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Reservoir characterization by multiattribute analysis: The Orito field case

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ABSTRACT

In order to characterize the Caballos formation reservoir in the Orito field in the Putumayo basin - Colombia, a multiattribute analysis was applied to a 50 km2 seismic volume along with 16 boreholes. Some properties of the reservoir were reliably estimated and very accurate when compared with well data. The porosity, permeability and volume of shale were calculated in the seismic volume by at least second order multivariate polynomial. A good correlation between porosity and acoustic impedance was observed by means of crossplot analysis performed on properties measured and estimated in cores or borehole logs as well as on properties calculated in the seismic volume. The estimated property values were well behaved according to the rocks physics analysis. With the property maps generated and the geological environments of the reservoir a new interpretation of the Caballos formation was established. High correlation coefficients and low estimated errors point out competence to calculate these three reservoir properties in places far from the influence of the wells. The multiple equation system was established through weighted hierarchical grouping of attributes and their coefficients calculated applying the inverse generalized matrix method.

Keywords: reservoir characterization, seismic attributes, seismic inversion, Caballos formation, Orito field.

RESUMEN

El análisis de múltiples atributos sísmicos fue usado para caracterizar el yacimiento a nivel de la Formación Caballos en el campo Orito ubicado en la cuenca del Putumayo - Colombia, para ello se usaron 50 km2 de sísmica y 16 pozos. Las propiedades del yacimiento fueron confiablemente estimadas y la validación con registros de pozo y datos de corazones indicó una apreciable exactitud. La porosidad, permeabilidad y volumen de lutitas fueron estimadas en los datos sísmicos a través de la aplicación de ecuaciones polinómicas multivariadas de segundo orden. Una alta correlación entre la porosidad e impedancia acústica fue estimada tanto en propiedades calculadas por múltiples atributos como en las calculadas mediante registros de pozo y corazones. Los resultados fueron consistentes con los establecidos mediante el análisis de física de rocas. La relación entre los mapas de propiedades y los estudios geológicos disponibles del yacimiento hicieron posible interpretar y caracterizar el yacimiento. Los resultados obtenidos muestran una importante capacidad para calcular propiedades del yacimiento en áreas fuera de la influencia de los pozos. Las ecuaciones polinómicas usadas para los cálculos fueron establecidas a través del agrupamiento jerárquico ponderado de atributos y los coeficientes fueron estimados usando la matriz inversa generalizada.

Palabras clave: caracterización de reservorios, atributos sísmicos, inversión sísmica, formación Caballos, campo Orito.

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Introduction

The Orito field in the Putumayo basin, one of the more developed and well known reservoirs in Colombia, is located at the southwest of Colombia near the Ecuadorian border (Figure 1). The Orito field is located on an asymmetrical anticline (north dome) limited by Orito fault at East, and at the north with a system of inverse faults oriented in NE-SW. The Caballos formation is part of the sandstone belt deposited during the Aptian –Albian over a Triassic-Jurassic eroded surface in an extent littoral system. In 2001 the Colombian State Petroleum Co. ECOPETROL, acquired a 3D volume of seismic data over an area of 50 km2 to provide high quality structural images. The field has 26 production wells located in this zone but only 16 drilled the Caballos formation.

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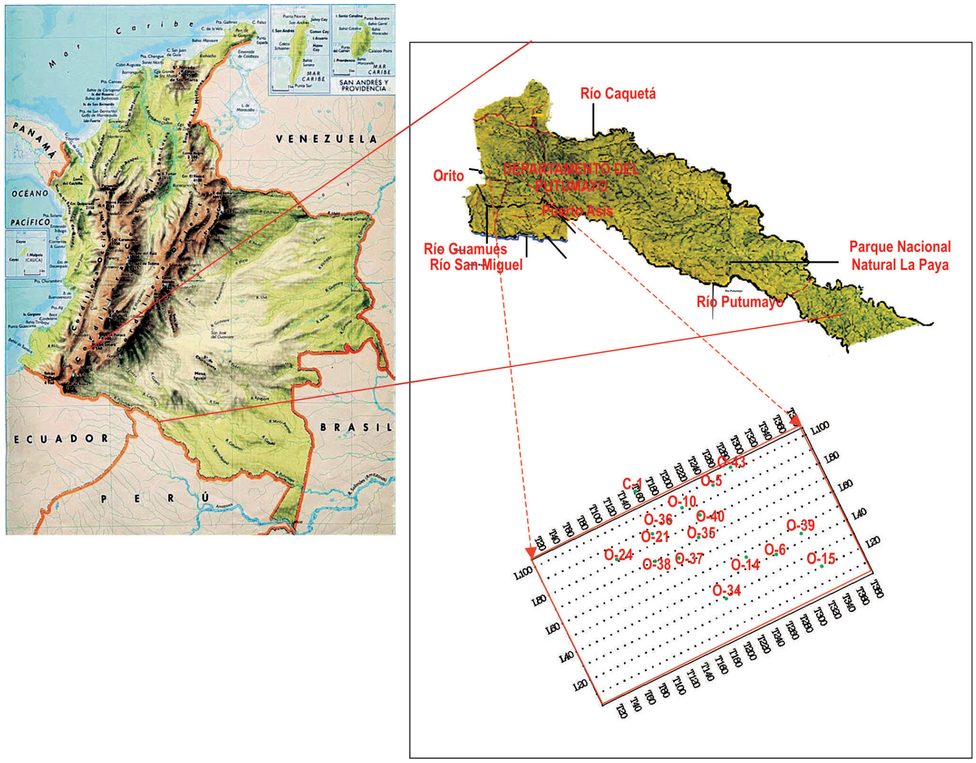

Figure 1. The Orito field is at SW of Colombia in the Putumayo basin, near de Ecuadorian border. At left the 3D survey with the 16 hole positions.

Ecopetrol´s internal reports. The more recent researches have established a geological model and also identified the depositional environment (Amaya, 1996; Amaya and Centanaro, 1997). According to them, the Caballos formation represents the oldest Cretaceous unit deposited immediately above the Triassic-Jurassic surface and is a retro gradational sequence deposited in an estuarine environment dominated by tides (Figure 2) and it is constituted predominant by medium to fine sandstone with local coarse grained and grey mudstone interbedded with organic matter, Glauconite and Pyrite.

By years, the main goal of seismic information has been to provide time - depth structural interpretation, discarding its capacity to predict rock properties although is widely accepted that 3D seismic data provides more information about the reservoir than borehole data, but with less vertical

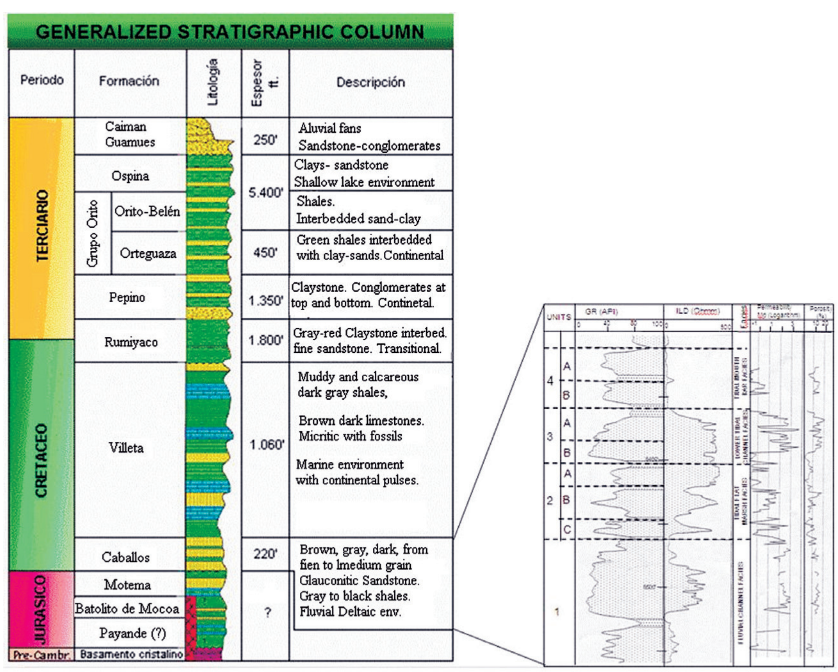

Figure 2. At left the generalized stratigraphic column of the Putumayo basin. At right the facies of the Caballos formation.

resolution. The basic assumption for extracting seismic attributes from seismic information is a good quality data (Tanner et al., 1979); however in Colombia just few studies have been published using the approach of seismic attributes involving multiattribute analysis (Gomez et al., 2005). The attributes are extracted from basic seismic parameters (time, amplitude and frequency, etc) with widely available tools to quantify and analyze geologically this information (Brown, 1996). Every attribute has a particular usefulness to give information about reservoir and to predict rock´s properties. This paper shows the advantage of using seismic information to predict reservoir properties by means of multiattribute analysis instead of the traditional use of wells and single seismic attribute analysis. Seismic attributes discriminate wave characteristics related to rock and fluid properties, as well as give them more validity according the area of influence of the wells. However it is necessary to corroborate the behavior of the calculated parameters according to its geological and physical properties to support the interpretation.

Geophysical data

The seismic volume was acquired on a rectangular area gridded in 25x25m^2 bin size with 10 km inline and 5 km Xline geometry survey, 2 ms sample rate and 4 seconds record length. After data processing, a post stack migrated volume was provided which depicts strong and well defined reflectors with frequency content ranging from 20 to 60 Hz. Sixteen wells are crossing the Caballos formation whose thickness varies from 200 to 300 feet along the field. Each well possess a set of well logs including gamma ray, sp, density, neutron, sonic, resistivity and caliper used to calculate petrophysical and physical properties like density, porosity, permeability, shale volume, p-wave velocity, acoustic impedance and to define lithology (Figure 3). The presence of washouts in wells was taken into account to evaluate the confidence of the calculated values.

Attribute analysis

There are several attribute classification, according to their use, dynamic/kinematics features and reservoir properties (Chen and Sydney, 1997), wave geometry, basic seismic characteristics (Browm, 1996), and others criteria. The dynamic/kinematic traces parameters and organized attributes are related to reservoir characteristics, identifying relationships between seismic attributes and petro physical properties. The Single Attribute analysis (SA) uses a linear or no-linear relationship between a seismic attribute and a property using a single trace parameter.

The Multiattribute Analysis (MA) term includes all geo statistical methods that use more than one attribute to estimate reservoir properties. There are three types of MA analysis methods: the co kriging technique that uses several attribute to predict a property, the neural networks which combine attributes by means of learning and training methods, and finally the covariance matrix that makes predictions using a weighted sum of incoming attributes (Rusell, 1997). These statistical approximations use polynomial relationships that match seismic attributes calculated and measured rocks properties in wells and may identify the set of seismic attributes which forecast the properties. The simplest case is a linear relationship involving only one attribute:

$$P = w_o + w_j A_j \qquad (1)$$

w_j is a weighted coefficient, defines the lowest value of the attribute, A_j is an attribute and P is the estimated property.

Assuming a linear relationship in a MA case, any physical or petro physical property is estimated as a linear weighted sum:

$$P = w_o + \sum_{j=1}^{n} w_j A_j \qquad (2).$$

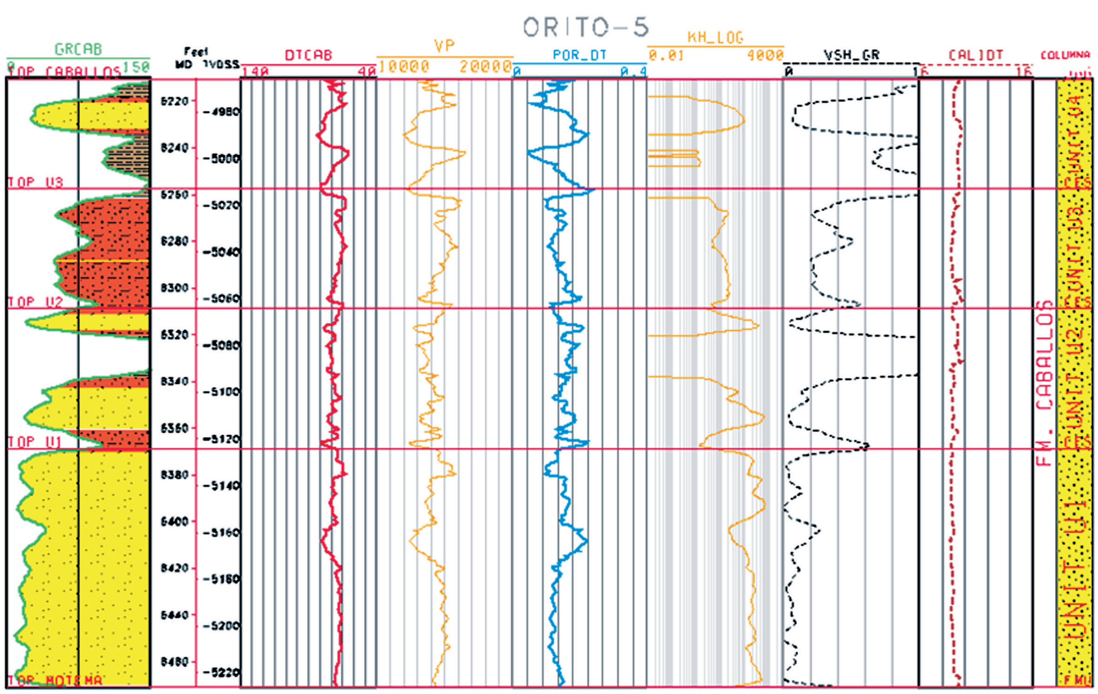

Figure 3. Log of the Orito 5 well, with Gamma ray (GRCAB), Sonic (DTCAB), calculated P wave velocity (V_P), calculated Porosity (POR_DT), calculated Permeability (KH_LOG), calculated Shale volume GR (VSH_GR) y Caliper (CALIDT).

Where w_j are weighted coefficients, A_j the related attributes and P the estimated property. Although complex relationships may be represented by different order equations, order higher that 2 are rare and without physical meaning, as:

$$P = w_{oo} + \sum_{k=1}^{n} \sum_{j=1}^{n} w_{kj} A_j^k \quad (3)$$

k is the order of the polynomial, w_{kj} the weighted factor, A_j^k the seismic attribute and P the property.

To establish w_{jk} the generalized inverse matrix was used:

$$w_{jk} = \left[A^T A \right]^{-1} A^T P \quad (4).$$

The A matrix contains the attributes values inside the seismic volume, P represents the property values measured in wells, A^T and A^{-1} are respectively the transpose and inverse matrix of A. The term $[A^T A]$ is the covariance matrix, which is a powerful statistical tool for multivariate data analysis, used in Wiener-Levinson deconvolution and others applications (Rusell et al., 1997).

The selection of attributes to be used as key predictors was done through hierarchical sorting of attributes and using correlation coefficient ***R*** and estimated error ε to measure similarity.

Table 1. Accuracy achieved by MA and SA compared with the value measured in the well.

Well	Measured	SA	MA
0-5	0,097	0,101	0,097
0-6	0,107	0,112	0,107
0-10	0,069	0,083	0,069
0-14	0,089	0,104	0,089
0-15	0,087	0,966	0,087
0-21	0,105	0,108	0,105
0-24	0,084	0,083	0,084
0-34	0,075	0,079	0,075
0-35	0,081	0,080	0,081
0-36	0,103	0,109	0,103
0-37	0,065	0,090	0,064
0-38	0,086	0,091	0,085
0-39	0,089	0,094	0,089
0-40	0,095	0,080	0,094
0-43	0,102	0,083	0,098

Table 2. Correlation coefficients and errors in the calculus of the attribute.

No Attributes	Attributes	C. Correlation	Error
A1	Average Zero Crossing	0,79834	0,00537551
A2	Avarage Trough Amplitude	0,93521	0,003047
A3	Peak Spectral Frequency	0,97097	0,00203953
A4	Correlation Length	0,99565	0,000789

Procedure

The migrated volume was tied to the wells and dominant frequency and vertical resolution were calculated to interpret the seismic volume. Porosity, permeability, shale volume, P-wave velocities and acoustic impedance were estimated first in the well using the borehole logs gamma ray, sp, sonic, neutron-density, resistivity and caliper. To be more confident, porosity and permeability in available core samples were measured and used to calibrate these properties in the well. In the research five properties were calculated in the well and forty two attributes were considered and generated in the seismic volume to know the more robust to predict properties in the Caballos formation.

Physical and petrophysical information in the well and attributes in the seismic volume were used to estimate petrophysical and physical properties according to rock physics. The MA analysis applied hierarchical grouping using highest correlation coefficients as criterion of similarity. The attributes were clustered according to correlation coefficients provided by the SA analysis between the attributes and the rock properties. The first selected attribute exhibits the highest single correlation coefficient, the second the higher of the remaining, then the next high value and so on, increasing the correlation coefficient and establishing the best relationship. To check the predictive confidence of the technique, two wells's information was not fed to define the polynomial relationships and instead their values were predicted by the method (O-15 and O-24 wells), as observed in table 1.

To estimate porosity by the MA, in the clustering procedure the following attributes were included: first average frequency zero crossing followed by average trough amplitude, then peak spectral frequency and finally correlation length. The second order polynomial relationship established between the porosity and the four mentioned attributes a correlation coefficient R = 0.995 and an error ε = 0.00079 were achieved. The acoustic impedance was related by a second order polynomial with the attributes average zero crossing, slope of reflection strength, dominant frequency rating (series), average signal to noise ratio and average instantaneous phase, provided an R = 0.998 and an ε = 0.00117. With an R = 0.990 and ε = 0.00137, the permeability was set by a third order polynomial related with dominant frequency – F2, bandwidth rating, variance amplitude, average trough amplitude and number of troughs. Finally, a second order polynomial relates shale volume with correlation window time shift to next CDP attribute, average zero crossing, slope of instantaneous frequency and maximum trough amplitude, with R = 0.989 and ε = 0.00737. For a wide and precise descriptions and application of attributes the references Brown (1996), PAL (2001) and Chen et al. (1997) are suggested.

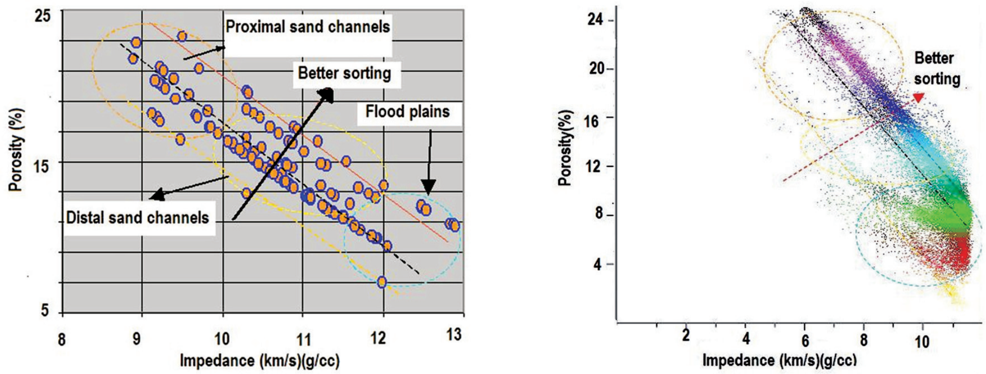

Figure 4. The same trend is present in core and well logs analysis (left) and in predicted seismic attributes (right), where the samples were discriminated according to environment previously identified in wells.

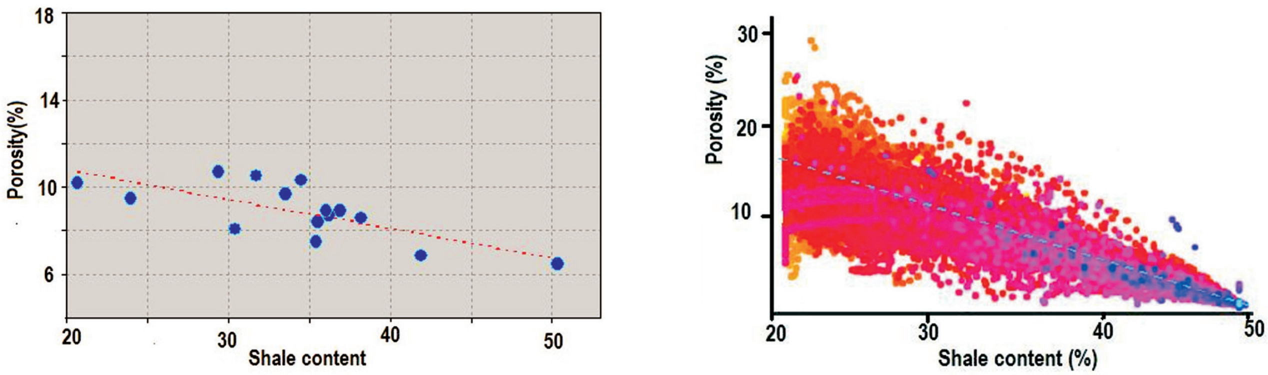

Figure 5. The same trend is present attributes established by cores and well logs analysis (left) and in seismic attributes predicted in the volume(right).

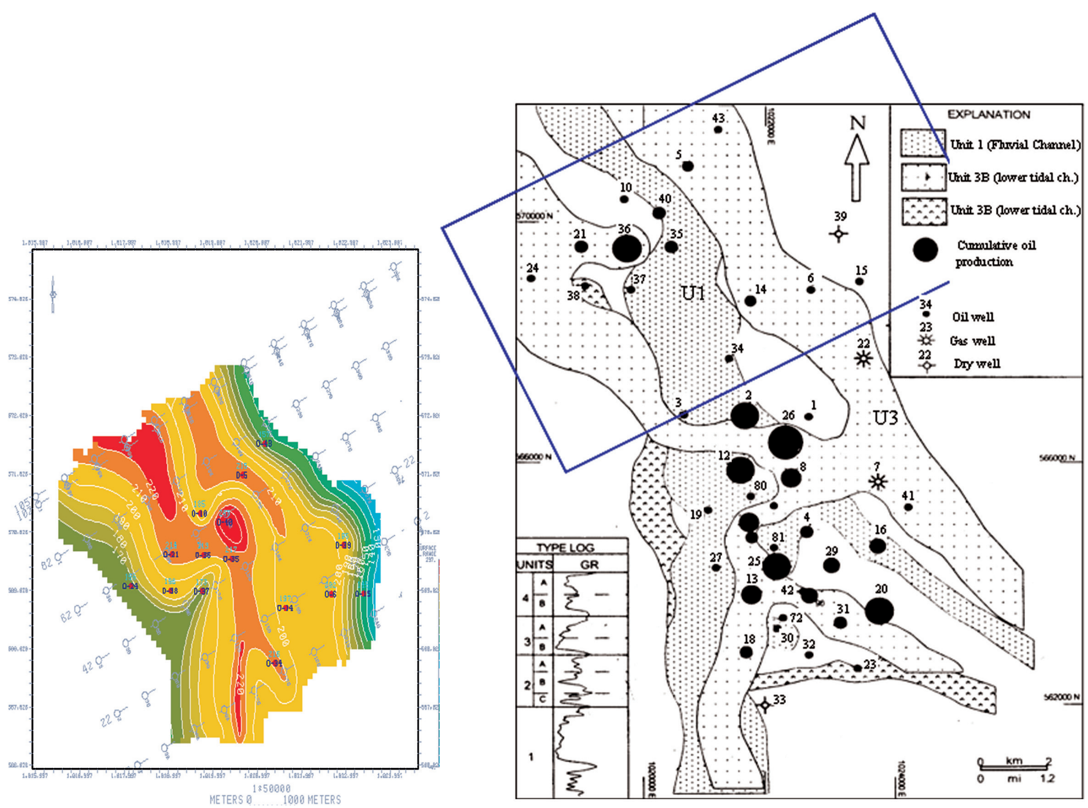

Figure 6. Net to gross map obtained from well information with an approximately NS body depicted at left, inside the marked square (Modified from Amaya, 1996).

To evaluate the validity of results provided by the SA and the MA methods, crossplot analysis were done. The first one relates porosity with acoustic impedance (Figure 4) and the second one relates porosity with shale content (Figure 5). The first analysis was done in attribute dataset calculated inside the volume: (Figure 4a) and also in properties calculated with borehole data (Figure 4b), with a similar trends observed in both. The second analysis threw similar trend in attributes measured in wells and in attributes estimated in the volume (Figures 5A and 5B). Finally the properties predicted by MA method inside the Caballos formation were mapped for a new geological interpretation in accord with the identified geological environments.

Using the information provided by the wells in the area, a net sand map for the Caballos Formation was generated and showed in Figure 6. The net sand distribution confirmed the presence of a body that was deposited in a paleo valley with an approximately NS main direction and the presence of isolated bodies that run almost parallel to the main body, as was interpreted in the facies map before Amaya (1996). He identified four events in the Caballos Formation deposition, the lower unit consisting of fluvial deposits with lower tidal influence (see at right of Figure 6), which grades toward estuarine deposits formed in tidal channels and tidal flats overlain by tidal channel deposits, which are eventually were eroded and overlying by deposits of mouth bar.

Results and Discussion

Although many properties were obtained using SA and MA, just porosity, impedance and shale volume were considered in this paper, because they show the most outstanding results obtained in the project.

The property calculations started with the attribute that owns the smallest error and the highest correlation coefficient and then more attributes were added until the highest correlation coefficient as R=0.995 and lowest error were achieved, see Table 1. The properties predicted in the Caballos formation volume supplied by MA and SA were compared against values established in the well, see Table 2. The MA method always provided values closest to true property values (porosity, acoustic impedance, etc), included those in O-24 and O-15 wells which were not involved as input data, whereas the values achieved with SA drastically depart from the real values.

The MA was applied to the Caballos formation volume to estimate porosity, acoustic impedance and shale content were. To verify that the predicted value trend are agree with that of data observed in wells, the estimated porosity was crossploted against estimated acoustic impedance. In Figures 4a and 4b a similar trend in predicted and measured in well data is observed assuring a reliable output, although the predicted porosity, acoustic impedance and shale volume values were calculated by polynomials independent of borehole data. According to petrophysical and physical considerations the observed results were interpreted so, highest porosities and smallest impedances are related to material with high sand content as found deposited in channel environment and lowest porosities and highest impedances are associated to materials with high content of shale found in a tidal flat marsh.

Two maps of porosity distribution in the Caballos formation were built, a first one generated by the SA method in Figure 8a and a second one by the MA method in Figure 8B. Comparing these two maps a higher contrast in porosity is clearly visible in the Figure 8B, providing a better discrimination of porosity distribution in the formation. A map of acoustic impedance generated by the MA is seen in Figure 9.

A shale content map (figure 8) was generated with multiattribute analysis, consistent with the net sand map (figure 6) where most of the low values of shale volume (yellow and red) coincide with the main body trend. However, there are outliers to the east side of the area which are not easy to explain except due to the possible presence of another channel along the Orito fault.

Finally through Figures 6,7,8B and 9, a geological interpretation depicted in Figure 8A was done. It is possible there to identify the environments in the Caballos Formation, including fluvial channels in the lower part (Unit U1), tidal channels (units U2 and U3), tidal flat marsh and crevasse splays, with the possible presence of channel bars. The interpretation map of figure 8A is geologically consistent with a previous interpretation map done by Amaya (1997) in Figure 8B, but a better discrimination of the channel and the other facies are visible in Figure 8A.

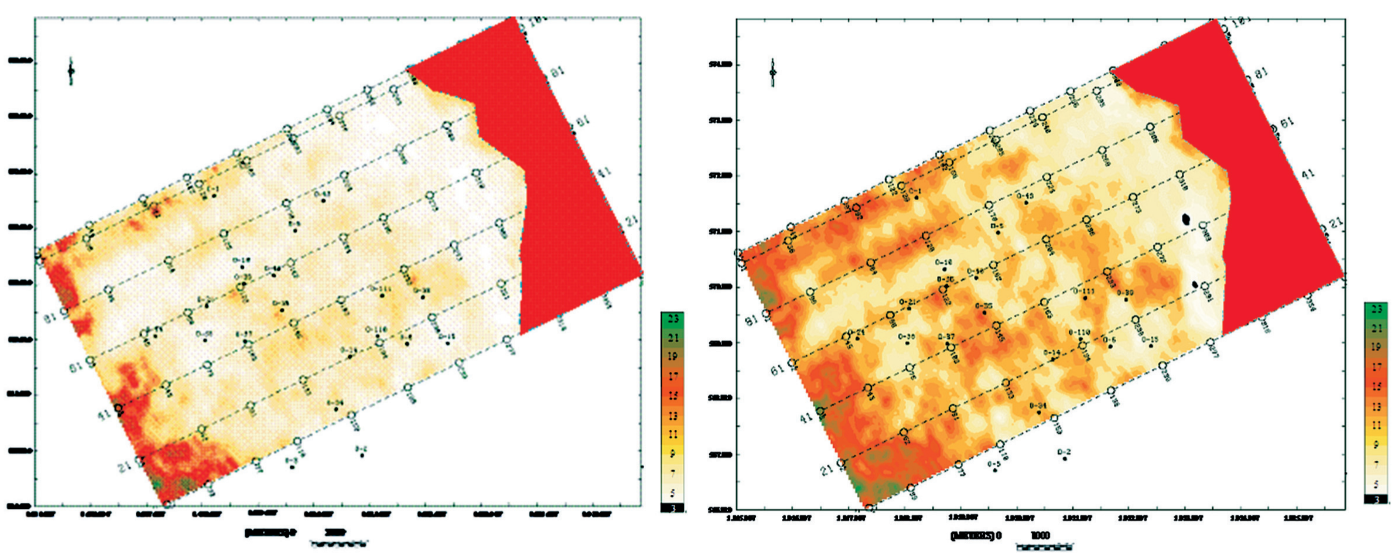

Figure 7. Porosity maps for the Caballos formation, on the left was calculated using the SA and on the right through the MA. The patterns and trends are clearer in the MA map.

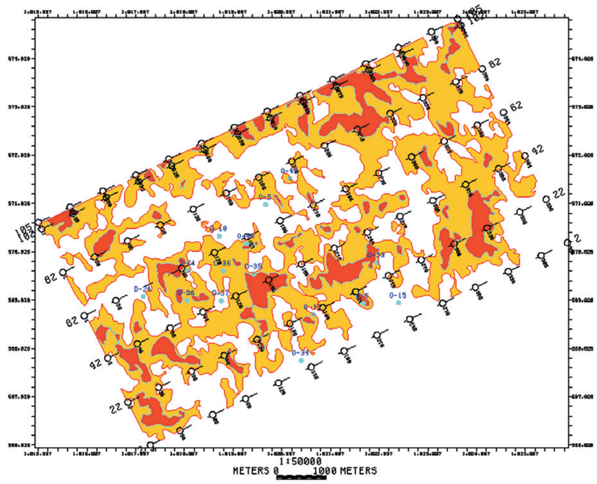

Figure 8. Shale content map generated by mutiattribute analysis.

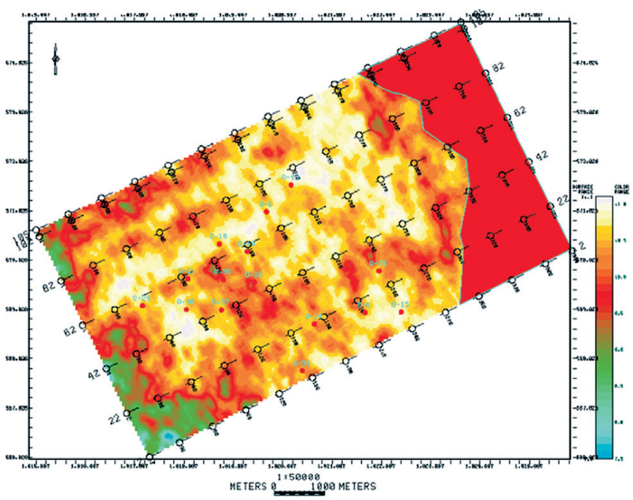

Figure 9.The acoustic impedance map shows a pattern of contrasts, better than the map obtained by simple attribute.

It allowed to discern different environments in the Caballos formation according with facies described in Figure 2, from fluvial channels in the lower part of the formation (Unit U1), tidal channels in the intermediate units (U2 and U3), tidal flat marsh and crevasse splay with the possible presence of channel bars.

The production wells were plotted on the interpretation map as seen in the Figure 9, the bubble sizes indicates the accumulated production in each well. It is noticeable that the wells with higher production are associated to main fluvial channel deposits (U1), in a second place the wells in tidal channels of U2 and U3 units whereas the lowest productions are from wells in deposits of tidal flat marsh.

Note the similarity in the bodie trend and the arrangement of the identified facies.

Conclusions

Single and multiattribute analyses were applied to the Caballos formation using 3D seismic information of the Orito field, Putumayo basin - Colombia. Comparative analysis indicated that MA estimates property values in the reservoir more confident than SA approach. The inverse relationships porosity - impedance and porosity – shale content observed in predicted in volume dataset were consistent with similar trend noted in estimated in wells dataset ensuring reliable predictive behavior and geological validness.

The SA analysis discriminates samples where the highest porosities with smallest impedances characterizes high sand content such as channel and where the lowest porosities with highest impedances characterizes high content of shale such as tidal flat marsh.

Moreover, maps of properties estimated by the MA method depicted higher contrast than those provided by the SA, indicating a higher content of information.

The equations relating the attributes depends on data and geological characteristic, so in areas with different facies the deduced equation certainly are not applicable, being necessary to establish a new polynomial, besides that the success of the anterior approach depends on quality of data and appropriate attribute selection.

The porosity and acoustic impedance maps permitted to create an interpretation map, identifying in the Caballos formation, fluvial channels in the lower part of the formation (Unit U1), tidal channels in the intermediate units (U2 and U3), tidal flat marsh and crevasse splay with the possible presence of channel bars. These environments were previously identified in well logs and available cores.

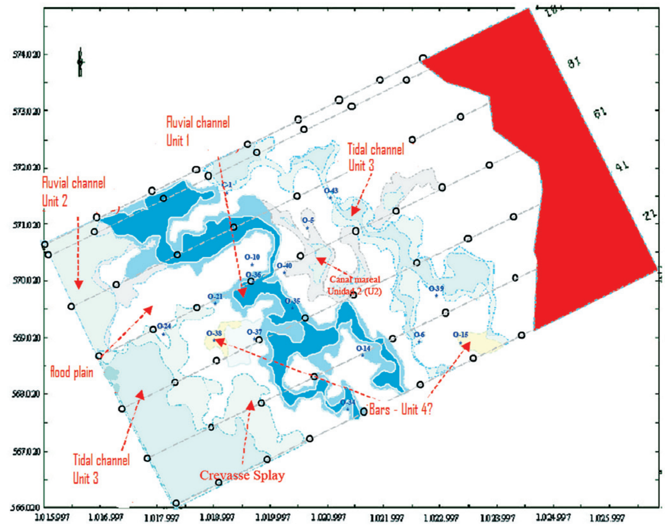

Figure 10. Facies's distribution interpreted from the MA's map (on the left - author, 2004) and its comparison with the facies's distribution generated from wells information (on the right, modified from Amaya, 1997).

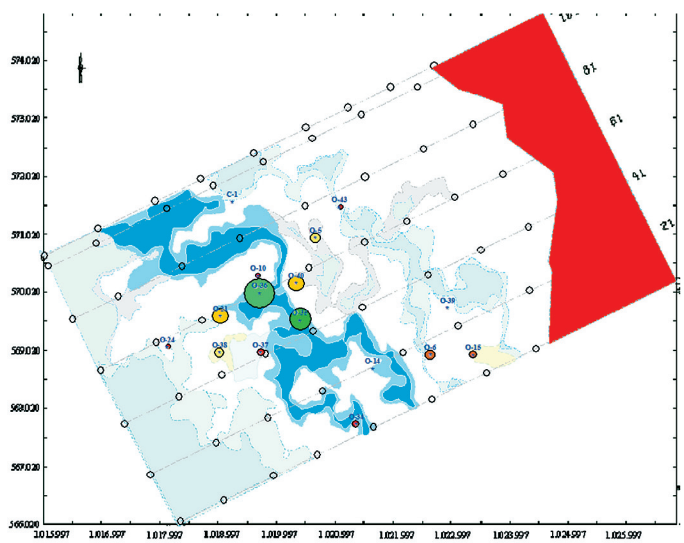

Figure 11. The higher production is associated to main fluvial channel, medium to tidal channels and lowest to tidal flat marsh.

Finally, plotting production wells on the interpretation map enhanced the fact that higher production are associated to main fluvial channel deposits, medium production wells to tidal channels whereas the lowest productions wells are in related to tidal flat marsh.

Acknowledgments

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