NMR APPLICATIONS FOR THE DETERMINATION OF SEDIMENTARY FACIES AND POROSITY SYSTEMS IN CARBONATIC CORE PLUG SAMPLES

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ABSTRACT
The use of NMR techniques to determine petrophysical properties of reservoirs has been described in many previous works [1, 2]. But, together with Gamma Ray logs, thin sections and capillary pressure curves, NMR can contribute further to the characterization of sedimentary environments and porosity systems.

In this work the results of the techniques mentioned above are presented. Almost 40 plug samples from a cored well in the formation "Escandalosa", member "O", of Cretaceous age from Borburata field in southwest Venezuela have been measured and described according to four sedimentary facies. We have found that the shape of the NMR T_2 distributions and thin section images of each sample show a corresponding pattern related to the sedimentary facies the samples belong to. Another contribution of this work is that, unlike other reservoirs in Venezuela, the shape of the T_2 distributions for the sample set can have one, two, three or four maxima or peaks depending on the porosity's system type e.g. intracrystalline, intercrystalline, fractures, synsedimentary fractured and vugs.

The correspondence between sedimentary facies and T_2 distributions allows us further to classify the rock quality as a function of the porosity, bound fluid and free fluid volumes expressed in the Timur-Coates permeability equation determined for each facies.

The results contribute to reduce the uncertainty in the petrophysical understanding of the reservoir and to improve the application of NMR technique in the sedimentology. Specifically, the agreements between T_2 distribution patterns, thin section images and depositional environments extend the applications of NMR techniques beyond the classical determinations of petrophysical variables and fluid properties.

INTRODUCTION

Study Area
The Escandalosa formation of Cretaceous age belongs to the trap Borburata that is located in the area of Barinas in the southwest of Venezuela (Fig. 1). It is located below the Navay formation of the La Morita member, which is an erosive surface, interpreted as

hiatus of 1.5 million years age [3] and as a sequence limit. In Barinas the Escandalosa formation was divided in four members [4] based on the lithology and electric logs characteristics. From top to bottom these members are: "S" corresponding to a shale regional layer, "R" made up of gritty glauconitic and calcareous sands, "P" which is an important reservoir of hydrocarbons, made up of gritty quartz inserted with carbonatic shales, and "O", the target of this study, which is also an important reservoir of hydrocarbons, made up of a mixture of calcite, dolomite and sands.

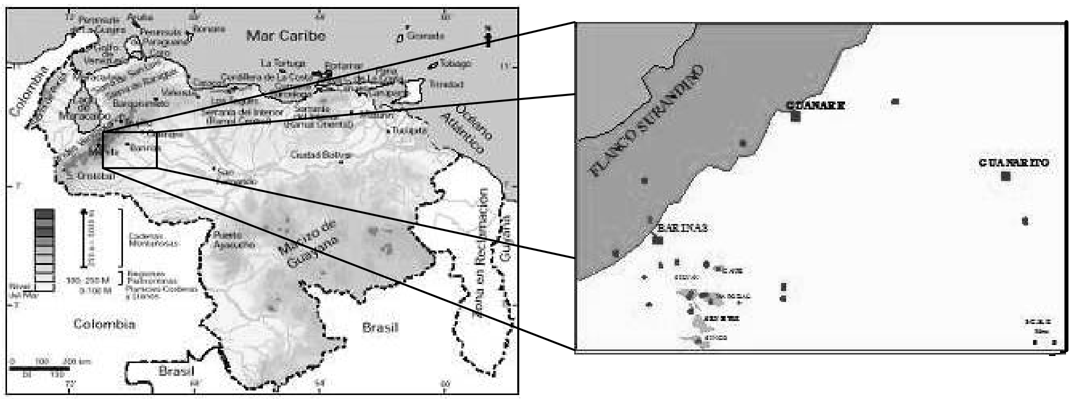


Figure. 1 -Geographical location of the Boburata Field, Barinas State, Southwestern Venezuela.

Nuclear Magnetic Resonance

The application of this new NMR technology allows the acquisition of essential data for the development of better reservoir models, to make quick decisions in the definition of intervals for completion and also help to evaluate the net productive thickness. In this sense NMR can contribute to provide information about grained pore size distribution, porosity, absolute permeability, capillary pressure, water and hydrocarbon saturations, T_2 cut-off between bound and producible fluids which are very important quantities needed for a detailed reservoir description [5].

Beside the standard information that NMR can provide, one reason for measuring the NMR response of the samples set is to contribute in the understanding of how this technique can contribute to classifying the complex depositional cycles and facies present in the reservoir. Especially relevant is the NMR response of laboratory samples with presence of intracrystalline and intercrystalline porosity, fractures and vugs, in order to achieve a deeper understanding of NMR logs by means of core-log correlations.

Sedimentological Analysis

The Member "O" of the Escandalosa formation has been divided into 9 cycles denominated 1',1,2,3,4,5,6,7 and 8 (see Fig. 2) [6]. These cycles are characterized by an alternation of units of clastics siliceous (gritty, siltstone and shales) and carbonates, presenting lateral and vertical variations. According to that observed in some cores, the cycles are constituted from the bottom to the top of facies of siliciclastics which were deposited in an infratidal or intratidal environment ending at the top with supratidal of calcareous dolomitized or massive dolomite environment. According to the definition of the cycles, a small discordance or area of exhibition subaerial should limit the top. However, this limit is not always clearly shown and in some cases it seems to be defined by a change of porosity and of supratidal facies to infratidal or intratidal, as lithological characteristics.

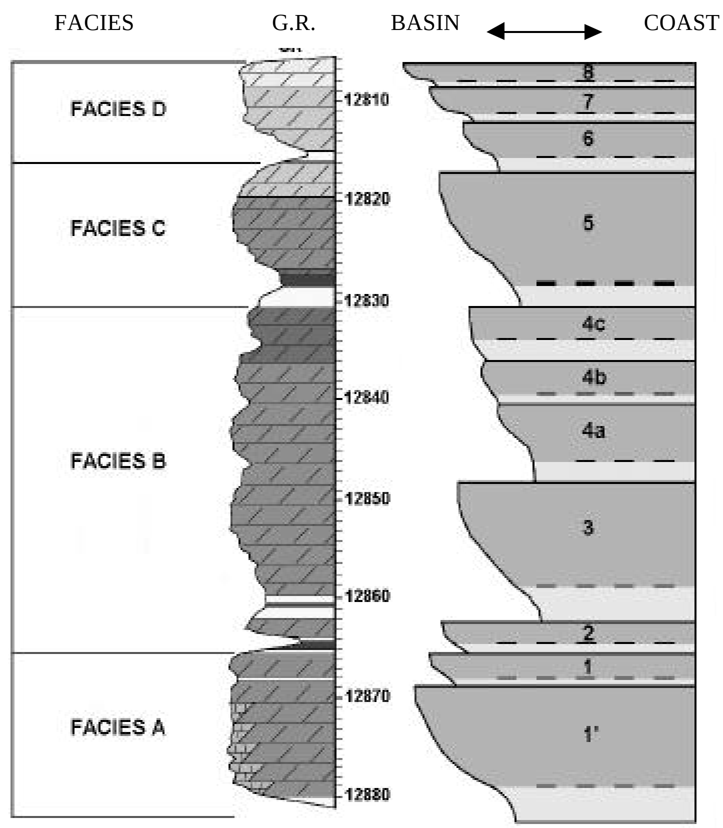


Figure. 2. Description of the Member “O” of the Escandalosa formation according four big facies sequences corresponding to main cycles.

The top of the cycles is defined normally by the presence of moldic and vuggy porosity types, that undoubtedly indicates the subaerial exhibition of the calcareous dolomitized facies, since this type of facies marks always the top supratidal.

In each cycle the bottom, represented by the infratidal or intratidal facies, is constituted by calcarenite or gritty and quartz-containing limolites, generally with little or without any porosity. The siliciclastics limolite generally indicate the level of maximum temporary flood. The top of the cycle is characterized by a calcite dolomitized or a dolomite with variable porosity.

These nine cycles are bounded in bigger 4 cycles or successions of facies, from bottom to top of the Member "O". The fact of synthesizing the cycles in four successions of facies is made because some cycles are very small (of 2 or 3 feet) and the lateral continuity is hindered by the change of facies. An example of this happens with the cycle 7, which is difficult to recognize in some cores or electric logs. On the other hand, the lateral continuity of the four successions of facies or bigger cycles is persistent in the logs and cores of the Member "O". The bottoms and tops of these bigger four cycles are easily identifiable in any electric log, making easier the petrophysical studies.

Facies System

The Member “O” presents 2 types of facies generalized in all the cycles: Facies of carbonates and facies of clastic silicates. These facies vary vertically and laterally in the amount of dolomitization and content of clastics siliceous as well.

The silts of carbonates are:

- Facies of massive dolomites
- Facies of calcareous partially dolomitized
- Facies of calcareous of grain fine dolomitized
- Calcarenite facies (clastics with matrix of carbonates)
- Facies of calcareous with wackstone texture

The silts of clastics siliceous are:

- Gritty of half grain to fine with matrix of carbonates
- Gritty quartz-containing of fine, angular and fairly chosen grain
- Limolites of quartz grains
- Shales

Porosities in the Cored Well: Origin and Types

All the porosities recognized in the studied cored well are related with dolomite facies. They are: intracrystalline (seldom), intercrystalline, moldic, vuggy and due to fractures.

The intercrystalline porosity is originated during the process of formation of the dolomite and it is located between the crystals of this mineral. This type of porosity allows the connection between the moldic and vuggy porosities, increasing the permeability. The microscopic study of some of thin sections with polarized light shows that great part of this porosity is occluded by clay minerals.

The moldic porosity is formed due to the disolution of shells or organic fragments of organisms whose mineralogy is mainly of aragonite and calcite-magnesium. The molds are preserved provided in a later process neither does precipitate calcite with low

Magnesium content nor the pore spaces are occluded due to the dolomatization process. The moldic porosity observed in the cored well is due to pelecyped fragments and in smaller grade gastropod.

The vuggy porosity is generated as a consequence of the increment of pore spaces initially developed as intercrystalline or moldic porosity, due to an active diagenesis and disolution caused either by meteoric acid waters, or by disolution of nodules of incipient evaporites by the same fresh waters.

The fractures, even when they only contribute slightly to the increment of the total porosity, are very important because they contribute essentially to the increment of the permeability and the connection of the moldic and vuggy spaces. The fractures can originate directly from the regional or local tectonics, which produced open but very scarce fractures, and horizontal or vertical fractures systems that are related with specific dolomite facies. This fractures system is probably the biggest permeability supplier in these facies.

METHODOLOGY

The transversal magnetization lost and the T_2 distribution curves were obtained using the Maran Ultra equipment for 2 MHz Hydrogen resonance frequency. About 40 core plugs from a cored well were taken, cleaned and saturated with formation water. The measured plugs are of 1 inch diameter and 2 inch height. Each plug is introduced in a glass tube before starting measurements. The measuring glass tube has two markers, among which the applied magnetic field can be considered homogeneous. Outside the markers the magnetic field can not be considered homogeneous, therefore the user needs to take care of placing the sample exactly among in the volume within the markers.

The final measurement of the decay of the transversal magnetization is an average of many individual runs performed on the sample placed in the resonance cavity. In each run the equipment measures a signal from the integral water content in the pore volume. This is why is very important to place the sample correctly in order to avoid a signal loss which can derived in a lower porosity.

The MaranUltra software that manages and acquires the data is called RiNMR. It is possible via menu to execute and control the measurement commands from the keyboard. This software makes an initial adjustment of a mono exponential function to fit the decay of magnetization and to calculate a main T_2 or characteristic decay time present in the curve. The program RiNMR has several prosecution sequences, being the most important: the sequence FID, INVREC and CPMG.

The sequence FID carries out an experiment of Free Induction Decay that adjusts the resonance frequency of the magnet, O1. This parameter adjusts the magnetic field frequency to achieve the resonance condition, when the hydrogen nuclei are excited at discrete energy levels. This sequence is executed before carrying out any measurement.

To measure the longitudinal demagnetization time T_1, which is an indicator for the total magnetization in the sample previous measurement of the transversal magnetization decay, the sequence of pulses INVREC or "inverse recovery" is used.

The sequence CPMG carries out an experiment of pulse sequences of radio frequencies, to obtain the transversal magnetization decay curve.

The software package the WinDXP performs the mathematical inversion procedure for determining the T_2 distribution curve, assuming a multiexponential relaxation function. The area under the T_2 distribution curve can be read on the screen and later calibrated in terms of porosity.

All the samples were saturated to 100% with formation water and then measured with the NMR equipment to obtain the porosity. Then, the samples were drained to irreducible water saturation and measured again with the NMR equipment, to obtain a measure with irreducible water saturation.

DISCUSSION OF RESULTS

The calculated NMR porosity of the measured samples correlates very well with conventional porosity obtained from gravimetry conventional method. This is shown in figure 3, where the correlation coefficiency is 91%. This result indicates that NMR is a reliable tool for determining porosities of the sample set.

The permeability was obtained using the Timur-Coates equation:

$$k_{NMR} = \left(\frac{f_{NMR}}{c} \right)^{a} \left(\frac{FFI}{BVF} \right)^{b} \qquad (1)$$

where:

K_{NMR} = *NMR permeability*

f_{RMN} = *NMR porosity*

FFI = *Free fluid index*

BVF = *Bound volume fluid*

a, b and c = *Constant for carbonates*

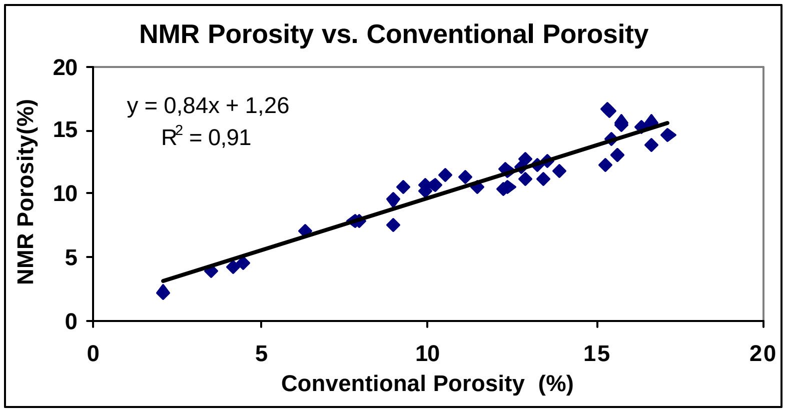


Figure 3. NMR and conventional porosities.

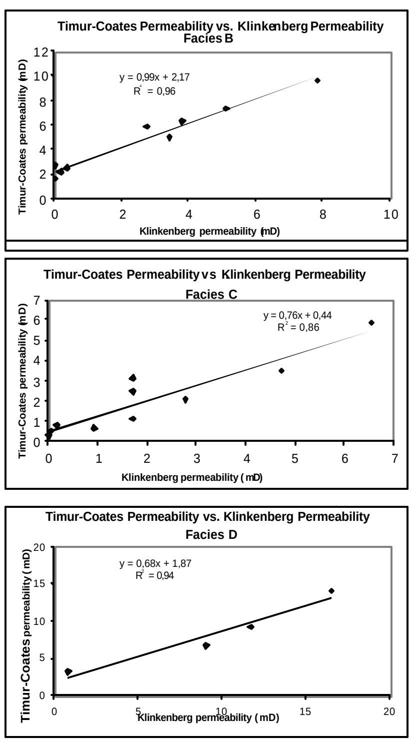
The comparison between modified Timur-Coates and Klinkenberg permeability is shown in fig. 4. It shows the correlations for each facies that are consider as very good for the sample set. The $T_{2\ cut\text{-}off}$ ´s were obtained for each facies by measurement average [7].

FACIES

B

C

D



$$k_{NMR} = \left(\frac{f_{NMR}}{1.45}\right)^{0.742}\left(\frac{FFI}{BVF}\right)^{0.378} \quad (2)$$

$T_{2\ cutt\text{-}off}$ = 111 ms

$$k_{NMR} = \left(\frac{f_{NMR}}{5.86}\right)^{1.076}\left(\frac{FFI}{BVF}\right)^{0.411} \quad (3)$$

$T_{2\ cutt\text{-}off}$ = 131 ms

$$k_{NMR} = \left(\frac{f_{NMR}}{8.35}\right)^{5.239}\left(\frac{FFI}{BVF}\right)^{-0.6961} \quad (4)$$

$T_{2\ cutt\text{-}off}$ = 123 ms

Figure 4. NMR vs. Klinkenberg permeability.

Lithofacies and Sedimentary Cycles

In addition to intergranular and fracture porosities, carbonatic rocks often contain vuggy porosity. Vugs are cavities formed in the matrix after diagenetic and disolution processes, up to 100 microns cavern size. A vug is typically characterized for an enlargement in its geometry with respect to intergranular pore shape. The vugs often are detected by a second peak in the T_2 distribution with T_2 values above 750 ms [7]. However, if the intergranular porosity has a very wide T_2 range, the distribution can be unimodal even if vugs are present but not resolved in their particular contribution to the T_2 curve.

Based on a detailed sedimentary study, the characteristic T_2 distribution patterns can be defined for the 100% water saturated samples. The relationship between sedimentary description and NMR response has help to an easy and faster identification of the cycles and sedimentary facies the samples belong to. This study is so far valid for the member "O" in the selected well; any extension of the results to other members in the formation is not yet confirmed.

Some T_2 distribution curves present a discontinuous behavior because of the appearance of peaks and valleys along the T_2 axis that are indicators of the presence of different porosity systems. Actually, the obtained T_2 distributions can show one, two, three or four peaks depending on the presence of intracrystalline, intercrystalline, fractures and vuggy porosities. Although we can confirm that the presence of vuggy porosity is reflected in T_2 values beyond 750 ms, the definition of T_2 timescales corresponding to other porosity types is not concluded at the moment and constitutes an actual research topic, where the total rock analysis has to be taken closer into account.

Fractures, Molds and Vugs

The figure 5 describes the T_2 distributions of some samples with presence of a mixture of tectonic and sinsedimentary fractures, moldic and vuggy porosity. The tectonic fractures are present in more or less horizontal direction, while the others are defined as sinsedimentary. The sample has been found to belong to cycle 5 and facies C at 12822 feet depth. The T_2 distribution curve for 100% water saturation shows T_2 times beyond 1 second, being a typical experimental evidence of the above described porosity type. The T_2 cut-off is 96.5 ms. The porosity and permeability values are 12.7 % and 0.30 mD respectively.

Synsedimentary Fractures

These fractures are present where a massive dolomitization took place with the generation of breaches texture (breccia). This texture is derived of the formation of fractures in a supratidal environment. The fractures increase the permeability with interparticle, intracrystalline and microvugs porosities. They are present in Cycle 4 and succession of facies B at 12840 feet depth.

The corresponding T_2 distribution curve for 100% water saturation is extended beyond T_2 times of more than 1 second, it also shows two peaks attributed to this type of fracture porosity system (Fig. 6). The T_2 cut-off is 132 ms. The porosity and permeability values are 16.4 % and 6.6 mD respectively.

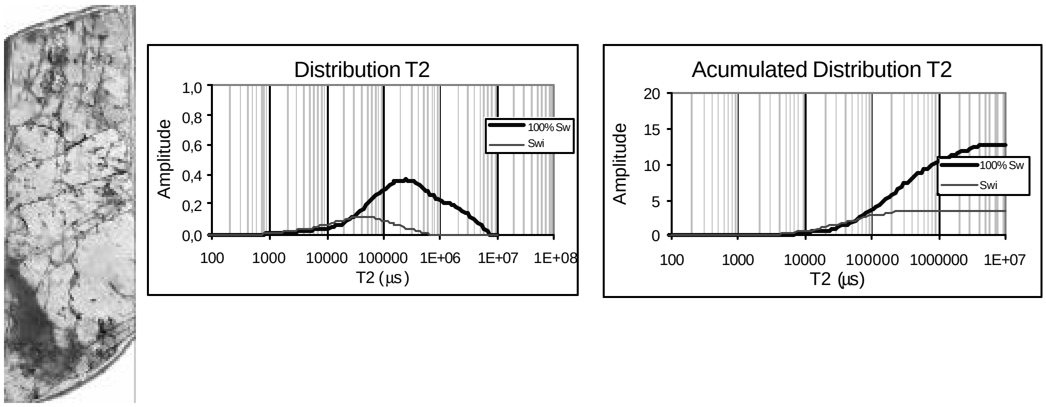


Figure 5. A sample with fracture, molds and vugs and the corresponding T_2 distributions**.**

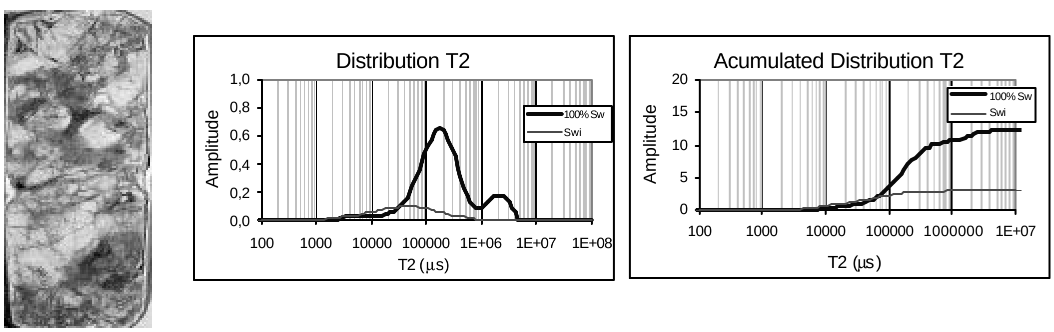


Figure 6. Sample with sinsedimentary fractures and the corresponding T_2 distributions

Intercrystalline

Intercrystalline porosity is derived from an initial depositational mudstone texture. This porosity type can be present in all cycles of Member "O", but in the cycles 6 and 7 it represents almost the whole porosity (Fig. 10). The T_2 cut-off is 157.2 ms. The porosity and permeability values are 13.1 % and 23.8 mD respectively.

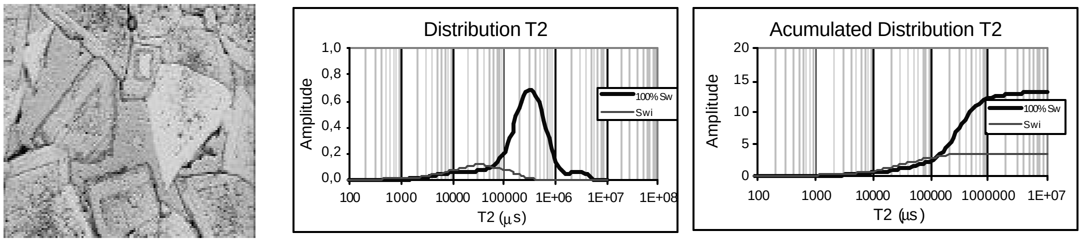


Figure 7. Sample with intercrystalline porosity and the corresponding T_2 distribution.

Intracrystalline

Intracrystalline porosity is developed by disolution within the internal crystalls during the first phase of zonation of the dolomite. This porosity is usually present in the cycle 4 of the succession of facies B. This porosity type increases the permeability (Fig. 8). The T_2 cut-off is 53.6 ms. The porosity and permeability values are 15.5 % and 12.7 mD respectively.

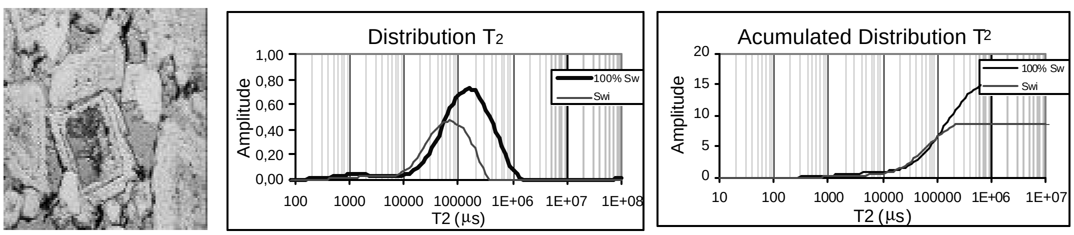


Figure 8. Sample with intracrystalline porosity and the corresponding T_2 distribution.

Moldic and Vuggy Porosity

Moldic and vuggy porosities are in facies were dolomite is present, this means in the cycles 4 and 5 belonging to the successions of facies B and C. These porosities are connected by interparticle porosity. The distribution curve T_2 100% saturated with formation water shows four peaks that evidence a very complex mixture of porosities systems in this facies (Fig. 9). The T_2 cut-off is 53.6 ms. The porosity and permeability values are 15.5 % and 12.7 mD respectively.

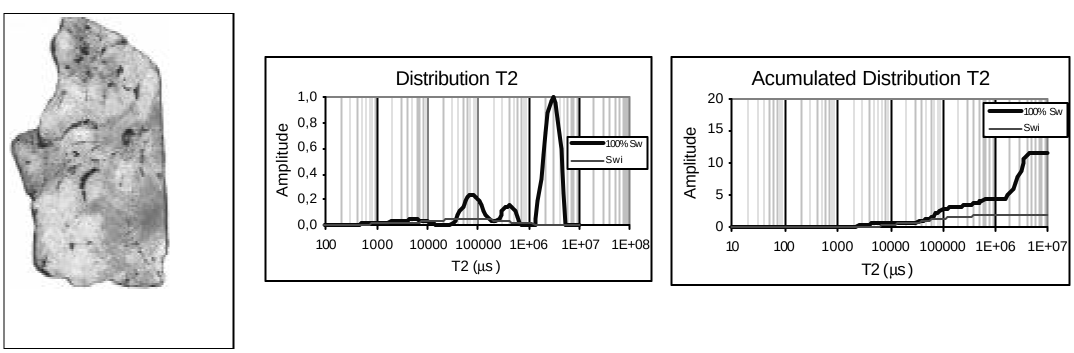


Figure. 9. Sample with moldic and vuggy porosity and the corresponding T_2 distribution.

Recognition of Sedimentary Facies

The recognition of sedimentary facies was possible by means of the use of the T_2 distribution curve. The figure 10 shows the typical curve for each facies sedimentary.

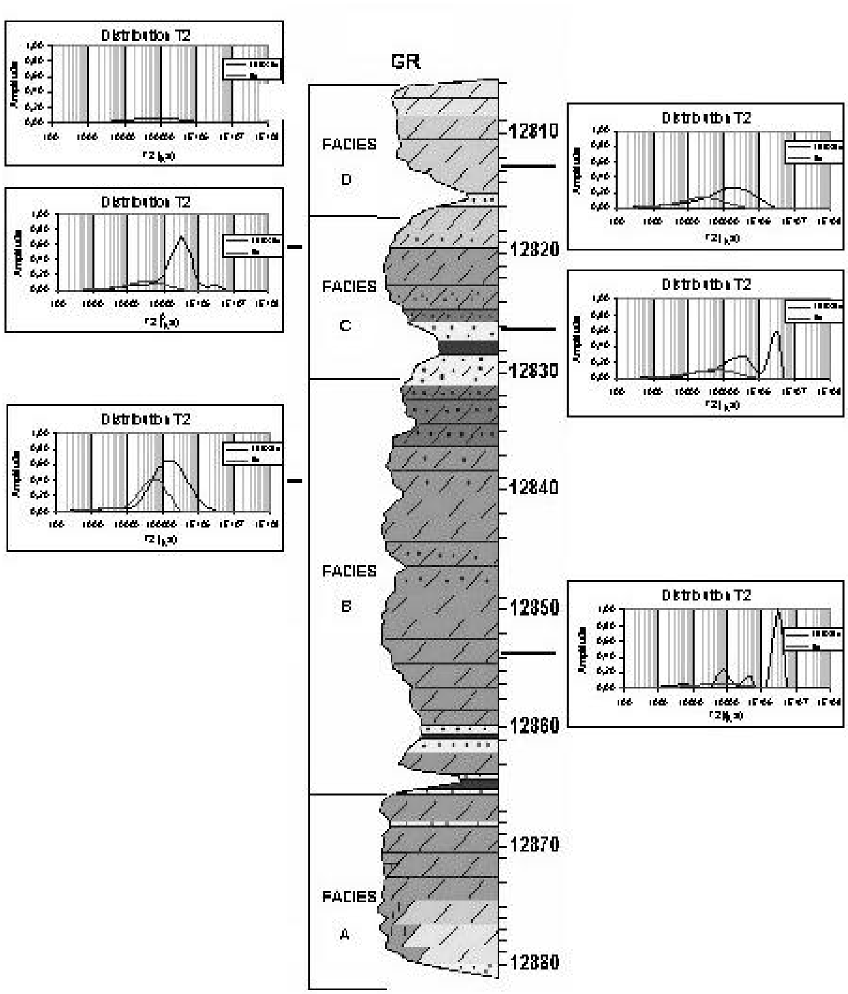


Fig. 10. Recognition of sedimentary facies

CONCLUSIONS

1. Recognition of sedimentary facies can be obtained from distribution of T_2.

2. The correspondence between sedimentary facies and T_2 distributions allows one to classify the rock quality as a function of the porosity, bound fluid and free fluid volumes expressed in the Timur-Coates permeability equation determined for each facies.

3. The results contribute to reduce the uncertainty in the petrophysical understanding of the reservoir and to improve the application of NMR technique in the sedimentology. Specifically, the agreements between T_2 distribution patterns, thin section images and depositional environments extend the applications of NMR techniques beyond the classical determinations of petrophysical variables and fluid properties.

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