Introduction

Carbonate reservoirs are usually highly heterogeneous at all scales, and it can be difficult to predict their quality and ensure high recovery factors. A major problem is the complex and heterogeneous nature of porosity in carbonate rocks, often leading to large ranges in permeability for any given porosity. An important issue that arises time and again in carbonate reservoir description and modeling is determining the permeability component to allocate to fractures and connected vug systems.

Natural fractures and solution vugs may have a significant role on carbonate reservoir performance (Jardine and Wilshart, 1987; Aydin, 2000). They may affect productivity of the producers and injectivity at injectors and can also control sweep efficiency and water breakthrough within the reservoir. Vugs and secondarily fractures, if densely distributed, can also increase significantly the porosity of the reservoir unit, in addition to the matrix primary porosity. Thus, an understanding of the three-dimensional geometries, connectivity and physical properties of fractures and vugs is essential to predict fluid flow and optimize the field productivity. This requires analyzing and integrating, in a rigorous way, all available data relevant to fractures, like cores, BHI data, structural information (3D seismic) and dynamic data. The end product should come up with a predictive fracture and vugs model directly usable by reservoir engineers for reservoir simulations and production forecasts.

The present paper focuses on the natural fractures and the complex system of solution cavities and vugs affecting the carbonate rocks of the Cretaceous reservoir of the Ku-Maloob-Zaap field (KMZ), Gulf of Mexico, off the coast of Tabasco and Campeche. The study area consists of a series of anticline structures limited by inverse faults striking N100, mostly developing during Tertiary times. A major fault zone, with a strike-slip kinematic component and N160 striking, bounds the field to the East. The Cretaceous reservoir is characterized by the presence of huge layers of breccias (known as breccia KT), mostly of sedimentary origin, which appear to be affected by a strong dolomitization process and associated vuggy porosity development (Ibarra, 2009, and references therein).

As fractures and vugs together play a major role on fluid flow in the reservoir, it is crucial to build up a 3D model of this dual-medium to quantify the impact on the dynamic performances of the reservoir. In particular the distribution and conductivity of vugs are difficult to determine and, therefore, usually they are associated to the matrix properties. In the present study, we propose an alternative method to model the vugs and their dynamic impact independently from the matrix.

This work has been performed using the FracaFlow\textsuperscript{TM} methodology for fractured reservoir analysis and modeling, developed by IFPEN/Beicip-Franlab (Cacas et al., 2001). The study included analysis of interpreted borehole imageries (BHI) recorded in 30 wells, standard logs, seismic characterization of fractures and vugs, dynamic analysis and 3D modeling.

Methodology and Results

The analysis of 30 selected BHI was focused on recognizing the layers of breccia at wells and the presence of continuous conductive traces, potentially corresponding to tectonic fractures with a potential impact of the reservoir performances. Massive breccias intervals characterize most of the Upper Cretaceous units even if some brecciated layers are also present on the Lower Cretaceous series. Breccias are often characterized by a dense system of vugs, which do not show any evident relationships with the presence of tectonic elements such as fractures or faults. However, the vugs density varies in the different rock-types previously defined in the field and show relationships with the total effective porosity PHIE. The continuous fractures were statistically analysed by the FracaFlow\textsuperscript{TM} software, which allowed to define 3 major families based on their relative strike directions: NS, N045 y N120. The fracture densities are in general quite low in the whole reservoir but vary in the different reservoir units: they are 3 times lower in the Lower Cretaceous units (around 0.1 fracture/meter) with respect to the Upper Cretaceous ones (around 0.3 fracture/meter). The fracture density logs highlighted also several fracture clusters crossing the wells. The presence of these clusters suggests that fractures related to faults and tectonic lineaments are also present on the field. The apparent width of the clusters is in general less than 10 m indicating that the volume affected by these objects is probably relatively small.
The seismic characterization of fractures and vugs began with a process of acoustic inversion, in order to increase the ratio noise/signal of the seismic data and the vertical resolution. Next step was to calculate seismic attributes that have been combined and synthetized to compute “meta-attribute” maps at the top and base of the Cretaceous reservoir. These maps integrate the information contained in each seismic attribute, highlighting the common part and attenuating the rest and, therefore, show the discontinuities present in the seismic, which could correspond to fractured areas and sub-seismic objects. The interpretation of these maps allowed picking sub-seismic faults and tectonic lineaments, which are large-scale objects not detected using conventional seismic interpretation (Figure 1).

Figure 1: Meta-attribute map for KS (Upper Cretaceous) horizon, shown as an example, with the seismic faults and the interpreted sub-seismic tectonic lineaments.

A robust relationship at wells between acoustic impedance and total effective porosity PHIE was also demonstrated in KMZ. As a conclusion, the acoustic impedance cube that resulted from the seismic inversion work could be used directly for the prediction of the PHIE distribution in the reservoir model. A 3D cube of the vuggy porosity was derived from the impedance cube after deduction of the matrix porosity computed using a 3D distribution of “non vuggy” facies, based on the rock-type definition performed by PEMEX.

The dynamic characterization of fractures complements the analysis of the static data. The objective is to detect the wells with a behaviour that could be explained by the effect of a second medium (fractures and/or vugs) and not of the matrix alone. The analysis focused on production data, interpreted pressure tests, PLTs, static pressure measurements and mud losses. The studied wells have a dynamic behaviour typical of reservoirs with strong influence of a second medium: KH values are very high; oil production is very large; the breakthrough of water and gas is earlier in certain wells than expected; static bottom hole pressure recorded at wells is almost the same throughout the field; mud losses are experienced when entering the formation. Some observations allow to conclude that the dynamic impact of vugs on reservoir performances is bigger that than of fractures. Primarily, observed fracture densities are not very high and do not allow obtaining the high KH values as observed. Additionally, the PLTs show a very homogeneous profile, whether or not there are fractures in the production area. Finally, there is no relationship between the intensity of a dynamic effect and the presence of fractures observed at well. Even if all these observations suggest that the dynamic role
of fractures is secondary with respect to the vugs, tectonic fractures may be responsible for the connectivity of this second medium.

**Fractures and vugs modeling, calibration and upscaling**

The 3D model for tectonic fractures and dissolution vugs in the Ku-Maloob-Zaap field was built up with the **FracaFlow™** software (Figure 2). This includes: 1. large objects (faults, lineaments); 2. three families of diffuse fractures (objects of metric size), whose density depends on the stratigraphic units and 3. vugs, whose density depends on the rock-types.

Calibration tests were able to assign consistent conductivity values to the different objects that constitute the fracture and vug model. The conductivity calibration is based on the KH values of those well tests that have good reliability. The graph in Figure 3 shows the ratio \( \frac{KH_{\text{simulated}}}{KH_{\text{observed}}} \): optimal calibration ratio is 1.

Finally, the equivalent properties of the fractures and vugs network were upscaled to provide horizontal and vertical permeabilities, and block sizes (or shape factor). The upscaled grid with matrix, fracture, and vugs properties can be used for dynamic simulation purposes.

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**Figure 2**: Examples of the fractures and vugs model visualized around a well. Lineaments are in green colour: a) diffuse fracture family N045; b) vugs in the rock-types 3-4; c) all the family of fractures and vugs; d) detail showing the discrete objects generated by **FracaFlow™**: fractures in blue and vugs in red colour, respectively.
Conclusions

This paper presents a case study of the complex interconnected system of solution vugs and natural fractures present in the Cretaceous rocks of the Ku-Maloob-Zaap field (KMZ; offshore Mexico), which is an excellent example of carbonate and brecciated reservoir affected by both tectonic and dolomitization/solution processes. We documented the presence of the two elements constituting the dual-medium in this reservoir: natural fractures and solution vugs, by studying BHI data, structural information (3D seismic) and dynamic data. Fractures consist of both faults and diffuse joints, which define orientation families consistent with the Tertiary structuration of the field. Diffuse fracture density depends on the stratigraphic layers and is significantly higher in the Upper Cretaceous than in the Lower cretaceous series.

Solution vugs occurrence in the field shows some relationships with the effective porosity and the rock-type distribution, which have been generated based on the acoustic impedance cube. Dynamic analysis showed that vugs have a major impact on the fluid flow in the reservoir.

The innovation of the present study is the modeling of the vugs, more than the fractures (with the software FracaFlow™), as independent objects overprinting the matrix properties. This allows to take into account and calibrate separately, from a dynamic point of view, the different objects providing the permeability to the studied reservoir.

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Selected References


Figure 3: Results of the calibration work for the selected wells. The ratio between the KH simulated by FracaFlow™ and KH observed in the well tests is shown.