to be chosen. From this consideration we can understand the significant Importance of  $m$  as a reservoir characterization property for spatial delineation of petrophysical Parameters like Porosity and Saturation in Carbonate and Clastic formations.

$$m = \frac{\ln \left( \frac{\phi_{ip}^{m(ip)}}{a_{(ip)}} + \frac{\phi^{m(v)}}{a_{(v)}} \right)}{\ln \phi_t} \quad (7)$$

R.E. 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 believe 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.

Further comparisons of electrical to geomechanical calculations of the  $m$  exponent have been done by Lucia and Wang for Carbonate formations, from this resulted that the Archie 's calculated  $m$  lays at an average lower position with respect to the sonic evaluated  $m$ .

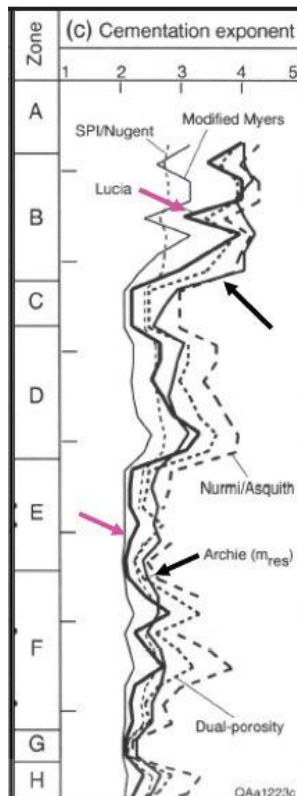


Fig. 3 Courtesy Lucia & Wang, and Ballay.

This is another observation reinforcing the theory that  $m$  is a key petrophysical parameter having an influence on the elastic seismic attributes and although its spatial variability and uncertainty represent a significant challenge for modeling purposes, it should be included in modeling studies of seismic reservoir characterization.

Further considerations have to be done about the parameter  $\mathbf{a}$  in Eq. 7.

Considering an example of the specific case of the Wang & Lucia Type I Dual Porosity Model in carbonate formations,  $\mathbf{a}$  depends upon the porosity type.

We can talk about  $\mathbf{a}_v$  for vuggy porosity and  $\mathbf{a}_{ip}$  for intercrystalline Porosity.

$\mathbf{a}_v$  is a macroscopic partitioning parameter (Lucia, Wang, Ballay, Meyers et al.) and we have:

$\mathbf{a}_{(v)} > 100$  for separate vugs

$\mathbf{a}_{(v)} < 20$  for touching vugs

$\mathbf{a}_{(v)} = 1$  for connected planar fractures

Extending the previous observations on carbonate it should be noted that the baseline modeling as far as the parameter  $\mathbf{a}$  is concerned will take the value  $\mathbf{a}_{(ip)}$  for simple matrix intercrystalline carbonate corresponding mainly to the Lucia class 1 while for the anomaly model, the parameters  $\mathbf{a}_{(ip)} + \mathbf{a}_{(v)}$  for presence of additional complex vuggy porosity have to be taken into consideration.

## A TRANSITION TO THE SEISMIC DIMENSION

To this point the petrophysical world and the micro-field. After introducing the petrophysical Electrical-Density into a seismic equation and trying to clear as much as possible at least at the beginning some uncertainty issues that should be absolutely considered by constructing such models, 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 to address the problem of a petrophysical input into the creation of new seismic elastic attributes.

$$\begin{bmatrix} R_p(\theta_1) \\ R_s(\theta_1) \\ T_p(\theta_1) \\ T_s(\theta_1) \end{bmatrix} = \begin{bmatrix} -\sin \theta_1 & -\cos \phi_1 & \sin \theta_2 & \cos \phi_2 \\ \cos \theta_1 & -\sin \phi_1 & \cos \theta_2 & -\sin \phi_2 \\ \sin 2\theta_1 & \frac{V_{P1}}{V_{S1}} \cos 2\phi_1 & \frac{\rho_2 V_{S2}^2 V_{P1}}{\rho_1 V_{S1}^2 V_{P2}} \cos 2\phi_1 & \frac{\rho_2 V_{S2} V_{P1}}{\rho_1 V_{S1}^2} \cos 2\phi_2 \\ -\cos 2\phi_1 & \frac{V_{S1}}{V_{P1}} \sin 2\phi_1 & \frac{\rho_2 V_{P2}}{\rho_1 V_{P1}} \cos 2\phi_2 & -\frac{\rho_2 V_{S2}}{\rho_1 V_{P1}} \sin 2\phi_2 \end{bmatrix}^{-1} \begin{bmatrix} \sin \theta_1 \\ \cos \theta_1 \\ \sin 2\theta_1 \\ \cos 2\phi_1 \end{bmatrix} \quad (8)$$

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

$$\begin{bmatrix} R_p(0^\circ) \\ R_s(0^\circ) \\ T_p(0^\circ) \\ T_s(0^\circ) \end{bmatrix} = \begin{bmatrix} R_{P0} \\ R_{S0} \\ T_{P0} \\ T_{S0} \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & \frac{V_{P1}}{V_{S1}} & 0 & \frac{\rho_2 V_{S2} V_{P1}}{\rho_1 V_{S1}^2} \\ -1 & 0 & \frac{\rho_2 V_{P2}}{\rho_1 V_{P1}} & 0 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 1 \\ 0 \\ 1 \end{bmatrix} \quad (9)$$

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

Recalling that:

$$\mathbf{R}_p(\mathbf{0}) = \frac{\mathbf{A}_r}{\mathbf{A}_i} \quad (10)$$

the Aki-Richards linearized Zoeppritz equation has the form:

$$\mathbf{R}_p(\theta) = \mathbf{p} \frac{\Delta V_p}{2V_p} + \mathbf{q} \frac{\Delta V_s}{2V_s} + \mathbf{r} \frac{\Delta \rho}{2\rho} \quad (11)$$

Where:  $\mathbf{p}, \mathbf{q}, \mathbf{r}$  are the weights as function of the incidence angle  $\theta$  which multiply the elastic parameters.

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

$$\mathbf{R}_p(\theta) = \mathbf{A} + \mathbf{B} \sin^2 \theta + \mathbf{C} \tan^2 \theta \sin^2 \theta \quad (12) \quad \text{Aki-Richards (Wiggins et al. modified version)}$$

Further, Fatti derived a linearization where the elastic parameters are expressed as Zero-Offset Reflections coefficients:  $\mathbf{R}_p(\mathbf{0}), \mathbf{R}_s(\mathbf{0}), \mathbf{R}_d$ .

Following this assumptions, both Wiggins variant and Fatti variant contain the elastic Parameter  $\frac{\Delta \rho}{\rho}$ .

Associated to this AVO equation is the definition of AVO classes: Class 1, 2, 3.

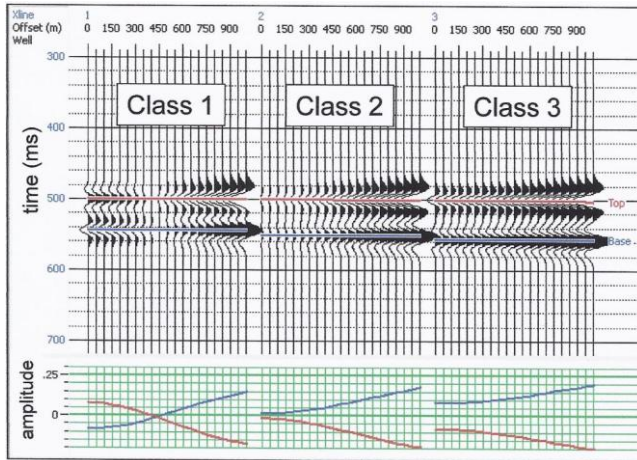


Fig. 4 AVO Classes (Courtesy Brian Russell, Dan Hampson )

### A BASELINE MODEL FOR ANOMALY IDENTIFICATION AND SEISMIC ATTRIBUTES CORRELATION

Following the Aki-Richards linearization the Electrical-Weighted Density can be introduced into the Acoustic Impedance expression and into the Wiggins et al. variant equation for the Reflectivity.

Considering that the elastic parameter  $\frac{\Delta\rho}{\rho}$  compares in all equations we can get

this as a function of the Electrical-Weighted Density:

$$\rho_{be} = \rho_{ma} + (\rho_f - \rho_{ma}) e^{\left[ \frac{\ln \frac{a R_w}{S_w^n R_t}}{m} \right]} \quad \leftarrow (13)$$

Further we can consider that for a simple case (Baseline pure Archie rock the parameters  $a, n, m$  can be expressed as numerical standard 1,2,2.

To simplify the model we can call the exponent of  $e$  (Ar\_Mod) which means: Simple Archie Model.

$$[Ar\_Mod] = \frac{\ln \frac{a R_w}{S_w^n R_t}}{m} \quad (14)$$

Therefore:

$$\rho_{be} = \rho_{ma} + (\rho_f - \rho_{ma}) e^{[Ar\_Mod]} \quad (15)$$

Resulting from this simplification we can write the elastic parameter  $\frac{\Delta \rho}{\rho}$  of the Aki-Richards equation in terms of Electrical-Weighted Density:

$$\rho = \frac{[\rho_{ma} + (\rho_f - \rho_{ma}) e^{[Ar\_Mod]}]_2 + [\rho_{ma} + (\rho_f - \rho_{ma}) e^{[Ar\_Mod]}]_1}{2} \quad (16)$$

$$\Delta \rho = [\rho_{ma} + (\rho_f - \rho_{ma}) e^{[Ar\_Mod]}]_2 - [\rho_{ma} + (\rho_f - \rho_{ma}) e^{[Ar\_Mod]}]_1 \quad (17)$$

Both in Fatti and in Aki-Richards (Wiggins) version the Zero-Offset Reflectivity and Intercept A are equal to:

$$R_p(0) = \frac{1}{2} \left( \frac{\Delta V_p}{V_p} + \frac{\Delta \rho}{\rho} \right) \quad (18)$$

$$R_s(0) = \frac{1}{2} \left( \frac{\Delta V_s}{V_s} + \frac{\Delta \rho}{\rho} \right) \quad (19)$$

The Zero-Offset Reflectivity can then be written as:

$$R_p(0) = \frac{\Delta V_p}{V_p} + \frac{[\rho_{ma} + (\rho_f - \rho_{ma}) e^{[Ar\_Mod]}]_2 - [\rho_{ma} + (\rho_f - \rho_{ma}) e^{[Ar\_Mod]}]_1}{\frac{[\rho_{ma} + (\rho_f - \rho_{ma}) e^{[Ar\_Mod]}]_2 + [\rho_{ma} + (\rho_f - \rho_{ma}) e^{[Ar\_Mod]}]_1}{2}} \quad (20)$$

$$R_s(0) = \frac{\Delta V_s}{V_s} + \frac{[ \rho_{ma} + (\rho_f - \rho_{ma}) e^{[Ar\_Mod]} ]_2 - [ \rho_{ma} + (\rho_f - \rho_{ma}) e^{[Ar\_Mod]} ]_1}{2 \frac{[ \rho_{ma} + (\rho_f - \rho_{ma}) e^{[Ar\_Mod]} ]_2 + [ \rho_{ma} + (\rho_f - \rho_{ma}) e^{[Ar\_Mod]} ]_1}{2}}$$

(21)

This can be called a Seismic-Electrical (S-E) Attribute and express reflectivity as a function of an electrical-weighted Density. The **Ar\_Mod** represents the simple Archie rock model , as baseline for correlations with well-calibrated S-E Reflectivities. However it is possible to calculate also Non-Archie Rocks Models, Complex Lithology or Dual-Water models in Clastic formations or modified Archie, Dual Porosity and Triple Porosity in Carbonate. It will be possible to apply the local equations for Saturation and **m**.

As a further development of this model we can use the “ Electro-Density” ( $\rho_{be}$ ) to calculate the Acoustic Impedance and compare it with the conventional Acoustic Impedance attribute from Seismic Inversion. This is a partial , e-Density controlled Seismic Impedance:

$$Z_e(\rho) = V_p [ \rho_{ma} + (\rho_f - \rho_{ma}) e^{[Ar\_Mod]} ] \quad (22)$$

This seismic attribute can be called “ $\rho$ -controlled Electrical Seismic Impedance”.

It can also be used to on the study of correlations and anomalies related departure from the simple Sand-baseline clastics or from the simple intercrystalline-baseline porosity type in carbonate and can be extrapolated through the seismic volume with geostatistical methods.

The attribute is proportional to  $V_p$  and the Electrical-Weighted Density.

The same can be created for S waves:

$$Z_e(s) = V_s [ \rho_{ma} + (\rho_f - \rho_{ma}) e^{[Ar\_Mod]} ] \quad (23)$$

If we introduce the slowness into the Seismic Impedance equation we can obtain the “Total Electrical Seismic Impedance” :

$$\tau_{pbe} = \tau_{ma} + (\tau_f - \tau_{ma}) e^{\left( \frac{\ln \left( \frac{a R_w}{S_w^n R_t} \right)}{m} \right)} \quad (24)$$

and then substitute  $V_p$  as function of  $\tau_{pbe}$  :

$$V_p = 1 / \tau_{pbe} \quad (25)$$

## TESTING THE MODEL

As an example the model was applied to a reservoir for anomalies interpretation where seismic data were available near an oil well. The model applied to the sand water table tested the sensitivity to the input parameters. The goal was to better distinguish oil from water and visualize this in a specific areas.

As baseline model a Density value from the  $\rho_b$  Density tool measurement was considered on the water table with high  $S_w$  values corresponding to low  $R_o$  values . This simulated the local baseline model pure Archie sand. This was what the seismic inversion originally produced.

The results show it was possible to delineate with higher resolution a reservoir area that previously was not delineated.

Both baseline relative to the local geology and the anomaly have been translated into electro-seismic attributes in a prestack seismic inversion model.

This represents a simple model how the possibility is given to extrapolate and map petrophysical properties in the 3D seismic volume. This mean that each petrophysical parameter can be modeled and its departure from the base model can be plotted in the 3D seismic volume in form of “electro-seismic attribute”.

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## 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
- 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., 1993. AVO analysis-tutorial and review. In Offset Dependent Reflectivity – Theory and Practice of AVO Analysis. ed. J.P.
- 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.

Dvorkin, and A. Nur, 1996, Elasticity of high-porosity sandstones: Theory for two North Sea data sets: *Geophysics*, 61, no. 5, 1363-1370, doi:10.1190/1.1444059.

Fanchi, R.J., 2001. Principles of Applied Reservoir Simulation. Gulf Professional Publishing

Fatti, J. L., G. C. Smith, P. J. Vail, and P. J. Strausset al., 1994, Detection of gas in sandstone reservoirs using AVO analysis: A 3-D seismic case history using the Geostack technique: *Geophysics*, 59, 1362-1376, doi: 10.1190/1.1443695.

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

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

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

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.

Kelkar, M. and Perez, G., 2002. Applied Geostatistics for Reservoir Characterization. Society of Petroleum Engineers Inc. Richardson , TX.

Ikelle, L.T. and Amundsen, L., 2005. Introduction to Petroleum Seismology. Society of Exploration Geophysicists

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

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 Interpretations, „Schlumberger SFE Review“ (1991)

Pickett, G.R., 1963. Acoustic character logs and their applications in formation evaluation. *J. Petrol. Technol.*, 15, 650–667.

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.

Thomsen, L., 1986. Weak elastic anisotropy. *Geophys.*, 51, 1954–1966.

Russell, B. and D. Hampson, 1991, A comparison of poststack seismic inversion methods: 61st Annual International Meeting, SEG, Expanded Abstracts, 876-878.

Russell, B. H., D. Gray, and D. P. Hampson, 2011, Linearized AVO and poroelasticity: *Geophysics*, 76, no. 3, C19-C29, doi: 10.1190/1.3555082.

Russell, B. H., K. Hedlin, F. J. Hilterman, and L. R. Lines, 2003, Fluid-property discrimination with AVO: A Biot-Gassmann perspective: *Geophysics*, 68, 29-39, doi: 10.1190/1.1543192.

Waxman, M.H. and Smits, L. J. M., 1968. Electrical conductivities in oil-bearing shaley sands. *Soc. Petrol Eng. J.*, 8, 107–122.

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.