Comparing some Rock Physics Methods that link Elastic Properties to relevant characteristics of Carbonate Reservoir

[1]Fredy A. Villaorduna Artola; [1]Carlos Sanz; [1]Julio H. Villalobos; [1]Roberto Castaneda, [1]Marcelo [1]Borderas and [1]Janet Ravelo.

[2]Rodolfo V. Camacho; [2]Blanca V. Gonzales; [2]Francisco Olarte; [2]Luis G. Alpires; [2]Arlen D. Garrido and [2]Osiel Flores

[1] Petrotechnical Services, Schlumberger, Mexico
[2] Pemex, Mexico

Abstract

In this article, we show the results obtained by the analysis performed on a heterogeneously fractured carbonate reservoir of mid cretaceous age at T-X Field, Gulf of Mexico, using three different rock physics approaches. Our motivation is to compare the robustness of three important rock physics methodologies and how the application of each of these methods can help us, in different ways, to understand the reservoir.

Introduction

Carbonate reservoirs continue occupying our attention because of its extraordinary complexity and the amazing manner of printing its singularity on various geophysical measurements. The more we try to understand the intricate mechanisms that determine the evolution of rock matrix construction and reconstruction, the thermodynamics that controls the directionality of interactions and mineralogical changes, the secondary changes of matrix frame due to effects of under saturated fluids and / or organic acids, configuration and reconfiguration of the pore space, the relations between these process and fracturing propensity at several scales, the more we are confronted with the intriguing details of the multiform and unexpected form of occurrences of these kind of rocks.

Because the importance of carbonate reservoirs in the oil industry, there have been many published studies of several topics about them. Regardless the approach, all of them are inspired on the need to characterize, in the best possible way, the non intuitive link among pore space storage capacity and hydraulic connectivity with carnonates elastic response. Understanding these singularities have direct implications on conceptualization process related to the static and dynamic aspects of carbonate reservoir characterization. This understanding is mandatory, mainly when we are planning and expecting a successful field development.

From the geophysical point of view, the main challenge is to establish meaningful relationships between carbonate rock features and elastic response in order to perform predictions related to reservoir properties using seismic attributes derived through robust inversion algorithms. In establishing these links, several models have been proposed based on Rock Physics theories and methodologies. Some of these are qualitative methods useful to discriminate reservoir intervals with good pore-space storage capacity and hydraulic connectivity. There are also, predictive rock physics models (quantitative analysis) that can be used to quantify fracture concentration indexes, stiff pores concentration and flexibility factor as direct link to permeability.

It is important to mention that this case of study is related to a carbonate reservoir with low matrix porosity (2-4%), potential presence of micro fractures and a significant variability of the pore structure. Although the well image interpretation shows a fracture density between 1-4 fractures per meter, this low fracture density (visible fractures) cannot explain the excellent response of the formation during the well production testing. Due to this inconsistence, some studies have been promoted to determine whether the assumption of a significant presence of micro fractures affecting the reservoir can be supported. This assumption is strengthened by the evidence found in thin sections (Figure 1).

Some theoretical studies show an unmistakable response of fractures to acoustic measurements (Sayers 2008), taken into account this theoretical consideration and if the rock that we are dealing with is actually affected by fractures, we should expect an obvious elastic response once the influence of irregularities of the borehole wall or high content of free gas are discarded. The approaches used in this study are, first, the velocity deviation method to predict pore type and possible permeability trends (Anselmetti and Eberli, 1999); second, the approach of Keys and Xu (2002) based on the extension of Xu and White model for carbonates (1995, 1996), and third, the approach that consider the pore structure-space effect on wave propagation (frame flexibility factor) based on the extension of Biot poroelastic theory developed by Sun (1994) and Sun and Goldberg, (1997).

Velocity deviation method

One feature of the carbonates rocks is the large dispersion in the relationship Vp-porosity. By considering this general behavior, it is not possible to directly, assess and / or forecasts rock properties (such as porosity, permeability, etc.) in a rigorous sense. This is because rocks with the same velocity value can be associated with rocks with very different porosities. Similarly, rocks with the same porosity value may have a notable difference on acoustic responses (velocities). In these scenarios, each point (data) must be understood in terms of their structural micro singularities. According to Anselmetti & Ebelli, 1999; Gregor et al., 2003 and others, the Wyllie`s time average equation can reasonably describe the trend of Vp-Porosity relation for rocks with inter particle porosity, inter crystalline porosity and micro porosity. The Wyllie`s equation can be written as:

$$\frac{1}{V_{rock}} = \frac{1-\phi}{V_{matrix}} + \frac{\phi}{V_{fluid}} \qquad (1)$$

In order to understand the physical meaning of the dispersion on the relation Vp-porosity due to heterogeneity of pore space types, Wyllie`s equation can be used to associate the (Vp-PHI) pair location to some pore structure type in function to its relative position to Wyllie`s curve. The pairs located above Wyllies`s curve will correspond, predominantly, to rocks with moldic or vuggy pores and/or carbonates affected by diagenetic alteration and intense precipitation. Furthermore, the pairs located below Wyllie`s curve will correspond, predominantly to carbonates affected by fractures (Figure 2). This intuitive assumption can be reasonable if there is no caving or irregularities of the borehole wall or high content of free gas. Based on this, we can obtain the deviation of Vp (measured data) relative to the curve obtained by Wyllie equation. Then:

$$\Delta V = Vp - V_p^{wyllie} \qquad (2)$$

In general,negative deviation values should correspond to reservoir intervals potentially affected by fractures. These fractures, depending on how they are embedded in the rock, may play an important role in the storage capacity and hydraulic connectivity of the pore space. Thus, the negative velocity dispersion could be associated to permeability. Following the logic of the method, positive deviations, in general, could be related to stiff pores or rocks affected by process of diagenetic alteration (it would have an obstructive effect in pore space connections). In other words, diagenesis would have a negative impact on permeability. This simple technique has significant potential as a diagnostic tool, but should be carefully applied because the complexity of pore space structure can be much more complicated than we think. In fact, it is possible to find some cases of carbonates with positive Vp deviation with a considerable pore space connectivity generated by some special diagenetic mechanism occurred at certain stages of modification of the primary or secondary porosity (not necessarily linked to fractures).

Keys and Xu's Approach for carbonates

Key and Xu (2002) derived the dry rock approximation solution of the DEM equations which dramatically simplifies the numerical computation of the coupled DEM equations. In order to apply to a specific rock, the pore space is partitioned into sets of pores, where the concentration of pores for each set must satisfy the conditions of Kuster and Toksoz (1974) equations. Thus, using the DEM scheme, Kuster-Toksoz (1974) equations converge to:

$$(1-\phi)\frac{dK}{d\phi} = \frac{1}{3}\left(K^{'} - K\right)\sum\nolimits_{l=S,C.} \nu_l T_{iijj}(\alpha_l) \qquad (4)$$

$$(1-\phi)\frac{d\mu}{d\phi} = \frac{1}{5}\left(\mu^{'} - \mu\right)\sum\nolimits_{l=S,C} \nu_l F(\alpha_l) \qquad (5)$$

where v_S and v_C are the volume fractions associated to stiff and compliant pores respectively (eg., moldic and fracture related pore space). The solutions of the equations 4 and 5 must be obtained numerically. By considering the special case of dry rock, the solution to this approximation is simplified as follows:

$$K(\phi) = K_o(1-\phi)^p \qquad (6)$$

$$\mu(\phi) = \mu_o(1-\phi)^q \qquad (7)$$

where,

$$p = \frac{1}{3}\sum_{l=S,C} \nu_l T_{lljj}(\alpha_l) \qquad (8)$$

$$q = \frac{1}{5}\sum_{l=S,C} \nu_l F(\alpha_l) \qquad (9)$$

where T_{iij} and F are functions of pore aspect ratio α_l. The pore space details are introduced using Xu-White methodology as an extension for carbonate case. The pore volume can be divided into different fractions depending on the predominant rock type (eg stiff pores, compliant pores, etc). After calculation of dry rock modulus, fluid effects are added by Gassmann`s equations or any other fluid substitution equations. In this way, it is obtained the final effective modules of saturated rock that is used in the process of velocity calculation.

Biot's theory extension for structural pore-space models

In order to provide a representation of the internal structure of a fine scale fractured porous medium, Sun (1994) developed a topological characterization of structural media that can provide a quantified consideration of internal structure of a fractured porous medium at microscopic scale, investigating the general mechanics and thermodynamics of fractured porous media. This author performed an extension of Biot`s theory for media containing interacting fractures. The poroelastic equation that describes porous fractured medium (without considering viscoelastic effects) is written as:

$$\begin{pmatrix} \rho^{11} & \rho^{12} \\ \rho^{21} & \rho^{22} \end{pmatrix} \frac{\partial^2}{\partial t^2} \begin{pmatrix} u^1 \\ u^2 \end{pmatrix} = \begin{pmatrix} P & Q \\ Q & R \end{pmatrix} \nabla\nabla . \begin{pmatrix} u^1 \\ u^2 \end{pmatrix} - \begin{pmatrix} N & T \\ T & S \end{pmatrix} \nabla X \nabla X \begin{pmatrix} u^1 \\ u^2 \end{pmatrix} - bF \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix} \frac{\partial}{\partial t} \begin{pmatrix} u^1 \\ u^2 \end{pmatrix} \qquad (10)$$

where u^1 and u^2 are the solid and fluid phase displacements respectively. *P, Q, R, N, S* and *T* are functions that depend on intrinsic modules of solid and fluid phases, ρ is the density, b is a constant and *F* is a parameter containing information about the micro structure, velocity related to solid and fluid phases and dynamic tortuosity. This equation differs from the Biot`s equation due to its advantage of allowing, explicitly, the definition of phenomenological parameters in terms of basic geometric parameters related to the internal structure and the physical parameters related to the solid and fluid components of the material.

The solution of equation (10) supports three types of elastic waves. The fast compressional wave, the slow compressional wave (generally it is not considered on Sun`s analysis) and the shear wave. Making a simplification of the Sun`s notation, beside expressions for Vp and Vs, it can be obtained expressions for K (bulk modulus), μ (shear modulus) and F_k (coupled effective factor) related to the incompressibility module as follows:

$$K = (1 - \phi_k) K_s + \phi_k K_f \qquad (11)$$

$$F_k = \frac{1 - (1 - \phi) f}{[1 - (1 - \phi) f] \frac{K_f}{K_s} + \left(1 - \frac{K_f}{K_s}\right) \phi} \qquad (12)$$

$$\mu = \mu_s (1 - \phi)^{\gamma_k} \qquad (13)$$

$$f = (1 - \phi)^{\gamma - 1} \qquad (14)$$

$$\gamma = 1 + \frac{\ln(f)}{\ln(1 - \phi)} \qquad (15)$$

where:
K_S = incompressibility modulus of the matrix
μ_S = shear modulus of the matrix
K_f = incompressibility modulus of the fluid
Ø = porosity
f = frame stiffness factor
ϒ = frame flexibility factor

According to Dou et, al. (2011) the frame flexibility factor in carbonate rock physics modeling context, can quantify the effect of pore structure on seismic wave velocity and can be directly related to permeability heterogeneity. Then, this parameter is related not only to the variation of the pore structure but also to hydraulic connectivity (solid/pore) and to the rock texture of carbonate reservoirs (Sun, 2004).

Application on Middle Cretaceous Carbonate reservoir, T-1DL well, T-X Field, Gulf of Mexico

The T-X Field is a new promising Field in an initial development phase. Currently there are five exploratory wells; all have reached carbonate rocks of Kimmeridgian age (Upper Jurasic).

In this field, there are two special prospective intervals. The principal is the Kimmeridgian oolitic bank (high potential) and the second, the Middle Cretaceous interval which is made up of carbonates displaying an important variability on mineral components and pore space structure. In the context of the Middle Cretaceous interval, only one of the five wells, has showed a good performance during well production testing (T-1DL well). Coincidentally, this well is the only one that reveals, in the mid cretaceous, a significant degree of dolomitization. The same interval in the other four wells is consisting of limestone with very low porosity matrix. In general terms, all five wells evidence a low porosity matrix but, something is different in the T-1DL well. What is causing this difference? Dolomitization?, Fracturing?, Low clay content?, All of them?

With the goal of understanding Middle Cretaceous reservoir performance in T-1DL well, and to capture its intrinsic characteristics as drivers that could guide us in searching for similar rock characteristics in the seismic volume, a rock physics analysis was carried out. We were inspired in the reasonable assumption that the main driver capable of making a difference is the presence of micro fractures and indirectly, the dolomitization level and clay content of carbonate rocks. Figure 3 is a cross plot (RHOB-Vp/VS) for all wells of T-X Field (KM). In there, we can tell that T-1DL well is the only one that is showing RHOB values greater than 2.72 gr/cc. In the other four wells, RHOB values are less than 2.72gr/cc. Here, we have a first important variation between the T-1DL and the other 4 wells clearly related to dolomitization effects.

Figure 4 shows the relations between the radioactivity and the dolomitization process. It is clear that low radioactivity is inversely proportional to the high level of dolomitization and, again, well T-1DL is the only one that shows intervals with low gamma ray values in the KM interval. In the remaining wells the concentration of clay mineral is relatively high. Thus, here we have the second important difference. In addition to these observations, it can be noted that well data demonstrates that dolomitization process tends to induce density and effective porosity increment (Figure 5).

Fracture Diagnostic and Prediction

To analyze the effects of fractures on elastic properties, we conducted three independent and different diagnostic processes using three rock physics methods.

The first analysis was done by means of velocity deviation criteria. We calculated Vp using Wyllie`s time average equation considering the mineral fractions corresponding to calcite, dolomite and clay. Figure 6 shows the cross plot of Vp-PHI with overlaid curves calculated by Wyllies`s time average equation for calcite and dolomite, independently. To compute velocity deviation we generated a pseudo Wyllie`s velocity trend line considering the contribution of each mineral fraction. The meaning of the (Vp, PHI) pair in the cross plot, is not only related to the pore structure but to the mineralogical content as well. In this way, we calculated velocity deviation curve (Figure 7) considering the rock as a compound material (calcite, dolomite and clay).

Depending on the mineralogical fraction, the points should correspond to carbonates with porosity related to dissolution cavities, inter or intra particle pores, fracture related porosity or a combinations of several pore space type. Figure 7 shows that, the velocity deviation is strongly negative in the upper part of the middle cretaceous; this can indicate that, this interval can be, severely affected by fractures. Then, from the reservoir quality point of view, in this interval, we could expect conspicuous pore space connectivity.

The second analysis was done by mean of Keys and Xu`s approach extended for carbonates. Using this approach (equations 6, 7 8 and 9) we modeled the relation between Vp and PHI in function of the variation of pore aspect ratio, and fracture concentration. We calculated Vp-PHI curves considering a large variation of internal parameters (geometrical and intensity). On calculation we considered the volumetric fractions of dolomite, calcite and clay. The model is represented as a reference rock (intercristaline and interparticle pores) plus a variable concentration of stiff pores and fractures. From the model curves, we inverted Vp-PHI relations for fracture concentration (Figure 8). It is clear that high values of fracture concentration are preferentially present in the upper part of the reservoir interval (similar result to the diagnostic done by qualitative analysis).

The third analysis is based on an application of a simplified rock physics model for carbonate rock that is a topological characterization of structural media (extended Biot theory of poroelasticity developed by Sun 2000, 2004). In this analysis, dolomite, calcite and clay are considered as the three principal minerals (the component fraction was calculated using information of logs as bulk density, neutron porosity and photoelectric log). Then, we consider the mineral components on calculation of the matrix bulk modulus. The frame flexibility factor is calculated using equations 11-15. Figure 9 shows the frame flexibility factor generated for the entire reservoir interval. In general, there is an intercalation of high and low values of this parameter. But the highest values are restricted to the upper part of the reservoir. It means that the upper part of the reservoir has, potentially, the best hydraulic connectivity and, as direct consequence, the best permeability.

All methods applied in this study allow us to obtain similar result. From the reservoir point of view, there is no doubt that the upper interval of mid cretaceous is the best. This is because the velocity deviation, the fracture concentration inferred from Keys and Xu`s approach and the frame flexibility factor suggest a high fracture concentration embedded in the rock (Figure 10).

Using the result obtained by the methodologies mentioned above, we predicted the possible distribution of fractured zones using a neural network scheme, fracture related pseudo logs and relevant volumes obtained by seismic inversion (Figure 11).

Conclusions

Despite of the first method's nature (qualitative approach), its performance as a diagnostic tool is notable. Thanks to this methodology we were able to identify that part of the reservoir which is intensely affected by fractures (the upper part of KM). This interval shows the largest negative velocity deviation. This deviation can be interpreted as an acoustic response of compliant rock due to fracture occurrence. The two other methods that represent quantitative approximations allowed us to deduct the fracture concentration and the frame flexibility factor (directly linked to hydraulic connectivity). The quantitative approach also indicated that the upper part of the analyzed interval is the most affected by fractures (Keys and Xu, and Sun`s approach).

From reservoir quality point of view, our Rock Physics analysis (using three different methodologies) points to the upper part of Mid Cretaceous as the main rock that is intensely affected by fractures. As consequence of this, it is reasonable to expect a conspicuous hydraulic connectivity. This conclusion is strongly supported by the successful production tests that were conducted in the interval mentioned above.

References

Anselmetti, F.S. And Eberli, G. P., 1999. The Velocity-Deviation Log: A Tool to Predict Pore Type and Permeability Trends in Carbonate Drill Holes from Sonic and Porosity or Density Log, AAPG Bull., 83, 450-466.

Colin, M. Sayers, 2008. The elastic properties of carbonates, The Leading Edge, 2020-2024.

Dou, Q.F., Sun, Y.F., Sun, Y.F. and Sullivan, C., 2009. Seismic detection of paleokarst system and its influence on carbonate reservoir compartmentalization. SEG Expanded Abstract, 28, 1731-1736.

Gregor, P. E., Gregor. T. B., Flavio,S. A., and Michael, L., 2003. Factors controlling properties in carbonate sediments and rocks. The Leading Edge, 654-660. July.

Keys, R. G., and Xu, S., 2002. An approximation for Xu-White velocity model: Geophysics, 67, 1406-1414.

Kuster, G.T., and Toksoz, M.N., 1974. Velocity and attenuation of seismic waves in two phase media: Part 1: Theoretical formulation. Geophysics, 39, 587-606.

Sun, Y.F., 1994. On the foundations of the dynamical theory of fractured porous media and the gravity variations caused by dilatancies [Ph.D.disert.]. Columbia Univ., New York.

Sun, Y. F. and Goldberg, D., 1997. Effects of aspect ratio changes on wave velocities in fractured rocks. SEG Expanded abstract, 67, 925-928.

Sun, Y.F., 2000. Core-log seismic integration in hemipelagic marine sediments on the eastern flank of the Juan De Fuca Ridge. ODP Scientific Results. 168, 21-35.

Sun, Y.F., 2004. Effects of pore structure on elastic wave propagation in rocks, AVO modeling. Journal of Geophysics and Engineering, 1, 268-276.

Xu, S. and White, R.E., 1966. A new velocity model for clay-sand mixtures. Geophysical Prospecting, 43, 91-118.

Xu, and White, R.E., 1996. A physical model for shear wave velocity prediction: Geophysical Prospecting, 44, 687-717.

Xu, S.Y., Payne, M.A., 2009. Modeling elastic properties in carbonate rocks. The Leading Edge, 66-74, January.

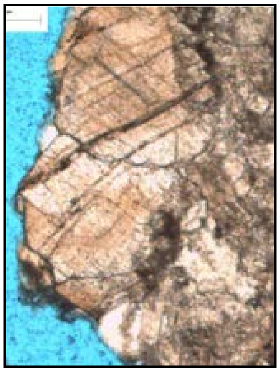

Figure 1. Thin section showing an intense fracturing. The sample corresponds to the upper part of the middle cretaceous interval

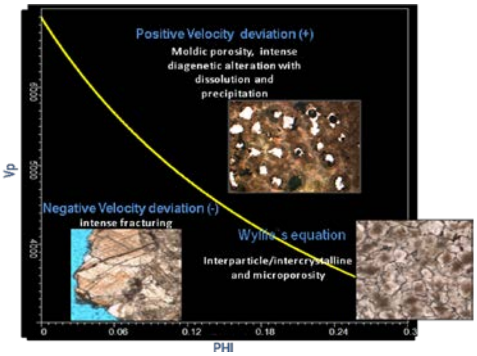

Figure 2. Vp deviation scheme explaining the dispersion of Vp-PHI relation as a response of the pore space heterogeneity. The Wyllie`s time average curve divide intervals dominated by stiff pores and compliant pores

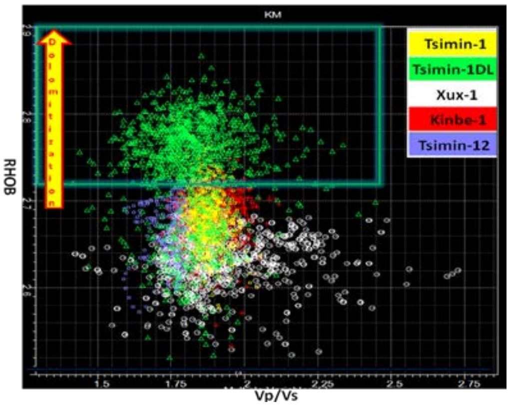

Figure 3. Cross plot showing a special characteristic of the KM interval of the T-1DL well. Only the T-DL1 shows RHOB values greater than 2.72 gr/cc related to dolomitization process affecting the rock

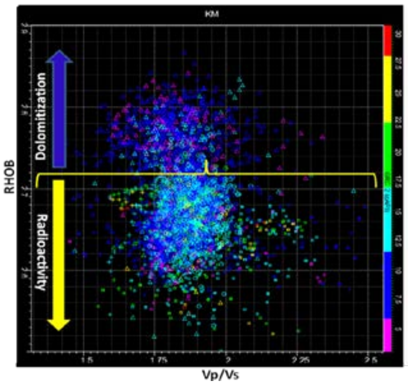

Figure 4. Cross plot showing the inhibitory effect of the clay minerals (relatively high levels of radioactivity) on dolomitization process

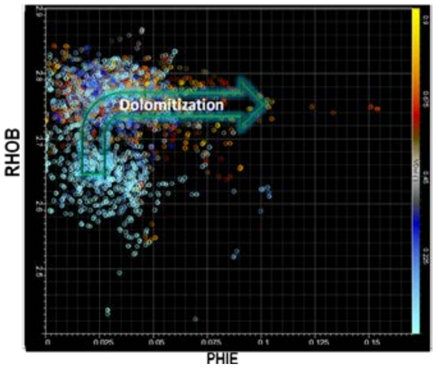

Figure 5. Cross plot showing the increment of density and effective porosity as a consequence of dolomitization process (T-1DL well)

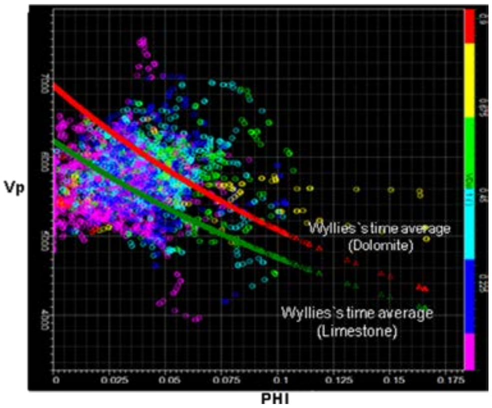

Figure 6. Large dispersion on Vp-PHI relation and Wyllie`s time average curves for dolomite and limestone

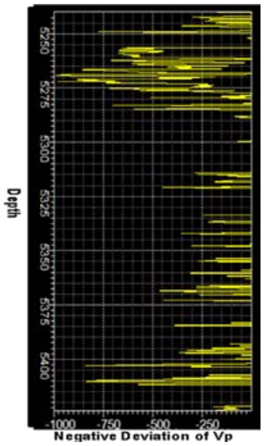

Figure 7. Negative Vp deviation related to potential fractured intervals calculated using Equation 2 and considering the fraction of mineral components

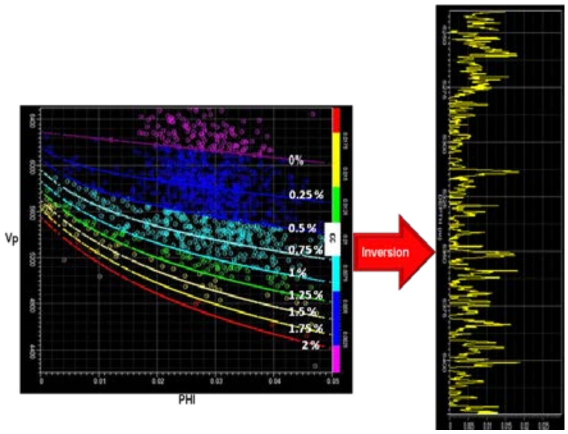

Figure 8. Modeling of the response of fracture and stiff pore concentration (in KM carbonate). A fracture concentration pseudo log is obtained by rock physics inversion

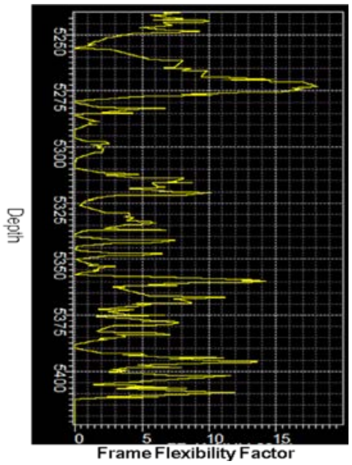

Figure 9. Frame Flexibility Factor pseudo log corresponding to same KM interval as in figure 8.

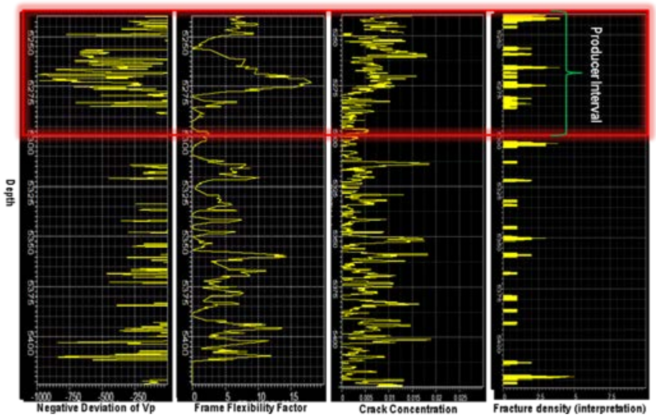

Figure 10. Comparison of the results of velocity deviation technique, fracture concentration prediction, frame flexibility factor and Image interpretation of open fractures. There is an agreement among the results of these four type of information

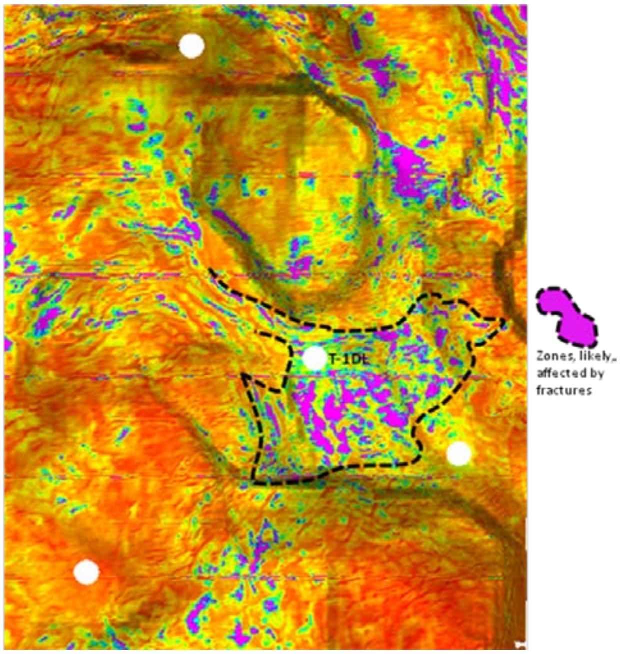

Figure 11. Map of the upper part of the middle cretaceous showing the distribution of the possible zones affected by fractures