Optimization of Rock Physics Models by Combining the Differential Effective Medium (DEM) and Adaptive Batzle-Wang Methods in "R" Field, East Java

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Abstract

The pore systems in carbonate reservoirs are more complex than the pore systems in clastic rocks. There are three types of pores in carbonate rocks: interparticle pores, stiff pores and cracks. The complexity of the pore types can lead to changes in the P-wave velocity by up to 40%, and carbonate reservoir characterization becomes difficult when the S-wave velocity is estimated using the dominant interparticle pore type only. In addition, the geometry of the pores affects the permeability of the reservoir. Therefore, when modelling the elastic modulus of the rock it is important to take into account the complexity of the pore types in carbonate rocks. The Differential Effective Medium (DEM) is a method for modelling the elastic modulus of the rock that takes into account the heterogeneity in the types of pores in carbonate rocks by adding pore-type inclusions little by little into the host material until the required proportion of the material is reached. In addition, the model is optimized by calculating the bulk modulus of the fluid filler porous rock under reservoir conditions using the Adaptive Batzle-Wang method. Once a fluid model has been constructed under reservoir conditions, the model is entered as input for the P-wave velocity model, which is then used to estimate the velocity of the S-wave and the proportion of primary and secondary pore types in the rock. Changes in the characteristics of the P-wave which are sensitive to the presence of fluid lead to improvements in the accuracy of the P-wave model, so the estimated S-wave velocity and the calculated ratio of primary and secondary pores in the reservoir are more reliable.

Index Terms: carbonate reservoir, Differential Effective Medium (DEM), Adaptive Batzle-Wang, optimization, pore type

1. Introduction

Carbonate reservoirs are one of the principal types of oil- and gas-producing reservoirs worldwide. Unfortunately, carbonate rocks are more complicated in structure than siliciclastic rocks, with the result that carbonate reservoirs are usually harder to model than sand reservoirs. The primary difference between carbonate reservoirs and sand reservoirs is the distance traveled before deposition. Whereas carbonate rocks are formed by local deposition, the grains that comprise siliciclastic rocks may travel hundreds of miles down river systems before deposition and lithification. The fact that deposition is local significantly affects the heterogeneity of carbonate rocks.

One of the methods that is commonly used to characterize carbonate reservoirs is rock physics analysis. This method can be used to calculate the often very complex mix of pore types in carbonate rocks from their elastic moduli. In terms of their geophysics, the porosities in carbonate rocks can be divided into three types: interparticle or reference pores, which separate the carbonate grains and are considered to be the dominant pore types in carbonates; vuggy pores, which represent moldic and stiff pores and are

usually formed as a by-product of the dissolution of grains and fossil chambers; and cracks, which represent micro-fractures and micro-cracks.

There are several methods available for calculating the quantity and distribution of pore types in carbonate reservoirs. These include the Self-Consistent (SC), Kuster-Toksoz (KT), and Differential Effective Medium (DEM) methods. In a previous study, Rosid et al.[1] implemented the DEM method to characterize the pore types within a carbonate reservoir. Candikia et al.[2] have also compared the KT and DEM methods and they conclude that the Differential Effective Medium method is better than the Kuster-Toksoz method in generating the V_s log and determining the carbonate reservoir pore types. Therefore, we will use the DEM method to generate the pore logs and the V_s logs corresponding to the fluid conditions in the carbonate reservoir, by incorporating the physical parameters of the reservoir fluid as measured in situ and not taken from the literature. Our expectation is that the correlation coefficient between the P-wave velocity V_p predicted by the model and the measured values of V_p improves. The correlation should improve because the value of V_p is very sensitive to the presence of fluid in the reservoir, and the model can incorporate conditions that are closer to the actual situation in the "R" field.

The data used in this study were taken from three wells. The first well is called RZ-14, and information is available about the depth of this well, the values of the effective and total porosities, the water saturation, the mineral and fluid fractions, the primary velocity (V_p), the density and the shear wave velocity (V_s). The two other wells are called RZ-35 and RZ-09. The datasets for both of them cover the same parameters as for RZ-14, except for the values of *V*s which are not available for either well. The data is listed in ***Table 1***.

2. Methodology

2.1 Voigt-Reuss-Hill method

The Voigt-Reuss-Hill method is used to construct the background model of the mineral mix in the solid rock phase in the carbonate reservoir. This method is effectively an average of two precursor methods, namely the Voigt method which arranges the rock matrix in series and Reuss method which arranges the rock matrix in parallel. Constructing a model of the solid rock phase is only a first step in carbonate reservoir modelling, as it assumes that the rock has 0% porosity and so consists entirely of minerals such as clay, dolomite and calcite. The bulk and shear modulus of the solid rock phase are calculated using the Voigt-Reuss-Hill formulas shown below:[3]

Voigt Method

$$M_V = \sum_{i-n}^{N} f_i . M_i$$

where M_V : Voigt elastic modulus
f_i : mineral fraction
M_i : elastic modulus of mineral

Reuss Method

$$\frac{1}{M_R} = \sum_{i-1}^{N} \frac{f_i}{M_i}$$

where M_R : Reuss elastic modulus
f_i : mineral fraction
M_i : elastic modulus of mineral

Voigt-Reuss-Hill Method

$$M_{VRH} = \frac{M_V + M_R}{2}$$

where M_V : Voigt elastic modulus
M_R : Reuss elastic modulus
M_{VRH} : Voigt-Reuss-Hill elastic modulus

2.2 Adaptive Batzle-Wang method

The Adaptive Batzle-Wang method is our modification of the standard Batzle-Wang method. The advantages of this method is that it can be adjusted to the field conditions in the location where the study is being performed. As a result, the fluid parameters can be chosen to be close to the reservoir conditions in that field. In the Adaptive method, the elastic parameters of the fluids are not necessarily the same at each depth and the distributions of the individual bulk moduli such as K_{water}, K_{oil}, and K_{gas} can be inserted in Wood's formula to calculate the bulk modulus of the fluid mixture at each depth in the reservoir. If we were not using Adaptive Batzle-

Wang method the elastic parameters of the fluids would be the same at each depth and the Differential Effective Medium method would not be optimized for the conditions in the reservoir.

Table 1. Availability of petrophysics data.

Parameter	RZ-14	RZ-09	RZ-35
Depth	√	√	√
Effective Pore	√	√	√
Total Pore	√	√	√
Water Saturation	√	√	√
Mineral Fraction	√	√	√
Fluid Fraction	√	√	√
V_p	√	√	√
V_s	√	X	X
Density	√	√	√

2.3 Wood's formula

Wood's formula is used to calculate a value for the mixed bulk fluid modulus at each depth in each well. The individual values of the bulk moduli for water, oil and gas are usually taken from the literature. But in order to optimize the DEM method for the conditions in the reservoir the elastic parameters of the fluids are calculated in advance using the Adaptive Batzle-Wang method and then entered into Wood's formula. The elastic modulus of the fluid mixture is calculated from the equation below:[3]

$$\frac{1}{K_{FL}} = \frac{S_{Water}}{K_{Water}} + \frac{S_{Oil}}{K_{Oil}} + \frac{S_{Gas}}{K_{Gas}}$$

where, K_{FL} : elastic modulus of fluid mixture
S_{water} : water saturation
S_{oil} : oil saturation
S_{gas} : gas saturation
K_{water} : water bulk modulus
K_{oil} : oil bulk modulus
K_{gas} : gas bulk modulus

2.4 Differential Effective Medium method

A common method used to model the elastic properties of a porous rock is the DEM (Differential Effective Medium) method. The principle behind the DEM method is that a two-phase composites can be constructed by incrementally adding a small fraction of pores to the rock matrix. In the DEM method, the effective moduli depend on the path taken to construct the final composite. In effect, the DEM method works by inserting inclusions into the background model, with the model continuously changing as the inclusions are added:[3]

$$(1-y)\frac{d}{dy}\left[K^*(y)\right] = (K_2 - K^*)P^{(*2)}(y)$$

$$(1-y)\frac{d}{dy}[\mu^*(y)] = (\mu_2 - \mu^*)Q^{(*2)}(y)$$

where y : porosity
$K^*(y)$: the effective bulk moduli of DEM
K^* : bulk moduli of matrix (phase 1)
K_2 : bulk moduli of inclusion (phase 2)
$P^{(*2)}$: geometry factor for an inclusion of material 2 in a background medium with effective moduli K^* and μ^*
$\mu^*(y)$: the effective shear moduli of DEM
μ^* : shear moduli of matrix (phase 1)
μ_2 : shear moduli of inclusion (phase 2)
$Q^{(*2)}$: geometry factor for an inclusion of material 2 in a background medium with effective moduli K^* and μ^*

The steps that are followed in the DEM method are not significantly different from those in the KT method. Like the KT method, the DEM method starts with a background rock matrix, the geometry factor, the elastic moduli of the inclusions and the fraction of inclusions as inputs. The difference between the methods lies in how these inputs are used. The background rock matrix is constructed using the Voight-Reuss-Hill method. Instead of looping the aspect ratio, the DEM method uses the value of the

aspect ratio as an input to generate the geometry factor. There are three aspect ratio values that need to be determined, namely the aspect ratios of the interparticle pores, the stiff pores and the cracks. These three values are fixed by the Zhao classification, which divides the values of the aspect ratio into three groups. The aspect ratio representing cracks ranges from 0.01-0.02, that for the interparticle pores ranges from 0.12-0.15, and that for the stiff pores varies between 0.7-0.8. The third step is to calculate the reference value of V_p with the assistance of the DEM equation, which depends on the aspect ratio of the interparticle pores, the fraction of inclusions or porosity, the elastic moduli of the rock matrix and the elastic moduli of the inclusions. The reference value of V_p acts as a controller, determining whether stiff pores or cracks are to be added to the rock matrix. If the reference value of V_p is lower than the measured value of V_p then stiff pores are added. But if the reference value of V_p is higher than the measured value of V_p then cracks are added to the matrix. Once the process is complete, the effective elastic moduli are calculated and compared with the actual data, so that the most representative model can be chosen.

3. Results and Discussion

The first step in the modelling process is to construct the background model using the Voight-Reuss-Hill method, from which we obtain the bulk and shear modulus of the solid rock phase under the assumption of 0% porosity. The values of the bulk and shear modulus of the solid rock phase are used as inputs to calculate the pore type inversion and estimate the value of V_s via the DEM method. The results of this step are shown in ***Figure 1***, ***Figure 2*** and ***Figure 3***.

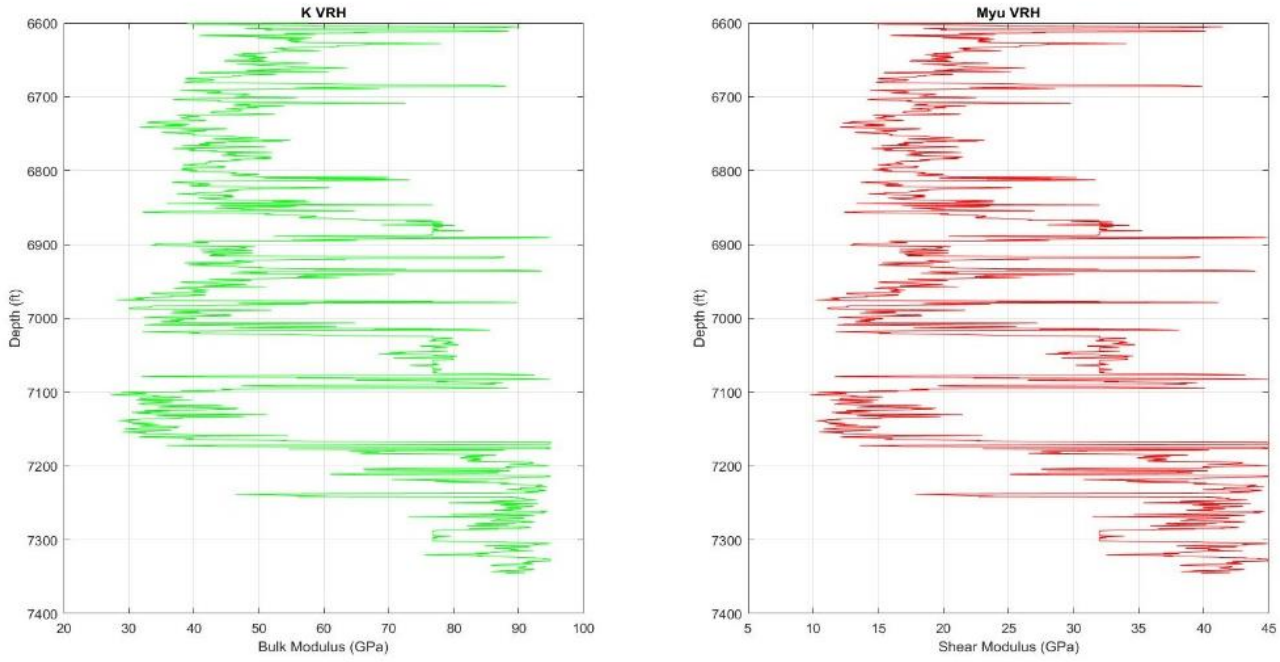

Figure 1. Bulk and shear modulus of solid rock model in RZ-14.

The fraction of secondary pore types - the stiff pores and cracks - is then calculated. The value of the S-wave velocity V_s in each well for which no V_s data is available is then estimated. In this step, we compare the results of the DEM method before and after optimization using the elastic moduli of the fluids generated by the Adaptive Batzle-Wang method. The Adaptive Batzle-Wang method is used to calculate the elastic moduli of the fluids at each depth under reservoir conditions, as shown in ***Figure 4***, ***Figure 5*** and ***Figure 6***.

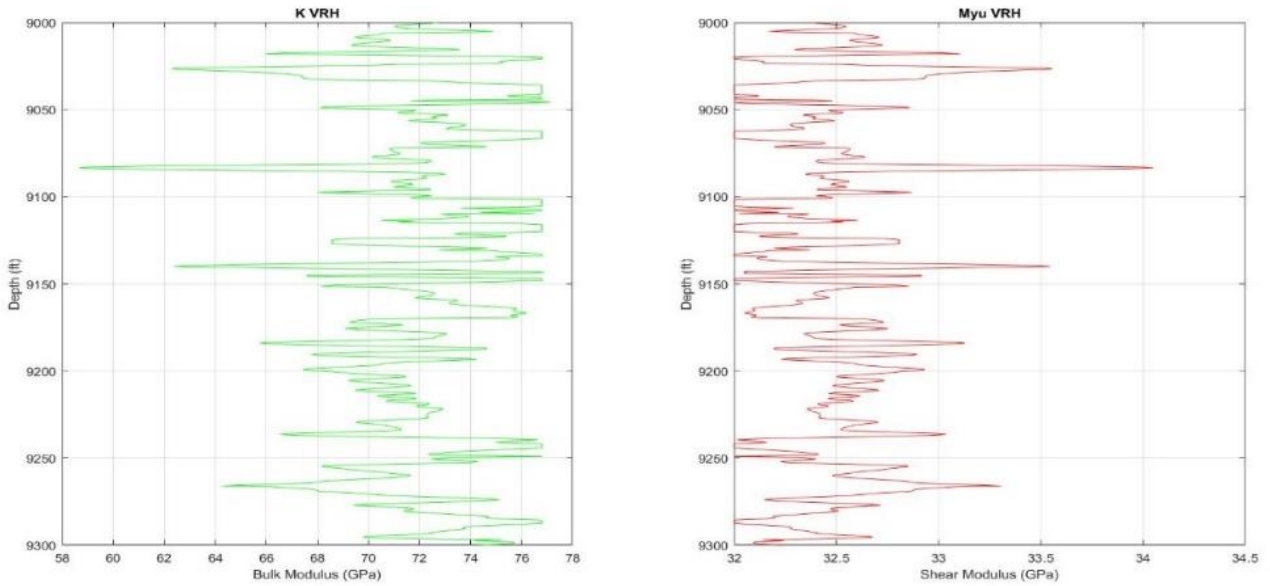

Figure 2. Bulk and shear modulus of solid rock model in RZ-09**.**

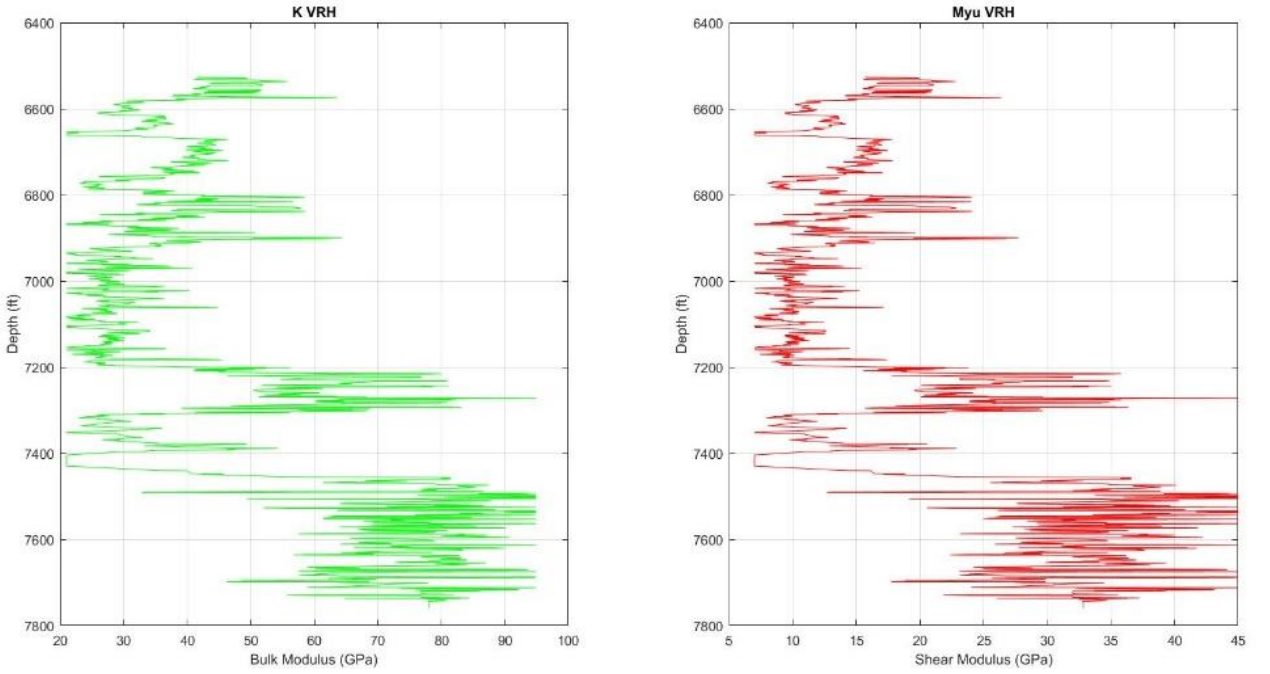

Figure 3. Bulk and shear modulus of solid rock model in RZ-35.

The fraction of secondary pore types and the estimated values of V_s in each well are then calculated using the DEM method. The DEM method models the porosities in the rocks. After applying this method, the likely pore types can be determined and the shear wave velocity can be estimated based on the effective moduli of the rocks. To determine the likely pore types, the inclusions are added to the rock matrix, after comparing the reference value of V_p to its measured value. To calculate the reference value of V_p we start with a rock~~s~~ model which contains 100% interparticle (dry rock) pores. The secondary pore type is added step by step, with a 1% fraction of inclusions added at each step to the dry rock model, until the value of V_p in the

model approaches the measured value of V_p. The value of V_p in the model is calculated using the DEM equation by inserting the effective bulk and shear modulus values into the equation for V_p, so as to ensure that the inclusion we add is of the appropriate type, as can be seen in ***Figure 7***, ***Figure 8*** and ***Figure 9***.

As can be seen in ***Figure 7***, the RMS error for RZ-14 decreases and the cross plot tends to be more linear after optimization because we have used more accurate input parameters. The more accurate input parameters we use, the more the RMS error value will decrease and the more accurate the calculated fraction of secondary pore types will be in each well.

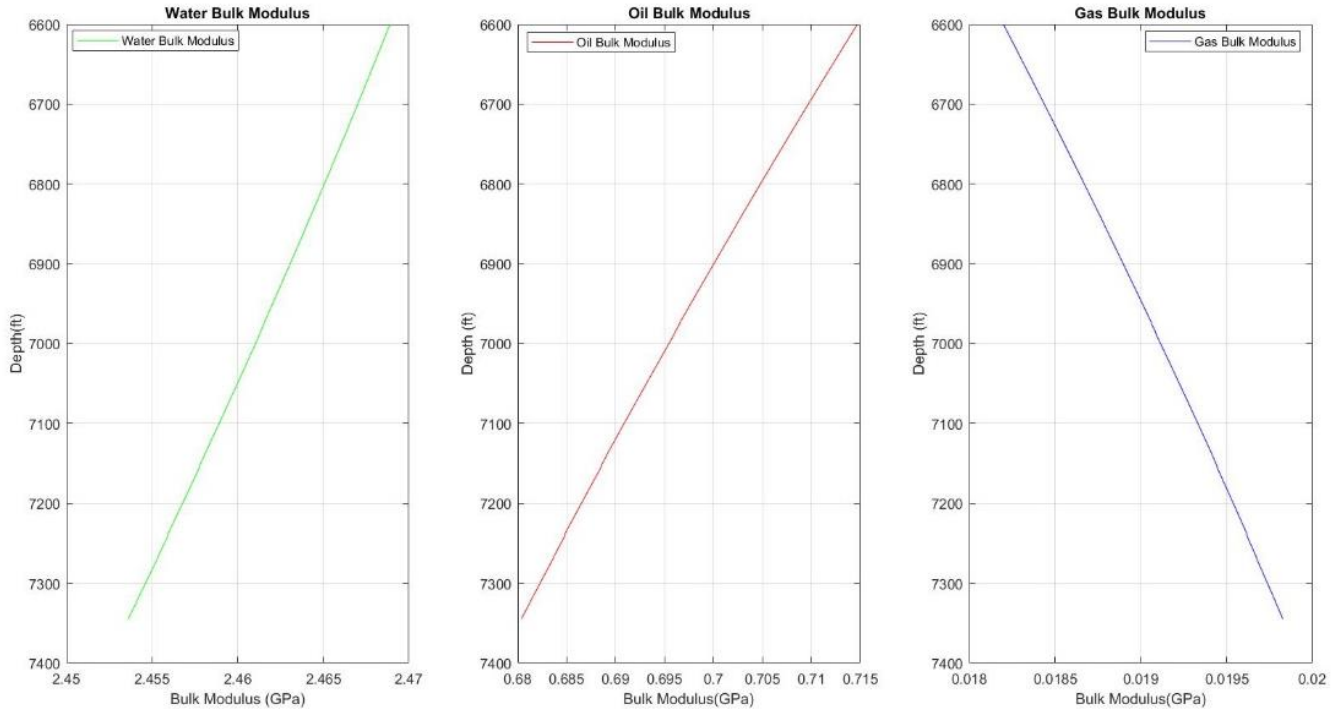

Figure 4. Bulk and shear modulus of solid rock model in RZ-35.

For well RZ-09, in ***Figure 8***, the DEM method is again successfully optimized and the RMS error decreases from 0.015256 to 0.015008. The final model should be a more accurate approximation to the actual conditions in the carbonate reservoir.

For well RZ-35, in ***Figure 9***, the model is again successfully optimized and the RMS error also decreases from 0.066157 to 0.065033, although there is still data scatter in the high clay zone. There is good reason to believe that there is no fluids content in the high clay zone, because of the impermeability of clay. So optimization using the Adaptive Batzle-Wang method may not be effective in the high clay zone.

We next compare the pore types calculated using the DEM method before and after optimization in ***Figure 10***. If we pay close attention to this figure, we can see the different fractions of secondary pore types before and after optimization. The differences are evident not only in the marked yellow boxes, but appear also along the whole range of well depths. The improved accuracy of the optimized pore type fractions is confirmed by the smaller RMS error in the cross plot between the value of V_p from the model and the measured value of V_p. However, in this figure the differences in the fractions of the secondary pore types are mostly not noticeable, unless we flip the image back onto itself.

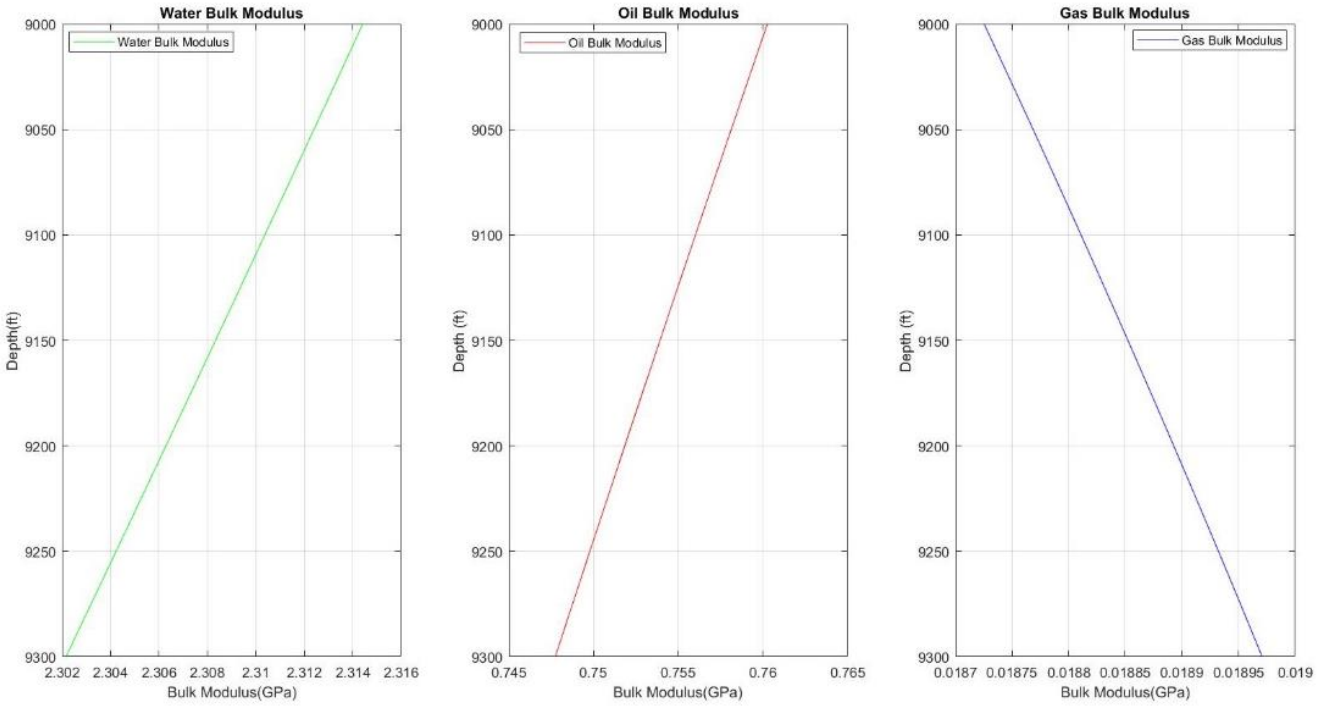

Figure 5. Elastic moduli of water, oil, and gas in RZ-09.

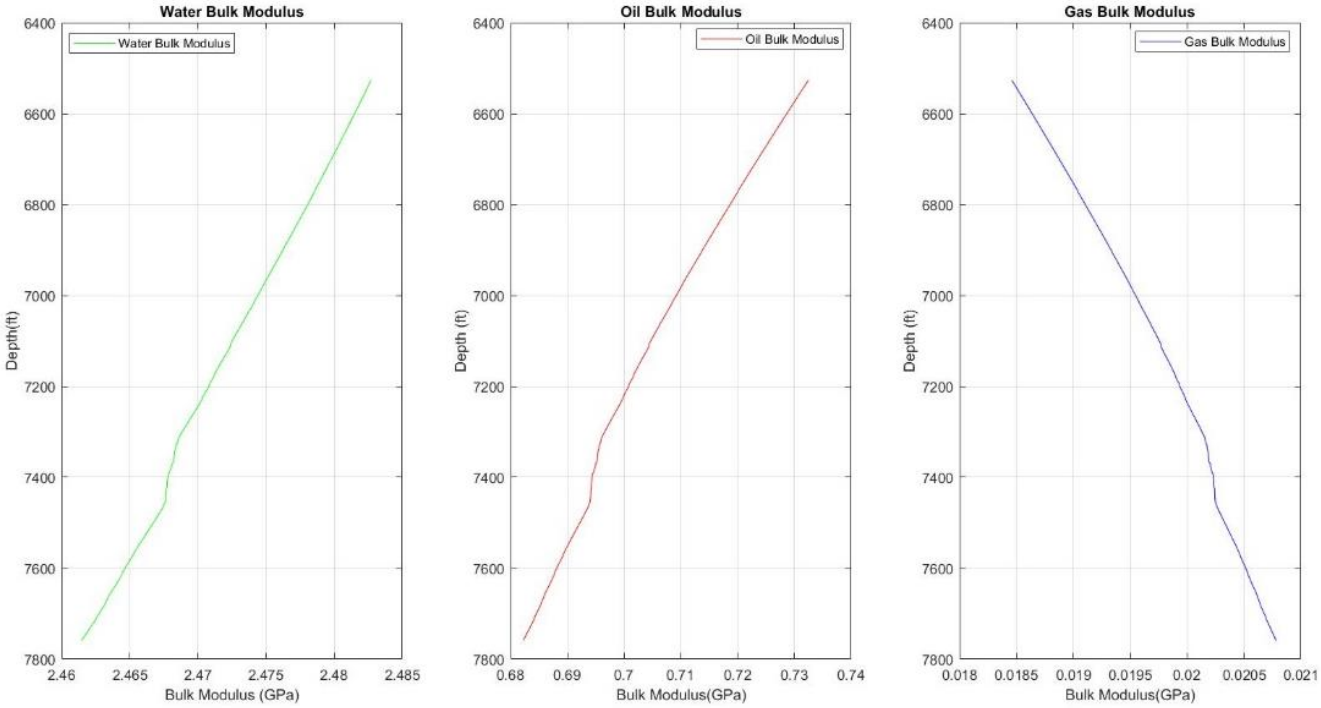

Figure 6. Elastic moduli of water, oil, and gas in RZ-35.

From ***Figure 14*** we can see the correlation coefficient between the values of V_p and V_s predicted by the model after optimization based on those results. ***Figure 14***, ***Figure 15*** and ***Figure 16*** show that the V_p – V_s trend has a quadratic correlation. The parabolic trend indicates that the reservoir in this research area is limestone, based on the Castagna's empirical V_p - V_s formula.[4]

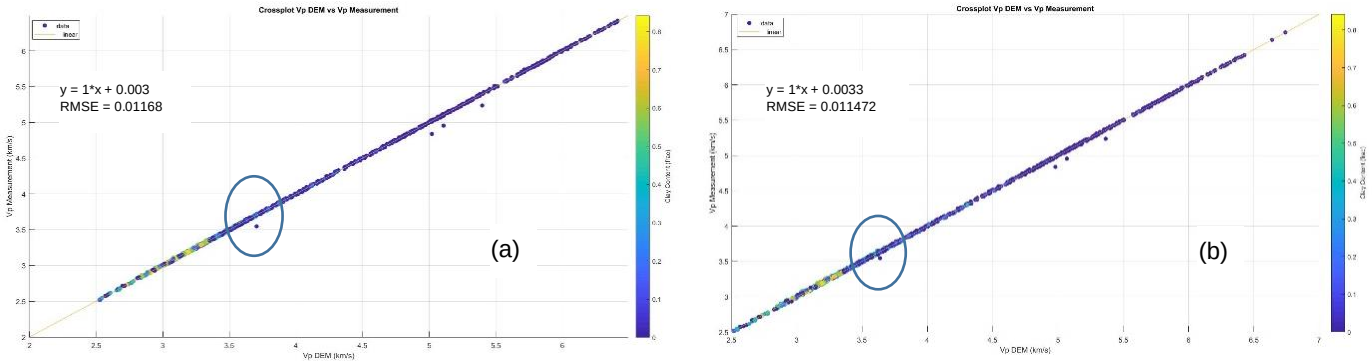

Figure 7. Cross plot between the value of V_p from the model and the measured value of V_p (a) before and (b) after optimization in RZ-14.

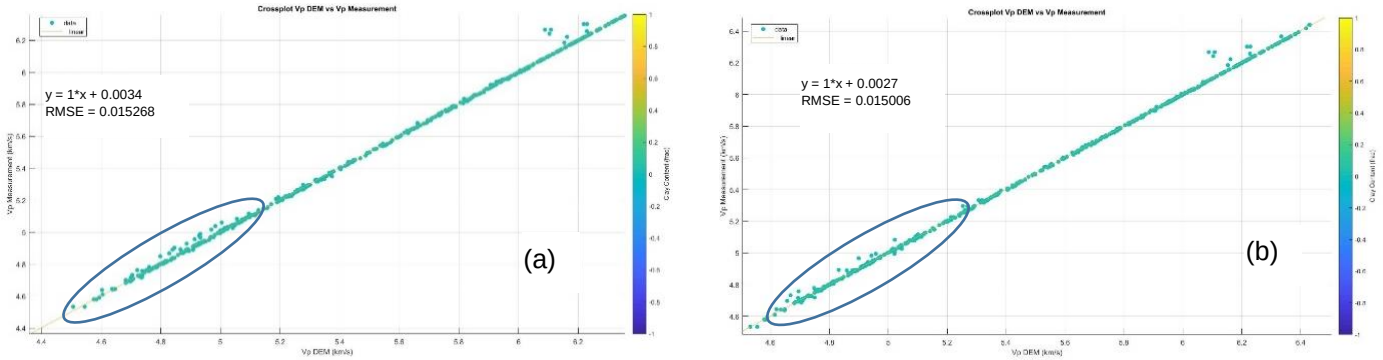

Figure 8. Cross plot between the value of V_p from the model and the measured value of V_p (a) before and (b) after optimization in RZ-09.

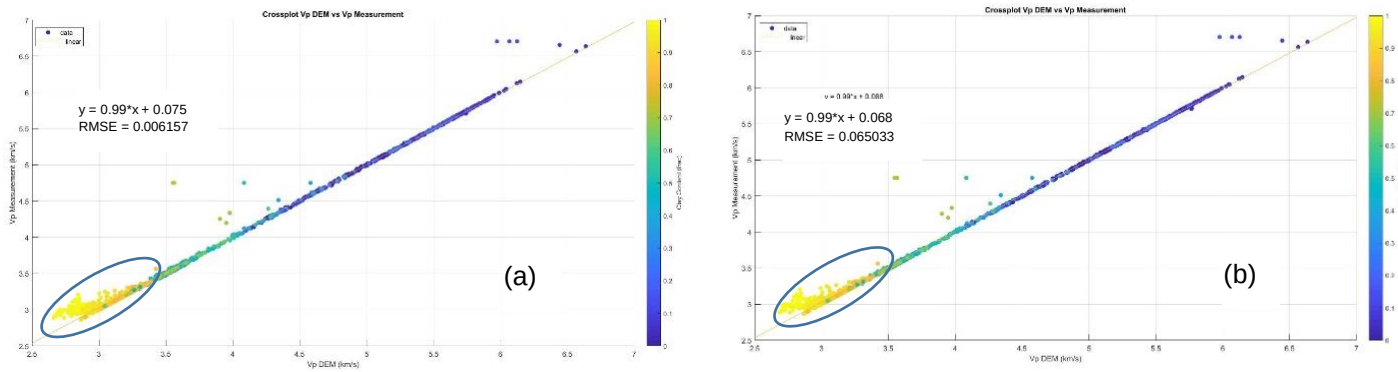

Figure 9. Cross plot between the value of V_p from the model and the measured value of V_p (a) before and (b) after optimization in RZ-35.

In RZ-09 the quadratic correlation coefficient is less than the linear one. This might be caused by the data scatter in RZ-09. In this case we conclude that there is some quartz mineral in the formation causing the linear correlation to be higher than the quadratic one, in line with the empiric V_p - V_s formula.[4]

4. Conclusion

Optimization of the rock physics modelling package DEM4 using fluid parameters obtained from the Adaptive Batzle-Wang method was successfully performed for the three wells RZ-14, RZ-09 and RZ-35. The value of the RMS error in the cross plot of the measured values of V_p against the values of V_p predicted by the model

can be minimized for each well, generating a rock model which closely approximates the actual conditions in the "R" field.

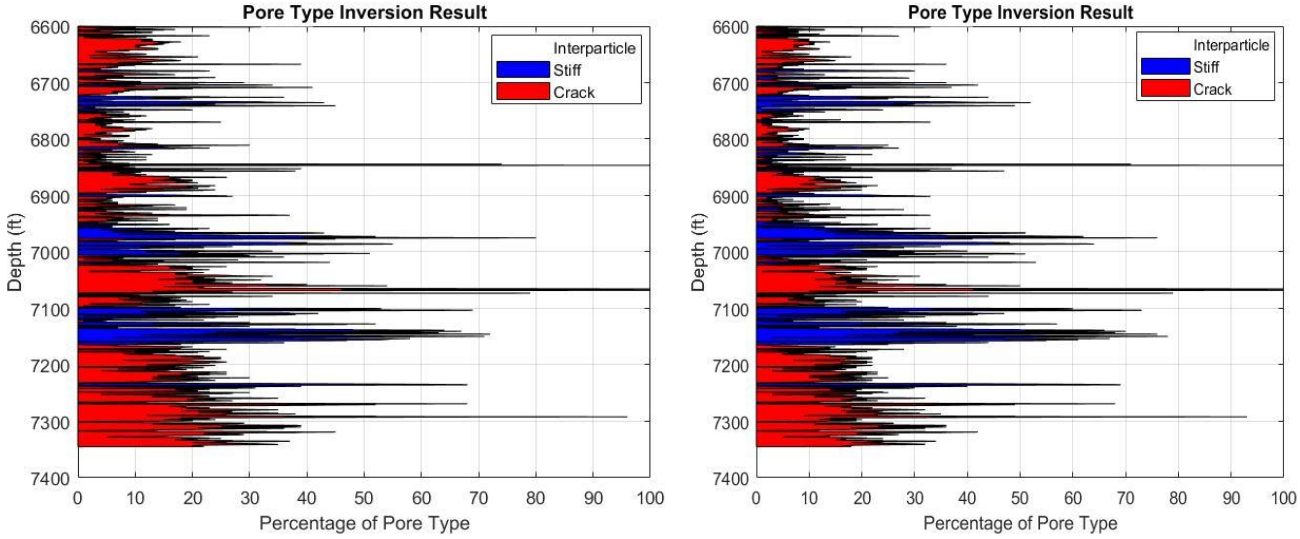

Figure 10. Pore Type Inversion before (left) and after (right) optimization in RZ-14.

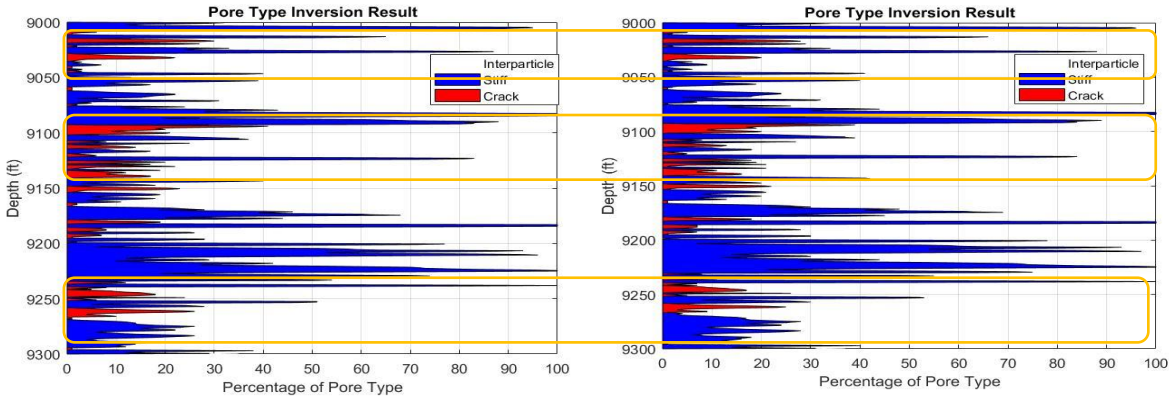

Figure 11. Pore Type Inversion before (left) and after (right) optimization in RZ-09.

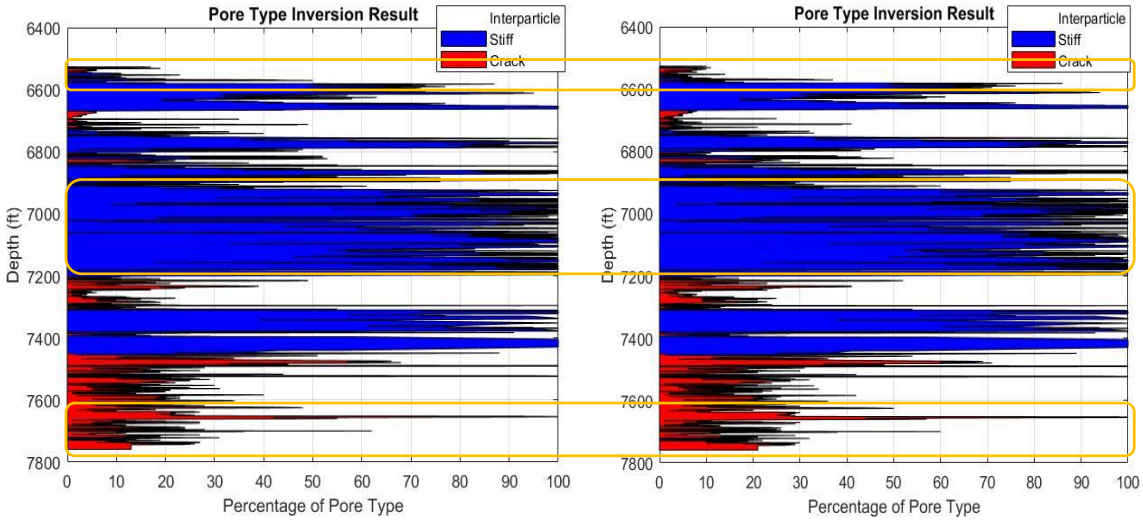

Figure 12. Pore Type Inversion before (left) and after (right) optimization in RZ-35.

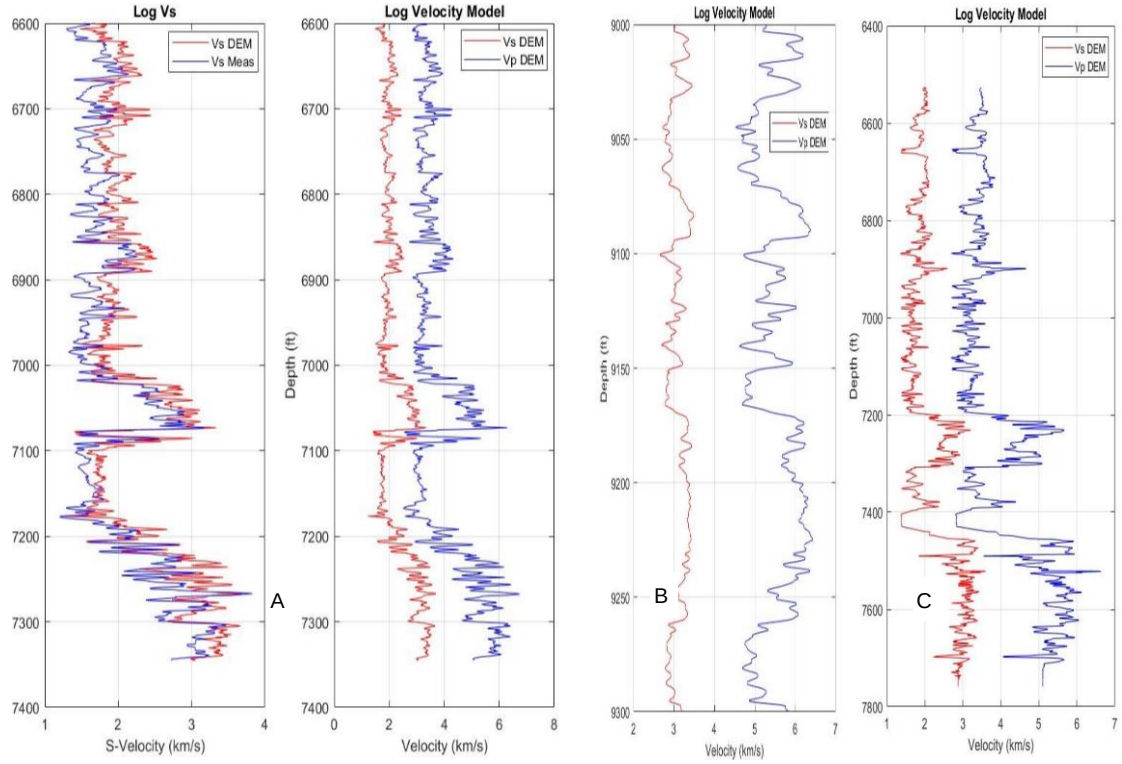

Figure 13. Optimized V_p and V_s log results in each well: (A) RZ-14, (B) RZ-09 and (C) RZ-35.

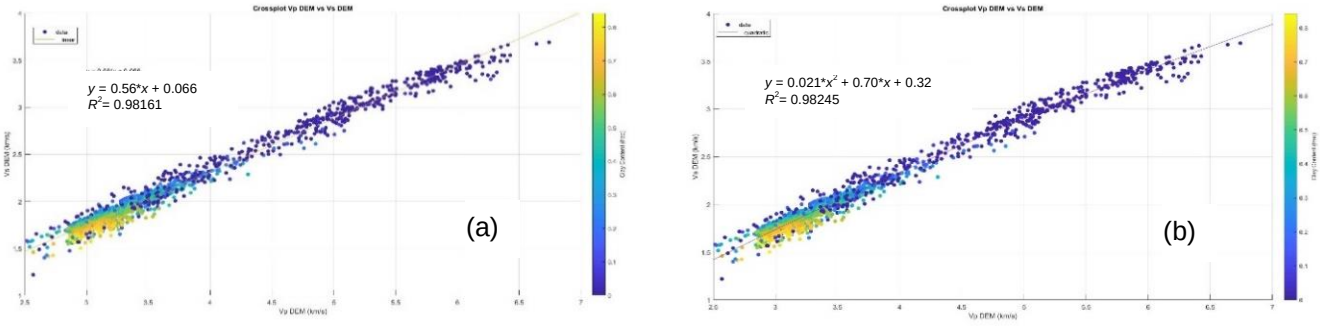

Figure 14. Cross plot between the values of V_p and V_s predicted by the model after optimization in RZ-14 using the (a) linear and (b) quadratic approach.

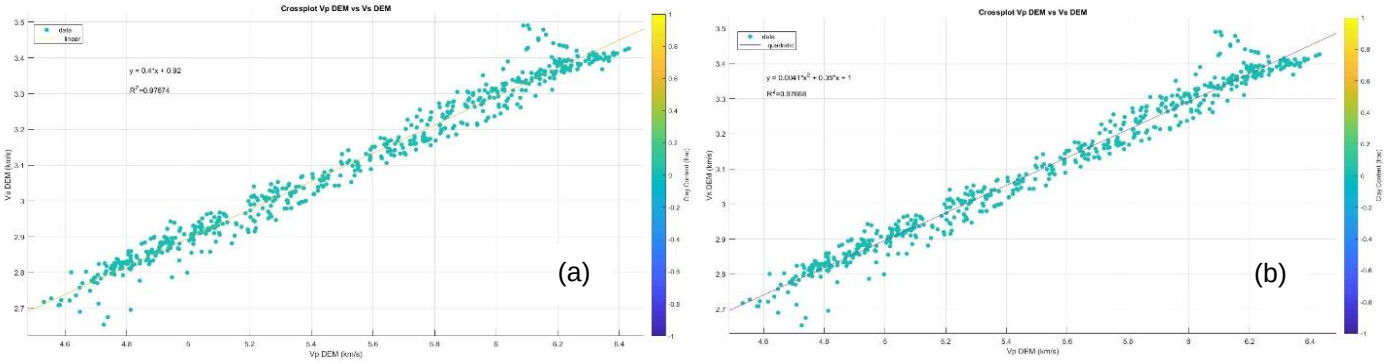

Figure 15. Cross plot between the values of V_p and V_s predicted by the model after optimization in RZ-09 using the (a) linear and (b) quadratic approach.

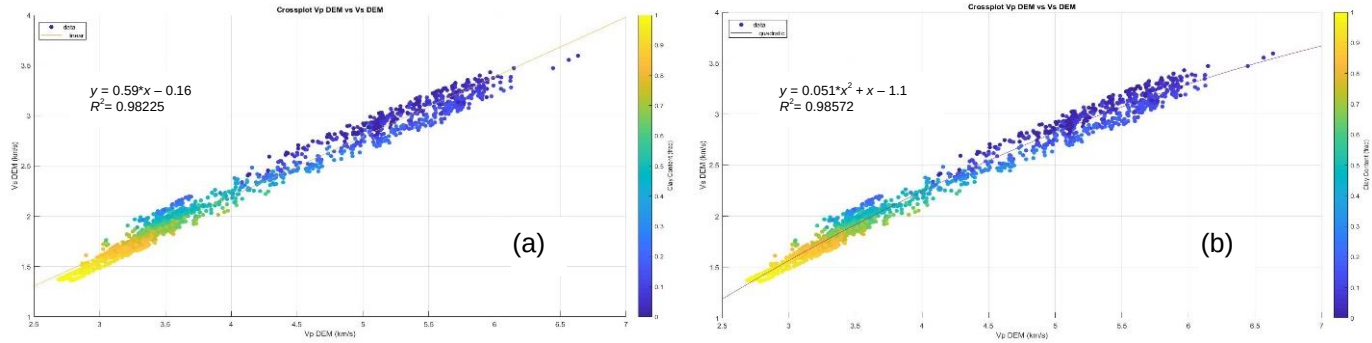

Figure 16. Cross plot between the values of V_p and V_s predicted by the model after optimization in RZ-35 using the (a) linear and (b) quadratic approach.

Acknowledgements

We would like to thank JOB–PERTAMINA Petrochina East Java for its permission to publish this data, as well as DRPM Universitas Indonesia for its financial support through the 2017 PITTA grant No. 663/UN2.R3.1/HKP.05.00/2017.

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