Application of Resistivity Data in Optimizing Fracture Network Model: A Mathematical Approach

NAM H. TRAN, AMNA ALI AND ABDUL RAVOOF

***Abstract*—** Seismic is widely considered as the most important data source in the energy engineering. It provides critical information for mapping and characterization of oil, gas, condensate, geothermal and coal bed methane reservoirs. In fractured media, however, its application is limited. This paper presents a mathematical model in which the relationships between seismic's P-wave / S-wave velocity and resistivity of reservoir rock and fluid are studied. To account for variances between the fractured and conventional pore-matrix media, primary and secondary rock and fluid properties integrally examined, including formation factor, primary porosity, secondary porosity, tortuosity, cementation exponent, partitioning coefficient, crystallisation and mineralisation. The relationship, being novel in fracture heterogeneity, is validated by data from a producing naturally fractured gas reservoir. It opens up several options to utilise new technologies in petroleum exploration: electromagnetic survey, magneto-telluric data, artificial neural network technique.

***Keywords*—** Seismic, Electromagnetic, Formation resistivity, Lithology, Fractured reservoir.

I. Introduction

A Majority of the world's remaining energy resources are contained within Naturally Fractured Reservoirs (NFR), which include oil, gas, condensate, geothermal and coal bed methane reservoirs. Development of such naturally fractured reservoir very complicated, as natural fractures occur at different scales and are highly heterogeneous. Production estimating from such reservoir needs a comprehensive and reliable fracture characterisation, where all available field data are utilised (Tran et al., 2006a). At the inter-well regions, this presents a challenge due to the limited data availability. In most cases, seismic data is the only inter-well data source available and so it is desirable to fully utilise it for the NFR characterisation process.

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Ouenes et al. (2004) review various techniques that utilise post-stack as well as pre-stack seismic data for NFR characterisation. The use of post-stack seismic in an integrated approach (combined with other geologic and engineering data), involving high resolution seismic inversion, spectral imaging, and static geological modelling, can provide a fracture reservoir model that can be applied in the simulation model natural fracture development. Pre-stack seismic can be used to image the actual fracture distribution utilising AVO (amplitude vs. offset) analysis.

Though techniques for better seismic data utilisation are now applied, additional data sources are still highly desirable to meet the challenge of inter-well NFR characterisation. Cross-hole EM (Electromagnetic) technology has been used in imaging thermal oil recovery operations and more recently for reservoir characterisation and water flood imaging (Patzek et al. 2000). While seismic waves are predominantly supported by the rock matrix, EM-induced currents primarily flow in the pore fluids. Thus, the combination of seismic and EM data allows high definition of both the rock matrix and pore fluids. Herein lays the basic motivation in the use of EM data for characterisation of fractures by better definition of the constituent fluids/minerals. These days, 3D Electromagnetic (EM) surveying techniques (Sea Bed Logging, Controlled Source Electromagnetic Surveying, etc.) are gradually finding their place in the hydrocarbon exploration industry. These surveying techniques are aimed at determining subsurface electrical resistivity and it is worthwhile considering the application of this data for NFR characterisation. The resistivity profile obtained could either be used as an input for the characterisation process or as verification for a fracture model derived from seismic. In the past, EM surveying has been used to tackle problems in sub-salt and carbonate exploration as well as for direct hydrocarbon detection (Constable 2005; MacGregor and Sinha 2000).

Successful implementation of EM data application for fracture definition would greatly depend on its integration with existing inter-well data sources (seismic). For the case of conventional reservoirs, Widarsono et al. (2004) highlight the relationship between resistivity and seismic attributes. A theoretical relationship is derived between resistivity and acoustic impedance and an Artificial Neural Network (ANN) is applied to predict resistivity at inter-well regions. Fractured reservoirs are significantly more complicated than conventional reservoirs and applicability of the relationship derived for the latter cannot be inferred to be valid for the former. Hence there is a need to investigate the relationship between resistivity and seismic attributes specifically for the case of NFR. Establishment of the relationship and its analysis can enable us to obtain more details on pore/fracture fluid properties from seismic data.

This paper derives the relationship between resistivity and seismic data attributes in fractured environment. The relationship is then verified by comparing resistivity values obtained from the equation with log measurement values. This comparison not only proves the validity of the relationship but also highlights additional factors that can be accounted for to improve the accuracy of the relationship. Finally the results are discussed in light of potential applications.

II. Mathematical Formulation

A mathematical model has been developed to relate resistivity of the naturally fractured porous medium with elastic properties of seismic waves. In contrary to conventional media, fractured media are greatly more heterogeneous. Additional parameters such as secondary porosity (porosity due to fractures), tortuosity, cementation exponent, partitioning coefficient, crystallisation and mineralisation have to be taken into account.

When a seismic wave passes through a rock, it induces a change in pore pressure which resists the compression and stiffens the rock. The speed of a P-wave in an elastic medium is given by (Mavko et al., 1998):

$$V_p = \sqrt{\frac{M}{\rho}} \quad \text{.... (1)}$$

where M is the P-wave modulus and ρ is the density of the medium.

The density of a fractured medium may be represented as a volumetric average of the constituent rock matrix and pore (and fracture) fluid densities as follows:

$$\rho = \phi_t \rho_f + (1-\phi_t)\rho_m \quad \text{.... (2)}$$

where ϕ_t, ρ_f and ρ_m represent the total porosity, fluid density and matrix density respectively. Considering water and hydrocarbon as the constituent fluids, fluid density is a simple volumetric average of the constituent water and hydrocarbon densities:

$$\rho_f = S_w \rho_w + (1-S_w)\rho_{hc} \quad \text{.... (3)}$$

where S_w, ρ_w and ρ_{hc} represent the water saturation, water density and hydrocarbon density respectively. From Eqns. 2 and 3, and assuming the pore space is only occupied by hydrocarbon and water, water saturation can be represented as a function of total porosity:

$$S_w = \frac{\rho - \rho_m + \phi_t(\rho_m - \rho_{hc})}{\phi_t(\rho_w - \rho_{hc})} \quad \text{.... (4)}$$

Substituting ρ from Eqn. 1 in terms of M and V_p:

$$S_w = \frac{M - V_p^2(\rho_m - \phi_t\rho_m + \phi_t\rho_{hc})}{V_p^2 \phi_t(\rho_w - \rho_{hc})} \quad \text{.... (5)}$$

Moreover, water saturation can also be presented as a function of porosity (ϕ) and resistivity (R_t). From Archie's equation (1942):

$$S_w^n = \frac{aR_w}{\phi^m R_t} \quad \text{....(6)}$$

However the Archie's equation is only valid for reservoirs where the inter-granular porosity is the sole porosity constituent. Two methodologies to make the Archie's equation applicable to NFR are: (1) selection of 'm' using a formation factor vs. porosity plot (Aguilera 1976) (2) calculation of ϕ_m as a function of primary and secondary porosity components (Aguilera 1976).

First, the cementation exponent (m) is related to the tortuosity of the pore space and so it is expected to decrease due to the presence of fractures. For the case of NFR, the porosity exponent m should be relatively small, ranging between 1.1 and 1.3 (Aguilera 1976). The Archie's equation relates formation resistivity factor (F) and porosity (ϕ) and can be expressed as:

$$F = \frac{a}{\phi^m} \quad \text{.... (7)}$$

Hence, the cementation exponent can be obtained as the slope from the log(F) vs. log(ϕ) plot.

Second, the equation below can also be used to extend the applicability of Eqn. 7 to fractured reservoirs (Aguilera 1976):

$$\phi^{-m} = \frac{1}{v\phi + {(1-v)}/{\phi_b^{-mb}}} \quad \text{.... (8)}$$

where ϕ_b is the matrix (primary) porosity with matrix porosity exponent m_b and v (partitioning coefficient) represents the fraction of total pore volume made up of fractures and is defined by:

$$v = \frac{\phi - \phi_b}{\phi(1-\phi_b)} \quad \text{.... (9)}$$

The above, being empirical relations, should be calibrated to the specific locations and formations of application. In the presence of shale, the equations must be modified to account for the shale effect on resistivity measurements.

Resistivity may now be represented as a function of porosity and seismic attributes. Substituting S_w from Eqn. 5 into Eqn. 6:

$$R_t = \frac{aR_w}{{M - V_p^2(\rho_m - \phi_t\rho_m + \phi_t\rho_{hc})}/{\left[V_p^2\phi_t(\rho_w - \rho_{hc})\right]^n}\phi^m} \quad \text{.... (10)}$$

where ϕ_m in the above equation can be obtained from Eqn. 8. In case the shear wave velocity and shear wave modulus μ is known, Eqn. 10 can be written as:

$$R_t = \frac{aR_w}{\mu - V_s^2(\rho_m - \phi_t\rho_m + \phi_t\rho_{hc}) / \left[V_s^2\phi_t(\rho_w - \rho_{hc})\right]^n \phi^m} \quad \ldots. \ (11)$$

P-wave velocity and density cubes can be obtained from a seismic inversion process and hence P-wave modulus (M) may be inferred from seismic data. Bakulin et al. (2000) have documented methods to obtain fracture parameters from reflection seismic for various fracture distribution models (single set, orthorhombic symmetry, monoclinic symmetry).

Eqn. 10 presents how resistivity can be obtained from seismic data in the case of NFR. Thus it is possible to obtain inter-well resistivity profile from seismic data which can provide much-needed information on the pore/fracture fluids. The presence of matrix density in the equation makes it susceptible to unknown changes in lithology at the inter-well region. However when 3D EM survey data is available, the resistivity profile can be used together with the seismic data to obtain matrix density profile at the inter-well region. This can prove to be a good indicator of lithology changes.

III. Case study

Data from a naturally fractured gas field are utilized to verify the applicability of the derived equation. This analysis also enhances understanding of the potential benefits and limitations of the relationship.

Resistivity values are obtained using Eqn. 10 at two well locations (wells A and B) and compared with direct measurements from resistivity logs. First, the tortuosity factor (a) is obtained as the intercept from a Picket plot (log(F) vs. log(ϕ)) from core samples. Second, water resistivity (R_w), a constant value, is available from the petrophysical study whereas bulk density (ρ) is obtained from the density log data. Third, matrix density (ρ_m) is obtained from petrophysical study of constituent rock type. Care should be taken when selecting this parameter especially in regions of varying lithology. Fourth, total porosity (ϕ_t), hydrocarbon density (ρ_{hc}) and water density (ρ_w) are available from the petrophysical study. Fifth, water saturation exponent (n) is set equal to cementation exponent (m) as per Aguilera's work (1976) on fractured reservoirs. Sixth, cementation exponent (m) is obtained as the slope from a Picket plot (log(F) vs. log(ϕ)) from core samples. The value obtained is relatively small as expected for NFR. The bulk density is utilised in place of the p-wave modulus (M) in the equation to obtain resistivity.

Two sandstone zones each are analysed in well A and B. Resistivity measurements from the log have been plotted against the theoretical values. Fig. 1 represents this comparison for the first zone for which the correlation co-efficient is calculated to be 0.96, which represents a high degree to which the calculated and measured values are linearly related.

Fig. 2 shows the same plot for the second zone of well A and the correlation co-efficient in this case is 0.88. The dashed line represents the x=y line whereas the solid line is the linear trend line.

Figs. 3 and 4 show the results in the zones 1 and 2 of well B. The correlation co-efficients are calculated to be 0.85 and 0.55 respectively.

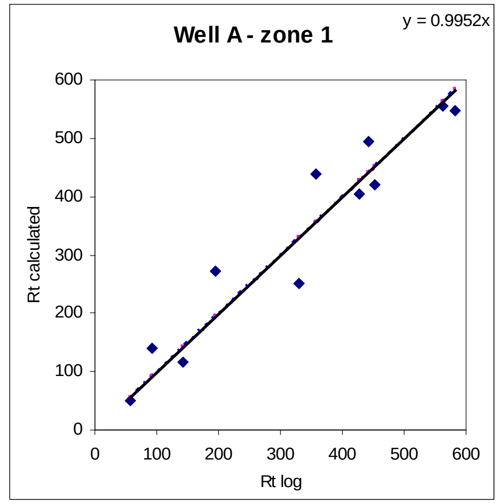

Fig. 1: Comparison of calculated resistivity values with log measurements for the first zone of well A; Correlation 0.96.

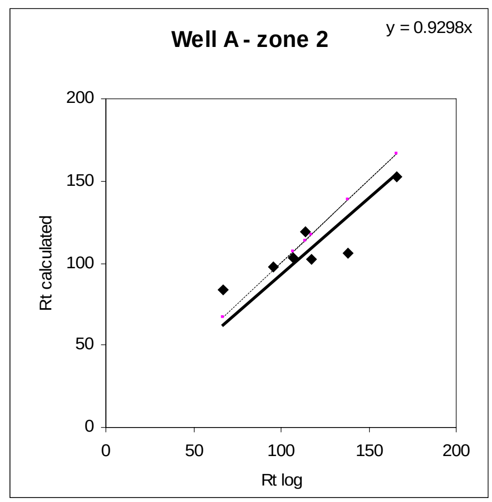

Fig. 2: For the second zone of well A; Correlation 0.88 (dashed line represents the x=y line; solid line is the linear trend line).

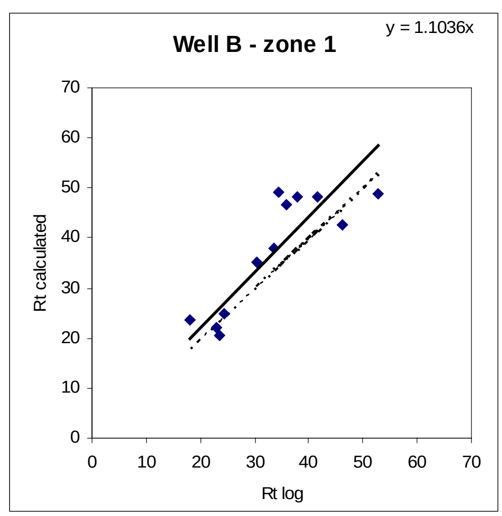

Fig. 3: For the first zone of well B; Correlation 0.85.

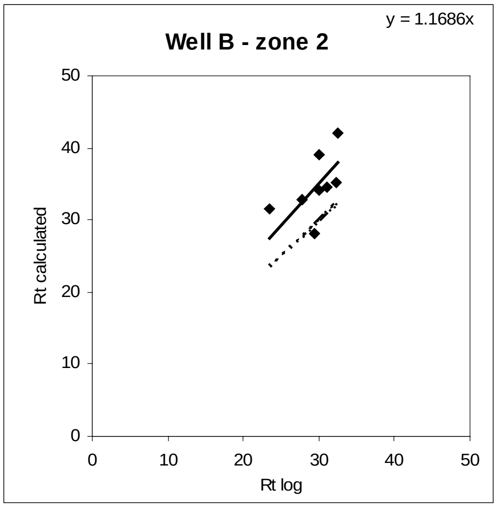

Fig. 4: For the second zone of well B; Correlation 0.55.

The comparison of the resistivity values calculated with the log values shows good results overall as evident by the correlation co-efficients obtained. Generally, higher correlation co-efficients are observed for well A. There are a number of reasons for this. First, one reason that can be inferred directly from log data is the presence of shale in the well B zones. Though corrections for shale have been applied to the calculated R_t based on the shale volume, these corrections may not be sufficient in this case. Second, another reason is mineral deposition which may lead to lower resistivity log measurements unaccounted for in the derived equation.

For each of the two wells, the correlation co-efficient also reduces with depth. The first zone of well A shows PEF (photoelectric factor) readings close to 2 (typical for sandstone). These readings are higher for well B and also exhibit a general increase amongst the zones with depth. Hence, the change in lithology may be the key factor behind the varying correlation co-efficients. Another factor to be considered is that temperature change has not been directly factored in Eqn. 10. Patzek et al. (2000) plot seismic velocity and electrical resistivity as a function of porosity, water saturation and temperature in water flooded sandstone cores. The plots show a higher sensitivity of the electrical resistivity to variations in reservoir conditions when compared to seismic velocity for the same conditions. While porosity and water saturation have been accounted for in Eqn. 9, temperature has not and therefore the calculated values for resistivity will not show an equivalent sensitivity to temperature change to what would be observed in the actual measurements.

IV. Application and Future trend

The field data verification enables us to identify significant directions for future research. These future directions would increase the accuracy of the inter-well pore fluid description by the inclusion of lithology and temperature changes. Moreover, having derived the theoretical relationship, application of ANN also becomes a logical choice to obtain values of resistivity from seismic data (as in Tran et al. 2006b).

The ANN may be trained at the well locations where the contribution of the drivers may be analysed and ranked. The networks can then be used to obtain resistivity values at the inter-well regions using the outputs of seismic inversion. It has been observed that the relationship is greatly affected by the matrix density and hence some input that indicates changes in lithology is desired. At the well locations such inputs are available in the form of Photoelectric Factors and Neutron Capture Spectroscopy etc. The relationship between such indicators and seismic may be investigated at the well location to see if seismic data is also able to provide the desired input for lithology indication.

This paper also delineates imperative avenues for the utilisation of new surveying technologies such as EM data for inter-well reservoir characterisation (in NFR) and sets the framework for methods that can be incorporated to improve the accuracy of the process. First, EM data provides the actual Rt measurements, which could be compared with the resistivity profile obtained from the derived relationship. Since Archie's equation has been used for the derivation, an underlying assumption for the equation is that water is the only constituent conductive element. Hence, differences between the predicted values from the equation and actual Rt measurements can be used to indicate zones in which changes in resistivity are not identified by Archie's equation (conductive minerals in fractures etc.). Differences between the predicted and measured Rt values can also indicate changes in matrix density and hence a lithology indicator can be derived at the inter-well regions using seismic and EM survey data. Second, in addition to being used as an input for the characterisation process, 3D EM data can also be used as a verification of fracture models derived from seismic. Moreover, EM surveys these days provide magneto-telluric (MT) in addition to resistivity data and so the use of MT data may also be analysed as an input for reservoir characterisation.

V. Conclusion

This paper presents a foundation relationship between elastic properties of seismic waves and resistivity of fracture medium. The relationship, being innovative in fracture heterogeneity, is validated by good results of the case study. The results show very good correlation, highlighting the efficiency of the approach. Analysis on zones of relatively lower correlation suggests that additional variables (lithology and temperature changes) need to be accounted for. As a direct result of this work, 3D and inter-well resistivity profile can be obtained from seismic data, which can provide much-needed information on the rock matrix/fracture system; pore/fracture fluids; mineral deposition in fractures (i.e. fracture identification), etc. In addition, by developing a foundation relationship, this work opens up several options to utilise new technologies in petroleum exploration. For example, when EM survey data is available, Resistivity profile can be obtained at inter-well regions from electromagnetic surveys, thus, allows higher definition of the rock matrix/fracture system and pore/fracture fluids. Comparison of the calculated resistivity profile from the derived equation with the measured values gives a direct indication of changes in lithology (including mineral deposition in fractures, matrix density profile, and hydrocarbon distribution) and this information is highly beneficial at inter-well regions. EM data can also be used to verify fracture models. Finally, the results of this work can be improved by incorporating corrections for lithological and temperature changes.

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