CORE AND LOG DATA INTEGRATION THE KEY FOR DETERMINING ELECTROFACIES

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ABSTRACT

The key for determining electrofacies is core and log data integration. Recognition of electrofacies in a wide variety of depositional environments can be achieved through inductive and deductive methodologies. In two different fields located in Argentina and Venezuela, open hole logs (spontaneous potential, gamma ray, caliper, shallow-medium and deep resistivities, neutron, density, sonic, photoelectric factor and nuclear magnetic resonance) were calibrated according to the lithological variations described in the cores. The potential capability of multivariate analysis in distinguishing each electrofacies was analyzed based on recognition of geological facies within the core samples. K-means cluster analysis in *n* dimensions was used to define electrofacies which were entirely associated with the facies observed in the core samples. Encouraging results were obtained after applying such techniques in eolian sand dunes and interdune deposits, mouthbars, distributary channels, meandering and braided deposits. Furthermore, porosity - permeability relationships were established according to the defined electrofacies. An example of a 3D distribution of the electrofacies performed in one field is presented as well. Results reveal the usefulness of applying this methodology for supporting reservoir characterization independently of the depositional environment.

INTRODUCTION

As a rule of thumb, using open hole log data petrophysical variables such as porosity, saturation, volumen of minerals-shale, permeability and their reduced parameters are estimated systematically in all wells operated by the company. These variables are crucial for generating the proper geological and engineering models.

However, in two different oil fields located in Neuquen Basin (Argentina) and Maracaibo Basin (Venezuela) it was necessary to obtain more information than usually pursued.

Consequently, in these two fields open hole log data was treated applying not only deductive methodologies but also inductive ones. Electrofacies were determined through calibration of the inductive results with core data. These were also related to geological facies described within the cores.

Therefore, it was possible to determine a variety of electrofacies in all wells of the fields based on calibrated core and log data. Furthermore, vertical and horizontal variations were recognized and correlated with seismic data.

METHODOLOGY

The petrophysical data was treated following deductive and inductive methods in order to get the most from both approaches (Doveton, 1994; Moss, 1997). Deductive methods comprise those methodologies that seek to differentiate the data by the computation of a set of component proportions whose identification is linked with wireline log data by some suite of response equations (Moss, 1997). The model is built considering the number of components and the number of variables (data curves). Normally, measures to detect mismatches and gross errors are included in the techniques although mathematical consistency is not a guarantee of geological accuracy. This situation is well represented by standard log analysis. On the contrary, inductive methods establish their classes or transformations based on the data set and do not depend on any pre-determined correlation among the components. These methods tend to isolate distinctive patterns and to derive classifications or new variables that can be interpreted with a physical meaning. Cluster analysis is one example of this type of methodologies.

The term electrofacies was originally defined as a set of log responses that characterizes a bed and permits it to be distinguished from the others (Serra and Abbot, 1980). They are determined by the physical properties of rocks to which the wireline logs are sensitive. It is worthy to mention that there exists a conceptual difference between electrofacies and geological facies related to their genesis. Electrofacies are based on characteristics taken from continuous remote measurements at scales of one meter and higher, whereas geological facies are based primarily on observational characteristics taken at scales down to millimeters (Doveton, 1994). Therefore, electrofacies is a set of technologies used to recognize rock types with common properties. These electrofacies are typically used to provide assistance in performing sequence stratigraphy and correlations. In addition they can be used to assign relationships for each rock type such as porosity/permeability equations.

Figure 1 shows an example of a rock type differentiation (sandstones, limestones and tuff) using gamma ray (GR), density (RHOB) and photoelectric factor (PEF).

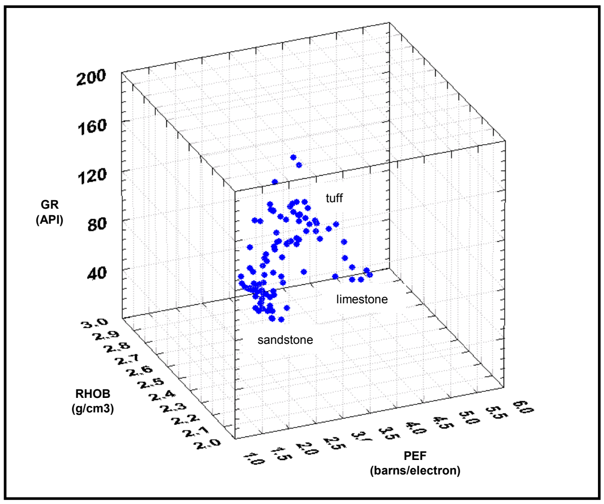

Fig. 1 *Electrofacies determination from GR, RHOB and PEF data (Stinco, 2001)*

For determining electrofacies, authors like Serra (1987), Doveton (1994), Moss (1997), Elphick and Moore (1999) and Stinco *et al*. (2001) suggest to use cluster analysis in *n* dimensions with each wireline log as a dimension.

CLUSTER ANALYSIS

Cluster analysis is one of the most common multivariate techniques found. Conceptually, it is based upon the fact that data can be clustered within groups that differ according to a specific meaning (Moss, 1997). Particularly, within a proper geological framework, dealing with petrophysical variables and measurement parameters, it is possible to find a logical meaning for each of them independently of the working scale.

In order to cluster the data it is necessary to follow a set of procedures.

First, the data matrix of *n* x *p* (*p* variables at *n* depths) is changed into a matrix of *n* x *n* similar distances between pairs of data from the overall. Secondly, a cluster method must be selected. In this work, the "K-means" technique was used (Hartigan and Wong, 1979). The K-means approach is a special case of a general approach called the EM (expectation and maximization) algorithm (SAS, 2000). Given a specific number of clusters, this method is practical for much bigger data sets than any other algorithm. This approach repeatedly alternates between cluster assignment and re-estimating cluster centers. The user must choose the number of clusters to find. The system then populates the *n* dimensions with the same number of points approximately evenly spaced throughout the data. The iterative steps then move the points toward the data populations (like gravitational attraction) until no more movement occurs. The final positions of the points are then taken to be the central positions of the clusters in the data.

The final number of wireline log data (*n* dimensions) is selected according to criteria that assures that every one is present in all the wells analyzed. This also tends to minimize the number of them.

The following examples are from two fields located in Neuquen Basin (Argentina) and Maracaibo Basin (Venezuela) respectively.

NEUQUEN EXAMPLE

Inductive methodologies were used in a field located in Neuquen Basin, Argentina. The target reservoir comprise sandstones of the Lower Cretaceous Mulichinco Formation. In this field there are three wells, two with cores taken in the reservoir units of study.

Editing and Normalization of Log Data. Before starting to analyze the wireline log data, the following subtasks were performed: edition of the digital wireline log data including re-sampling to a common increment where necessary; comparison of the digital data with the paper logs and repaired where differences occurred; merging of logging runs choosing the best data from any overlaps or repeat sections; performing standard editing to remove obvious data errors, spikes, etc.; performing depth shifting for each logging suite to the resistivity suite; removing SP drift; performing environmental corrections; depth shifting of all core data to logs and added to the database; plotting out cross-plots and histograms of all curves.

Figure 2 is a multiwell crossplot of compressional transit time *vs* density.

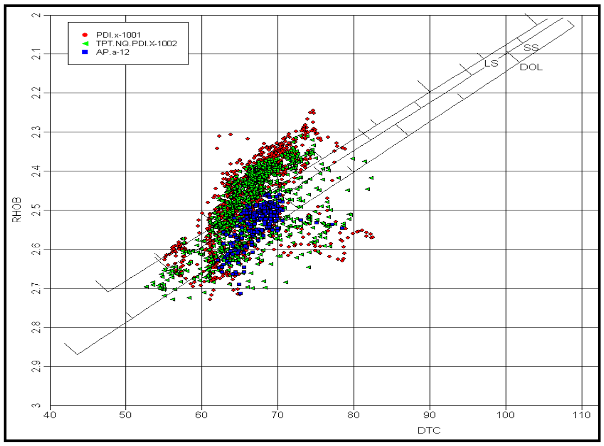

Fig. 2 *Multiwell crossplot of compresional transit time(DTC) vs density (RHOB)*

Standard Log Analysis. For volume of shale estimation, the SP drift corrected and the GR were used. The petrophysical model comprises carbonates-sandstones-shales plus porosity. The term sandstones includes a variety of lithologies (clusters of electrofacies not yet defined) that certainly are reservoirs. The total porosity was estimated from the neutron-density crossplot and the effective porosity was calculated from the total porosity by applying a correction proportional to the shale content. Figure 3 shows a multiwell histogram of the shale content.

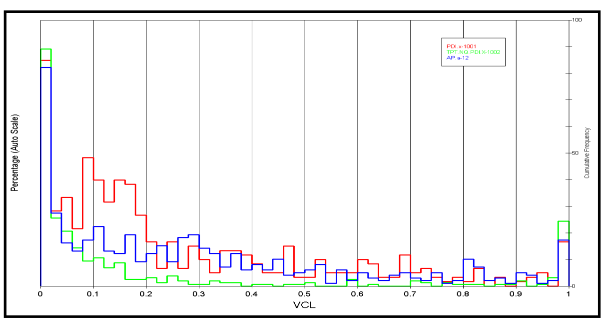

Fig 3 *Multiwell histogram of shale volume*

Water saturation was estimated using the Simandoux model (1963). Cementation (m=2) and saturation (n=2) exponents were taken from standard core analysis results. Water salinity values, taken from measurements of produced water samples, were of 90,000 ppm.

In figure 4 a standard log analysis presents a comparison between core and log porosity. Additionally, it includes dipmeter tadpoles, water saturation and volume of mineral estimation.

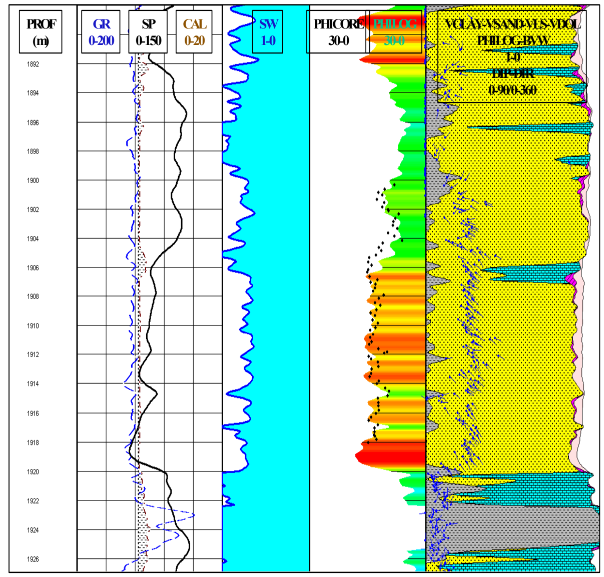

Fig. 4 *Core and log porosity comparison. Track #1 is a depth one. #2 contains GR (0-200), SP (0-150) and caliper(0-20). #3 shows the calculated water saturation (1-0). #4 contains core and log porosities (30-0). #5 shows dipmeter tadpoles (0-90/0-360), volumen of minerals: clay, sand, limestone, dolomite and shale, porosity (1-0).*

The saturation model was accepted as valid through a direct comparison of the estimated results against production data.

Electrofacies Determination. The potential capability to use multivariate analysis to distinguish different electrofacies and consequently to link them with the facies recognized in the core was tested. Having validated the petrophysical model, the following steps included facies analysis from cores and electrofacies determination from wireline logs. As it was mentioned before, core data was available in two wells (12 and 1002). In well 12, paleoenvironmental interpretation describes eolian sand dune and interdune deposits. Fluvial, eolian, channels and flooding deposits are also described.

On the basis of the wireline log data availability it was decided to use density (RHOB), compressional transit time (DTc), shallow resistivity (SFLA) and the computed volume of shale (VCL).

At this stage a fundamental requirement had to be checked. Having selected the curves to use, it was necessary to verify that all the facies described in the core could be clustered using the correspondent curves. As it is shown in figures 5 and 6, it is possible to cluster each depositional environment described in the core in a space defined by the selected curves.

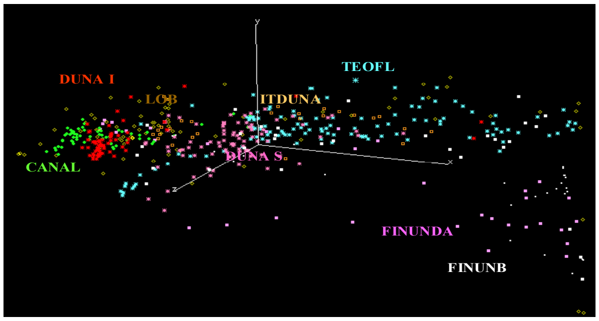

Fig. 5 *Depositional environments described in the core clustered according to VCL (x), RHOB (y), SFLA (z)*

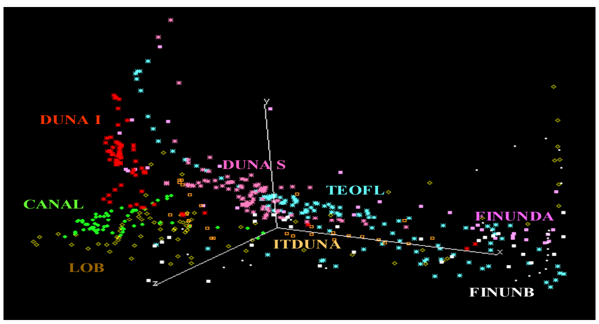

Fig. 6 *Depositional environments described in the core clustered according to VCL (x), DTc (y), SFLA (z). DUNA I= lower dune, DUNA S= upper dune, ITDUNA=interdune, TEOFL= transitional eolian-fluvial, CANAL= channel, FINUNDA/FINUNB= flooding surface, LOB= lobes*

It was possible to define groups of rocks with well defined characteristics in space using wireline logs together with core facies. It is possible at this stage, to apply multivariate analysis in order to cluster all data independently of the core descriptions. After a number of iterations it was decided that the minimum number of clusters needed was 14. Figures 7 and 8 show the results of the multivariate analysis.

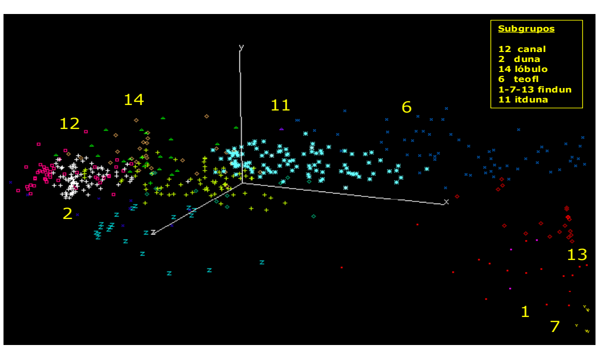

Fig. 7 *Clusters defined by multivariate analysis using VCL (x), RHOB (y), SFLA (z)*

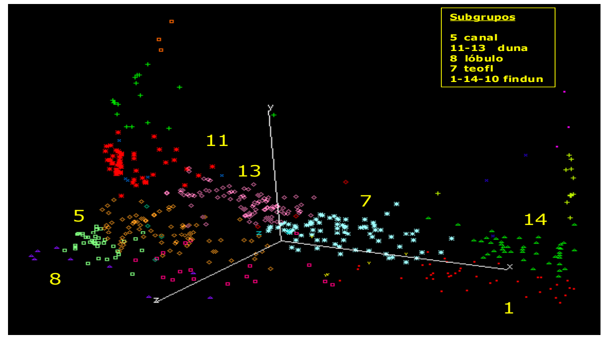

Fig. 8 *Clusters defined by multivariate analysis using VCL (x), DTc (y), SFLA (z).*

A thorough analysis of figures 5, 6, 7 and 8 revealed that there was a direct correlation among geological facies with electrofacies. From the central position of each cluster was possible to determine the exact value of every wireline log that characterizes different electrofacies.

The number of facies described in the core constrains the minimum quantity of clusters to use. Consequently, all wireline logs available in well 12 were compared against the clusters (figure 9)

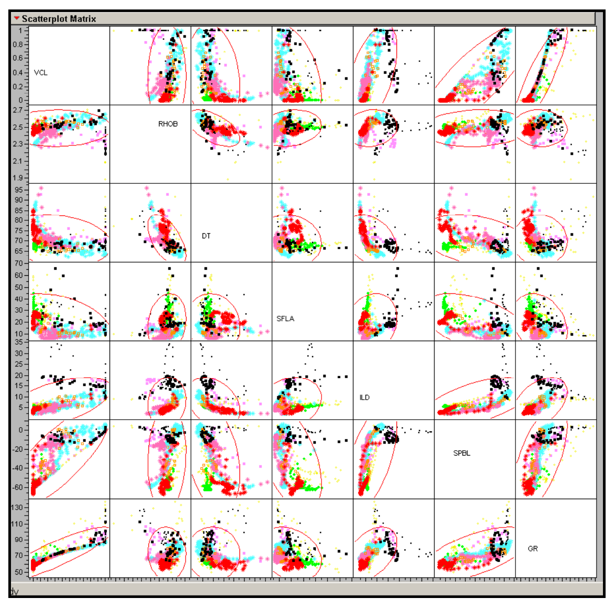

Fig. 9 *Clusters as a function of wireline logs*

A software that solves the wireline logs responses for the central points defined for each cluster was used in order to effectively determine electrofacies (Mitchell and Nelson, 1988). The original number of clusters (14) was reduced to 6 due to the limited quantity of curves available. This selection process involved grouping of the clusters that were closer and behaved consistently from a geological point of view as well as discarding those of very limited representation in a number of individuals.

For example, the electrofacies dune is defined by: VCL= 0.03, RHOB= 2.47, DTc= 74 and SFLA=20.

On the other hand, lobe is recognized by VCL=0.19, RHOB= 2.55, DTc=68 and SFLA= 23.

Figure 10 shows the electrofacies determination together with the core description. This figure clearly shows the consistency of the different facies-electrofacies relationship.

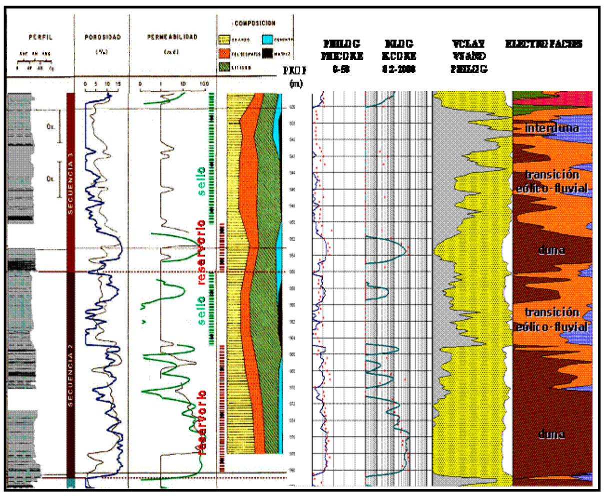

Fig. 10 *Core and log data integration in well 12. Track #1 shows grain size. #2 core and log porosity (0-15). #3 permeability (0-100 mD), seal (green) and reservoir (red). #4 mineral composition: quartz (yellow), feldspars (red), lithics (green), cement (cyan), matrix (black). #5 is depth. #6 core and log porosity (0-50). #7 core and log permeability (0.2-2000). #8 volumen of clay, sand and porosity. #9 electrofacies: dune (brown), transition (orange), interdune (blue).*

The same parameters were used to evaluate well 1002. Actually, this well also had a core hence the electrofacies determination could be checked against the real data. (figure 11).

Note that every time the "interdune" electrofacies appears in the last track, porosity is markedly reduced and also the tadpoles from the dipmeter data diminish their dip.

All these characteristics have been confirmed from the core depositional description and therefore validate the petrophysical approach.

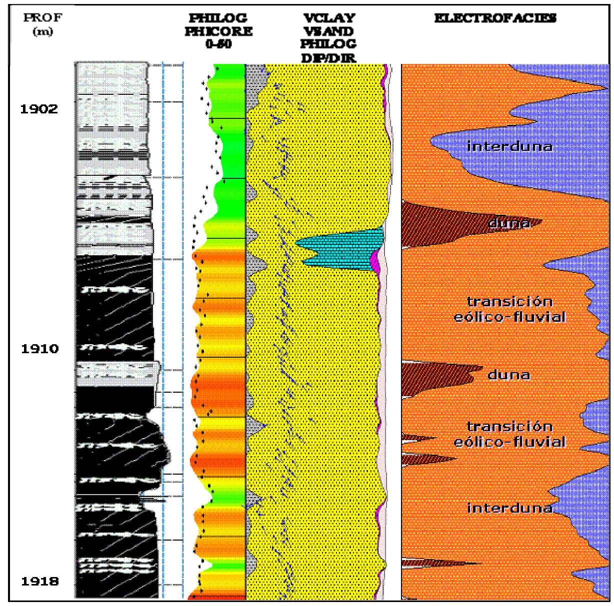

Fig. 11 *Core and log data integration in well 1002. Track #1 is depth. #2 contains grain size. #3 shows core and log porosities (50-0). #4 shows dipmeter tadpoles (0-90/0-360), volume of minerals: clay, sand, limestone, dolomite and shale, porosity (1-0). #5 electrofacies: dune (brown), transition (orange), interdune (blue).*

MARACAIBO EXAMPLE

The above described techniques were also applied in the following example belonging to Maracaibo Basin, Venezuela. The reservoir units are developed within the Eocene Mirador Formation.

From a total of ten wells drilled in the field, two of them had cores in the interval of interest (wells #3 and #5). The interpreted depositional environments correspond to alluvial plains, mouthbars, distributary channels, meandering and braided rivers.

The deductive approach was performed to estimate the shale content using the GR log, to compute the porosity from the density/neutron crossplot and to calculate the water saturation through the Waxman-Smits model (1968).

The inductive methodologies were used with the GR, density (RHOB) and deep resistivity (Rt) logs. In this case, these logs best represent the geological facies and also defined the electrofacies.

The first step was to represent the facies described in one core in a space defined by the three logs selected (GR, RHOB and Rt). Figure 12 represents the facies core data and figure 13 shows the electrofacies after applying multivariate analysis.

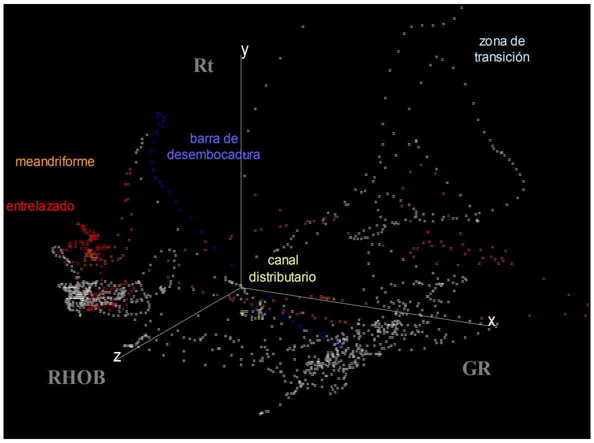

Fig. 12 *Depositional environments described in the core clustered according to GR (x), Rt (y), RHOB (z). Entrelazado= braided, Meandriforme= meandering, Barra de desembocadura= mouthbar, Canal distributario= distributary channel, Zona de transición= transition zone.*

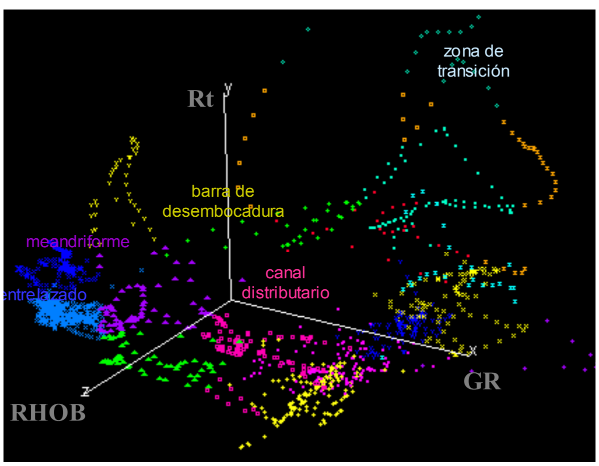

Fig. 13 *Clusters defined by multivariate analysis using GR (x), Rt (y), RHOB (z)*

The results of the core and log integration are presented in figure 14. Additionally, a porosity/permeability relationship was developed taking into account the type of electrofacies. This technique provides a geological input for defining the poro/perm correlation.

Finally, a proper upscaling of the electrofacies was performed in order to extend the two dimensional data into a three dimensional set. This was done calibrating the electrofacies with seismic data. The procedure is out of the scope of the paper but the results are shown in figures 15 and 16.

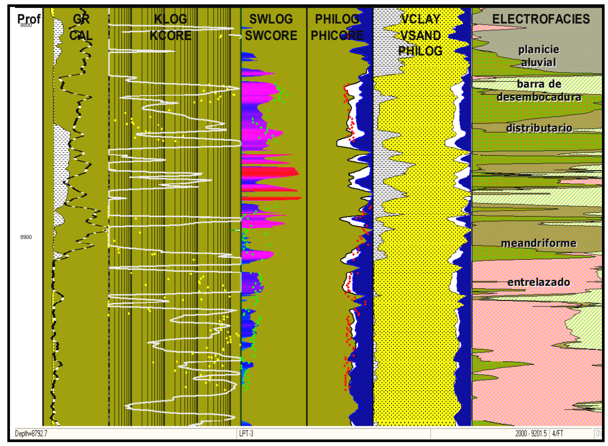

Fig. 14 *Core and log data integration in well 3. Track #1 is depth. #2 shows GR and caliper. #3 core and log permeability (0.2-2000 mD). #4 shows core and log water saturation. # 5 contains core and log porosities. #6 shows volume of sand, clay and porosity. # 7 electrofacies: entrelazado= braided, meandriforme= meandering, barra de desembocadura= mouthbar, canal distributario= distributary channel, planicie aluvial= transition zone.*

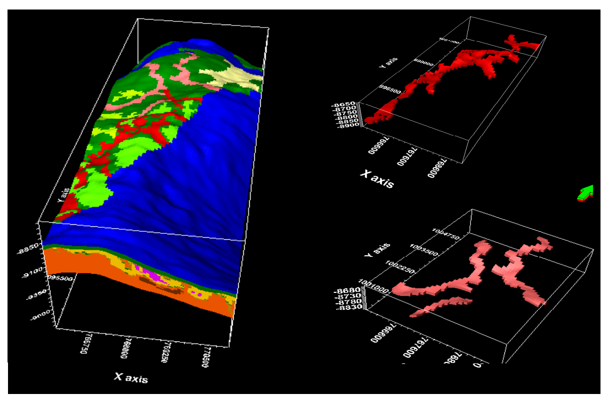

Fig. 15 *Volumen of electrofacies: transition zone (dark green), mouthbar (red), distributary channel (pink), meandering (light green), OWC (blue).*

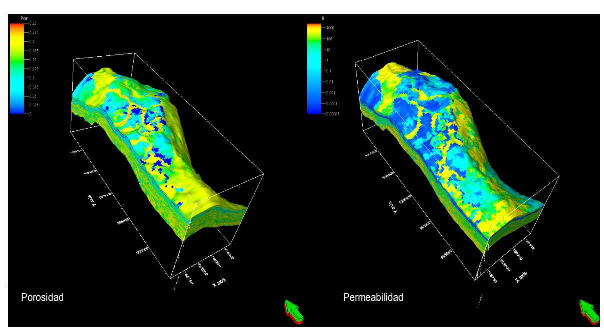

Fig. 16 *Volumes of porosities (left) and permeability (right)*

CONCLUSIONS

- Formation evaluation and electrofacies determination based on deductive and inductive methodologies proved to be very useful in two different fields located in Argentina and Venezuela.
- Multivariate analysis optimized the value of acquiring wireline logs and core data allowing the usage of additional methodologies normally discarded. Consequently, not only standard data was determined for both reservoirs but also it was possible to relate geological facies with electrofacies.
- The working sequence here presented shows that this approach can be used for different wireline logs (at least open hole logs) in a wide variety of geological paleoenvironments.
- Undoubtedly, it is fundamental to have core data. This provides the hard data that enables calibration of the standard parameters and the proper facies.
- Wireline log selection for electrofacies determination depends on the availability of them as well as the capability of discriminating the different features that characterizes each depositional paleoenvironments.
- Finally, with the help of this techniques a deeper understanding of the dynamic responses of the reservoirs could be achieved.

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