Geophysical pore type characterization in carbonates: Cretaceous and Kimmeridgian carbonates, TS oil field, Gulf of Mexico

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This paper was prepared for presentation during the 14th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, August 3-6, 2015.

Abstract

In this paper, we show the processes carried out and results of a geophysical characterization of pore types in Jurassic and Cretaceous carbonates in the TS oil field, Gulf of Mexico. In order to make predictions, we carried out a physically consistent petrophysical evaluation and used borehole image interpretation, core analysis and thin section observations. This information was used in the construction of rock physics models that consider various arrangements of pore shape and fracture concentration. After testing the predictability power of our rock physics models, we obtained, by rock physics inversion, the prevalence of various pore types and fracture concentration within the intervals of interest. Once the physical links between the micro structural properties (type and shape of the pores) and elastic properties were established, we proceeded to make connections with attributes obtained by seismic inversion processes. These connections were formed using deterministic and probabilistic approaches where the results are volumes of intercrystalline porosity, dissolution porosity and fracture porosity.

Introduction

The TS oil field is one of the most important new oil fields located in the southern marine region of Mexico. The main reservoir interval correspond to Cretaceous and Kimmeridgian carbonates that show favorable geological conditions to migration and the accumulation of hydrocarbons generated from the rich total organic carbon (TOC) of Tithonian carbonates.

These conditions are associated with the presence of heterogeneously distributed fractures within partial and sporadically dolomitized carbonates, especially between the upper and middle cretaceous. A second interval of interest exists and is known as an Oolitic bank of kimmeridgian age. It is constituted by intensive dolomitized carbonates with relatively high effective porosity, predominantly related to inter crystalline and dissolution pore space development, sporadically affected by fractures.

The Inter crystalline porosity in the cretaceous carbonates is very low (usually less than 5%). In this context, the fracture intensity, its radius of influence, and the fracture network efficiency define the effective storage capacity. Because of the irregular occurrence of highly fractured areas, it is critical to know the intervals and zones with high fracture development probability.

The effective porosity of the oolitic banks varies between 8-10% and is controlled by the variable contribution of inter crystalline and dissolution pore space. Knowledge of the predominance of one over the other and the respective vertical and lateral distribution is of fundamental importance to understand the efficiency of the hydraulic connectivity. This has relevance in the programs of optimization applied to the development of the oil field and the reasonable control of production. Currently, priorities for geoscientists and engineers involved in the TS oil field focus on the identification of intervals and areas heavily affected by fractures (in the Cretaceous), the definition of the lateral distribution of oolitic banks and the knowledge of the relationship between inter crystalline/dissolution, pore distribution and their impact on the flow efficiency.

In order to minimize the uncertainty of diagnosis, the intervals mentioned above were analyzed by some techniques based on different assumptions and principles including qualitative and quantitative rock physics approaches. The convergence of the diagnosis, using different techniques, was part of the corollary of another study developed by Artola, et al, 2013. Thus, the results obtained by rock physics can be used along with attributes obtained by seismic inversion in order to make predictions about the 3D distribution of the most important reservoir properties, as pore type and fracture intensity affecting carbonate reservoirs.

Rock Physics Models

The rock physics modeling begins with the conceptualization of micro structural characteristics of the rock. This process is carried out by representing the grain arrangement, mineral type contribution, total porosity, large pore shape variability, fractures with variable concentration and saturating fluids. In this study, we used the rock physics effective model of Kuster & Tokzos (1974) and Key & Xu (2002). These are "inclusive" models. The equations together with the Gassmann's equations (for the fluid fraction of the rock) enable us to model acoustic responses of the variability of pore types, including fractures and other micro-structural features of carbonate rocks.

Additionally, in order to obtain further evidence for diagnosis and the identification of fractured intervals and zones with high potential of hydraulic connectivity, the micro structural theory based on Biot`s equations (Sun, 2004) was used. Using this approach, it is possible to obtain parameters related to hydraulic connectivity. One of these parameters is the frame Flexibility factor (FFF).

This parameter is dependent on porosity and, in the context of low matrix porosity, the presence of fractures, induce a very high values related to FFF. In addition, we suggest reading the paper of Artola, et al, (2013) in order to find another analysis for fractured interval identification in carbonates. This method is based on the velocity deviation obtained from the difference between the measured velocity and the velocity calculated using the heuristic Wyllie equation. The value and the sign of the deviation can allow us, qualitatively, to identify intervals affected or unaffected by fractures.

A Simple Testing of Models

Our rock physics models which contain the most important characteristics of the rock for each interval is represented mathematically by an effective medium theory. The singularity of our rocks is a function of the mineral constituent fractions, elastic properties associated with each fraction, pore types, fracture concentration, fluid types, etc. Each input has a certain degree of uncertainty.

The calculated rock physics models must be able to make predictions of basic rock properties (compressional and shear velocities). For this reason, models should be tested for predictability (Figure 1). In the case that, through our models, we get acceptable predictions, we can consider the models as valid. On the other hand, we must review the most sensitive input parameters to elastic properties in order to obtain better models and, as consequence, make accurate predictions.

Rock Physics Inversion

After completing the predictable tests, we can invert the pore type and fracture concentration from rock physics models and acoustic and porosity data obtained from the wells. The models generated should cover, in Vp-porosity space, all physically significant data points (within the bounds of Voigt & Reuss or Hashin–Shtrikman). The characteristics of the pore shape and fractures are represented, mathematically, using information observed in a wide collection of thin sections. Each model is associated with points in the plane velocity-porosity (Figure 2).

From these links, we can invert for the micro- structural features of interest (Figure 3) such as fracture porosity, intercrystalline porosity, porosity by dissolution. Whereas the rock physics models have been constructed based on elastic attributes, predictions of micro structural features are strongly dependent on the elastic module of the mineralogical constituents and their volume fractions.

In order to perform rock physics inversion we used a similar methodology presented by Luanxia, et. al (2013).

Vertical Distribution of the Pore Type of the Oolitic Bank

The Kimmeridgian rocks are the most important of the Jurassic - Cretaceous column, mainly by the occurrence of oolitic banks holding prolific characteristics from the point of view of storage capacity and connectivity between pores. The storage capacity and connectivity are controlled by a complex combination of various kinds of pore shape. The most important is the occurrence of intercrystalline and dissolution pore space and, in less degree, fractures. In general, the oolitic banks, from a mineralogical point of view, consist predominantly of dolomite. The dolomitization process had, at least, two stages of dolomite content "increasing". The first one was given by replacing (calcite by dolomite) generating a very good intercrystalline porosity. In some intervals of oolitic bank, the intercrystalline porosity generated by mineral replacement, has deteriorated significantly by precipitation and / or overgrowth of dolomite crystals, obstructing the intercristaline spaces generated in the first stage of dolomitization. Moreover, in some intervals of oolitic bank and in some areas of TS field is observed the predominance of pore spaces generated by dissolution. There is evidence of some connectivity between many pore spaces related to different pore types, although overgrowth of dolomite crystals have also affected the pore spaces generated by dissolution. In some cases it can be observed a small fraction of fractures (in the context of Oolitic Banks). In general certain type of pores predominates with respect to the other. Knowledge of the vertical and lateral distribution of each type of pore is very important because it may help us to understand the fluid dynamics based on the predominance of certain types of pores.

Practically, in all cases, we have observed that there is an inverse relationship between the content of dolomite and effective porosity; the effective porosity decreases with increasing the dolomite volume fraction (see cross plots VdolxPHIE). The "message" of this inverse relationship is that the first stage of mineral replacement (calcite by dolomite), generated a significant intercrystalline porosity, but it is followed by phases of dolomite crystal growth. This growth affect the porosity generated in the first phase, gradually impairing by cementation, establishing a final inverse relationship between dolomite content and effective porosity. Therefore, for the cases studied, the content of dolomite is not a direct indicator of rocks with good effective porosity (storage capacity), it depends on the severity of dolomite crystal growth and the effectiveness of dissolution processes. The possibility of pore type identification in the context of oolitic bank can be considered as the "vector" that should guide the search for rock types with best features from the point of view of storage capacity and flow.

Finally, it is possible to identify, in the relation V_{dol} x PHIE two types of scattering points Figure 4). The first type shows an inverse relationship with little dispersion and corresponds to rocks that are most affected by dolomite crystal overgrowth processes and the second one shows an inverse relationship with strong dispersion and is less affected by dolomite crystal overgrowth processes. Based on analysis of Winlan a strong spread of data has better characteristics in terms of reservoir quality (Figures 5).

Seismic Pore Type Characterization

The rock physics models built and the properties obtained by an inversion process (pore type, fracture porosity and frame flexibility factor (FFF) are linked to attributes obtained by simultaneous seismic inversion (Figure 6), by probabilistic approach using the Bayes theorem (Figure 7).

Here, we integrated rock physics and seismic attributes in order to make predictions of pore type 3D distribution for Kimmeridgian carbonate rock and fractured cretaceous rock in term of probabilities.

From the seismic point of view, we used attributes obtained by simultaneous inversion. From these attributes, we selected attributes which allows us to establish the better correlation with the properties that we planned to predict in terms of 3D distribution.

In this context, some classes are established based on cut off values of rock properties. These classes are related to elastic attributes and density (well data). Using these classes we generated probability density functions (PDFs). These functions are applied to seismic attribute volumes in order to make probabilistic prediction. In this study, we predicted the fracture concentration distribution of rocks with matrix porosity greater than 1.5%. The scale ranges varies from 0 to 1 (Figure 7). We also generated

Volumes of FFF, Oolitic Bank distribution and dissolution related pore space distribution (Figures 8-11).

Conclusions

The approach that combines rock physics and seismic attributes allow us to identify rock intervals with better features from the point of view of reservoir, this, in the context of Cretaceous and Jurassic Kimmeridgian.

We get a singular contribution of fracture porosity, intercrystalline porosity and porosity by dissolution using rock physics inversion (by rock physics modeling and inversion).

In the context of cretaceous rock, the main index is related to fracture concentration. There is a convergence of results obtained using different methods and approaches tested in this work.

Despite the uncertainties inherent to the main input data for the study, the results show a high level of consistency. The predictions are compatible with the observed data available from the main wells drilled in TS Oil field (small pilot study area). This fact encourages us to apply the methodology to the whole Field.

Acknowledgements

We want to acknowledge to Pemex for permission to publish this paper.

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Figures

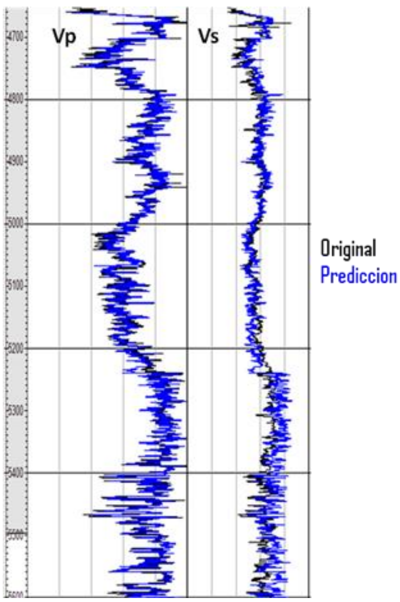


Figure 1. Comparison between the original and synthetic Vp and Vs, obtained from rock physics modeling.

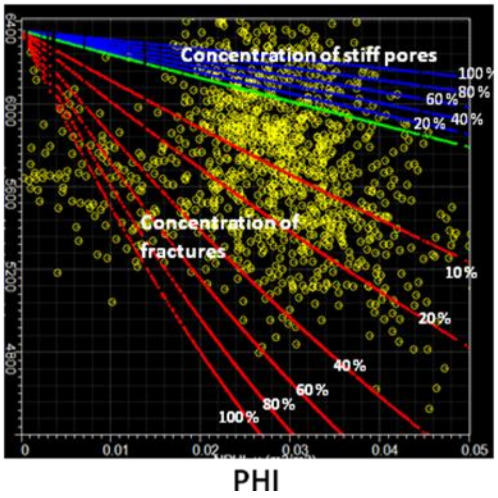


Figure 2. Rock physics models using the plane Vp x PHI

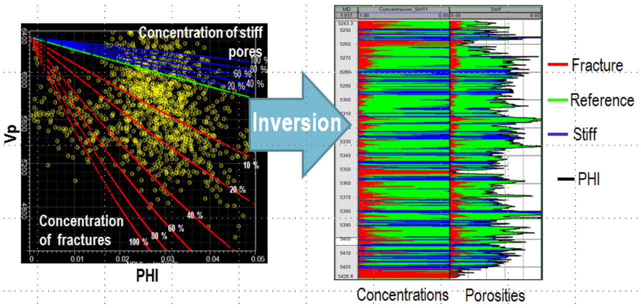


Figure 3. Rock physics inversion in order to obtain the micro structural features of interest (fracture porosity, intercrystalline porosity, porosity by dissolution, etc.)

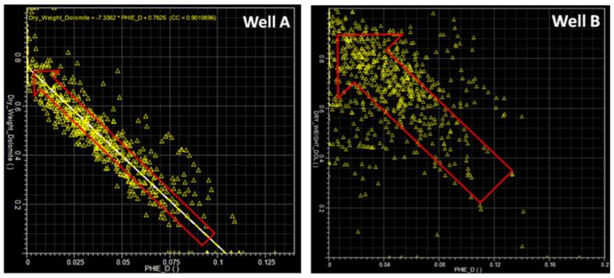


Figure 4. Two types of scattering points in the relation V_{dol} x PHIE.

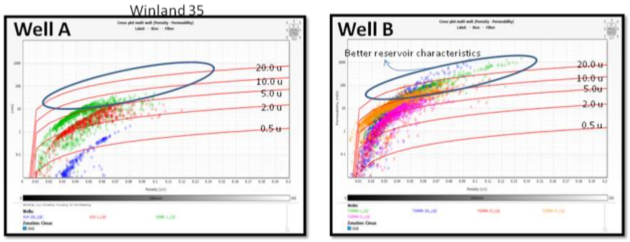


Figure 5. Based on analysis of Winlan, a strong spread of data has better characteristics in terms of reservoir quality.

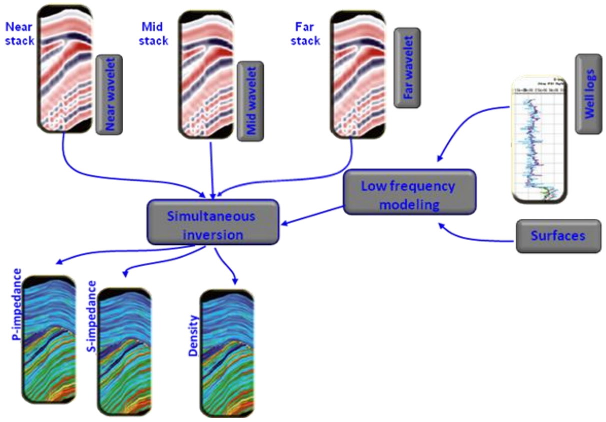


Figure 6. Simultaneous seismic inversion scheme.

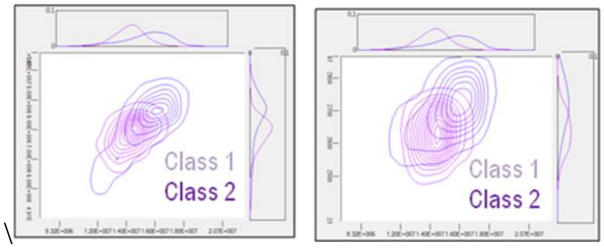
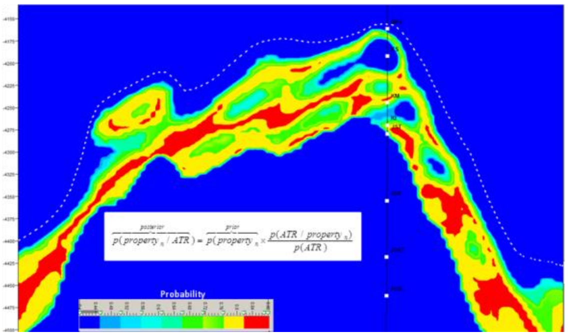


Figure 7. Class discrimination probability density function calculation.



$$\overbrace{p(property_k \mid ATR)}^{posterior} = \overbrace{p(property_k)}^{prior} \times \frac{p(ATR \mid property_k)}{p(ATR)}$$

Figure 8. Section showing the probability of high values of fracture concentration (Cretaceous)

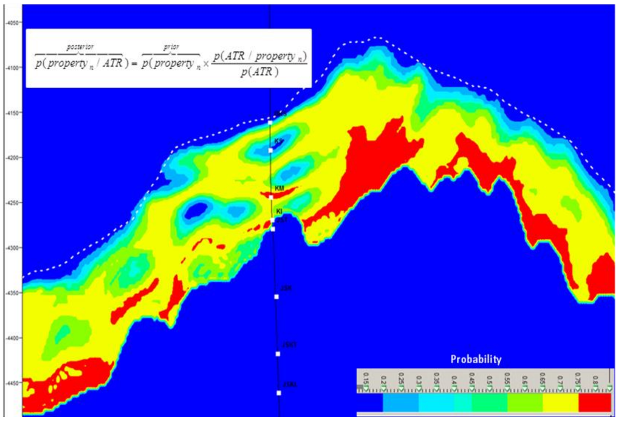


Figure 9. Section showing the probability of high values of frame flexibility factor (cretaceous).

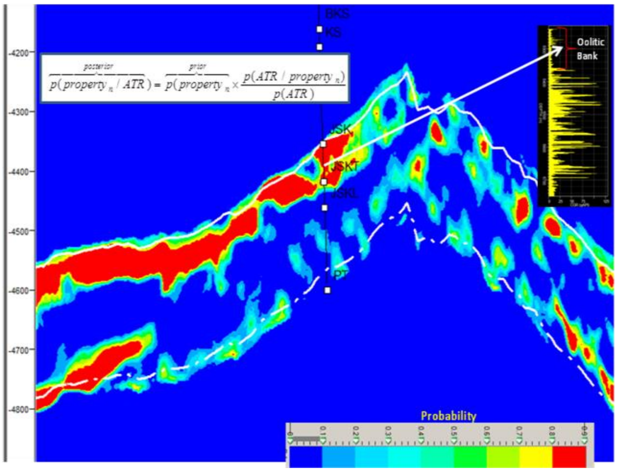


Figure 10. Section showing the probability of distribution of Oolitic Bank (Kimmeridgian).

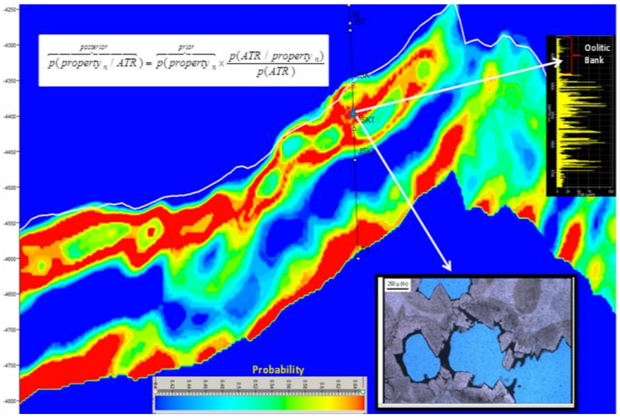


Figure 11. Section showing the probability of distribution of high value dissolution related pore space (Kimmeridgian).