Geostatistical Inversion for the Lateral Delineation of Thin-Layer Hydrocarbon Reservoirs: A Case Study in San Jorge Basin, Argentina.

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Summary

This paper reports on the experience gained with a pilot project aimed at quantifying the value of geostatistical inversion for the detection and delineation of thinly bedded hydrocarbon reservoirs. The study interval is located within the lower member of the Bajo Barreal formation. Hydrocarbon reservoirs in this formation consist of fluvial sandstones with an average thickness of 4 meters. Acoustic impedances yielded by trace-based seismic inversion satisfactory resolved the petrophysical variation of stacks of individual sand layers. However, hydrocarbon-producing reservoirs are found in only a few of the sand layers contained within a sand stack. It is therefore highly desirable to resolve individual sands with a stack. Conventional seismic interpretation techniques are not applicable because of their lack of vertical resolution. Instead, an extrapolation of petrophysical data from existing wells was performed via geoestatistical inversion of acoustic impedance. The use of this technique has been facilitated by the generation of synthetic sonic in wells where that information was not available. A total of 20 wells were used in this study. Distances between wells ranged anywhere from 30 to 600 m. Wells were used selectively to analyze statistically the gain in vertical resolution in terms of individual sand layers as a function of the distance from key control wells. As a result, we were able to delineate individual sand layers otherwise poorly defined by trace-based inversion because of their reduced thickness and/or poor acoustic impedance contrast with the surrounding rocks. Examples are shown of how vertical resolution is improved in the vicinity of key wells to distances required by new development and step-out well proposals.

Introduction

The main hydrocarbon producing unit in San Jorge Basin, Argentina, is the Bajo Barreal formation and its equivalents, which to date have supplied more than 90 % of the oil produced in the basin. Reservoir characteristics vary according to the lateral location in the basin. In the case of La Itala field, the reservoirs exhibit two shapes: the first is a multi-story complex deposited in conditions of low A/S ratio (accommodation/sediment supply), the second is made up of isolated sandstone bodies within much thicker shale levels (high A/S conditions). Both reservoirs types are part of stratigraphic cycles that show evidence of stratigraphic base level variations. The thickness of these cycles ranges from 30 to 40 meters.

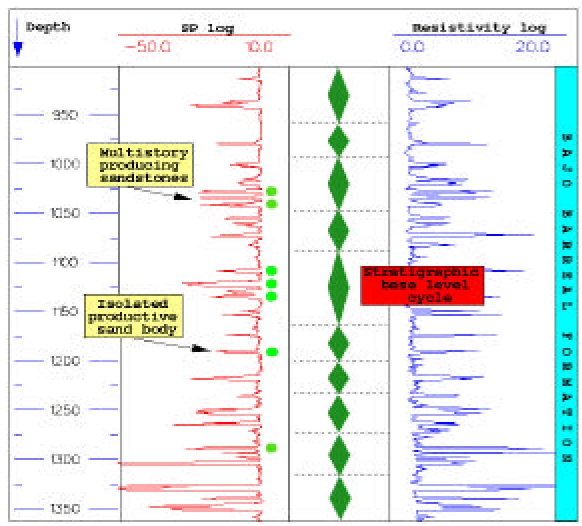

Fig. 1: Sedimentary sequence of the hydrocarbon-producing interval in La Itala field, San Jorge Basin, Argentina

Statistically, hydrocarbon production originates not only from multi-story complexes (which have the best petrophysical properties) but also from isolated sandstone bodies. Moreover, very often oil from the multi-story sand complexes has been drained due to the high amalgamation exhibited by these bodies. In such cases, individual sandstone bodies exhibit a good stratigraphic seal hence allowing for efficient entrapments. The accumulated production per well in this field is approximately 157,000 barrels with an average of 5 oil-saturated beds per well. This difficult exploration and development scenario makes it necessary to make use of non-conventional sand detection techniques that can distinguish and delineate individual sand bodies.

Trace-based inversion of 3D post-stack seismic data was the first interpretation technique used in San Jorge Basin that yielded results closely related to the petrophysical property of reservoirs (clay volume, porosity, etc). The mapping of acoustic impedance classes quite satisfactorily resolved lateral variations of sandstone stacks in terms of gain or decrease of net sandstone thickness. What was not possible to obtain from acoustic impedance inversion, because of lack of resolution of the seismic data, was information on the distribution of sand bodies within the multi-story bedded complexes. Another limitation of the lack of resolution of the seismic data is the poor seismic response from isolated sandstone bodies whose acoustic impedance contrast with the surrounding rocks is not large. With the objective of increasing vertical resolution, it became necessary to incorporate a piece of information independent from the seismic data. For this, extrapolation of well-log data was used through geostatistical inversion. The objective was to complement the very good lateral resolution of 3D seismic data with the high vertical resolution of wireline logs. Geostatistical inversion is a stochastic simulation procedure that populates the space between wells with petrophysical variables statistically linked with acoustic impedance. What is important in this procedure is that each simulated variable not only honors wells data but also honors the 3D seismic data between wells. Our objective was to extrapolate well-log data to improve reservoir definition for distances equivalent to customary development-well spacing (350-400 meters). A limitation was the paucity of sonic logs necessary for the calculation of acoustic impedances. This was overcome with the generation of synthetic sonic logs by way of a multi-linear regression technique based on the decomposition of the frequency content of available logs.

Seismic Data

The 3D seismic data set acquired in La Itala area were sampled at 2 ms and exhibit a frequency band from 6 to 85 Hz, with a central frequency of 38 Hz. Figure 2 shows a seismic time horizon in the area of study. The 3D seismic survey consisted of 700 in-lines and 500 cross-lines regularly spaced at 25 m intervals. At a frequency of 50 Hz, and assuming a P-wave velocity of 3200 m/s, the tuning wavelength amounts to 12.5 m. This thickness was the best vertical resolution one could hope to recover solely from the seismic data. We focused our attention to a subset of the field that comprised approximately 20 Km^2 (Figure 2, lower part)

Generation of Synthetic Logs

As mentioned above, one of the objectives of this study was to assess the value of geostatistical inversion for the delineation of thinly bedded reservoirs. This could only be achieved with the use of a considerable number of wells logged with both bulk density and sonic measurements. Because not all of the available wells had sonic information, a decision was made to synthesize the required measurements from the existing suite of logs. The synthesis of sonic logs makes use of a decomposition of the available suite of logs into low and high frequency components. Low frequency components are indicative of local compaction trends, whereas high frequency components are associated with local petrophysical variations. The first step of the synthesis consisted in the matrix analysis of the multi-linear correlation between different sets of logs. Such an analysis indicated that neutron and conductivity logs provided the best correlation with sonic logs. Low frequency components were derived with the use of low-order running polynomials. The next step was to separate the high from the low frequency components by direct subtraction from the original log. A multi-linear regression was then applied separately to the high- and low-frequency components. Correlation coefficients obtained this way were subsequently applied to wells with no sonic information. Sets of correlation coefficients were obtained within specific formation markers. It was found that both deep electrical conductivity and neutron porosity logs provided the best reconstruction of sonic logs. A last step of the generation of synthetic sonic logs consisted in the addition of the independent reconstructions of low- and high-frequency components. This reconstruction procedure yielded a total of 18 synthetic sonic curves, which added to 2 wells possessing measured sonic logs, amounted to a total of 20 wells with acoustic impedance information.

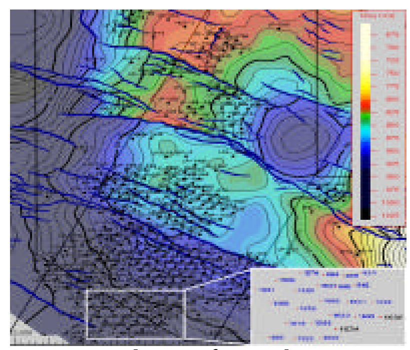

Fig. 2: Time structural map of La Itala prospect including existing well locations. The location of the area of study reported in this paper is shown the lowest portion of the map.

Trace-Based Inversion of Post-Stack 3D Seismic Data

Trace-based inversion of 3D seismic data was carried out with a constrained sparse-spike algorithm (Debeye and Van Riel, 1990). Wavelet estimation was performed using the two wells with original acoustic impedance logs as well as two wells with synthetically generated sonic logs. Synthetic seismograms showed favorable seismic-to-well ties thereby providing additional credence to the generation of synthetic sonic logs.

A significant amount of time was devoted to performing quality control of the inverted acoustic impedances. It was concluded that the inverted acoustic impedances (AI) satisfactorily resolved multi-story sand complexes as high AI anomalies, whereas shale intervals were resolved as low values of AI.

Geostatistical Inversion of Acoustic Impedance

The results provided by trace-based inversion could be complemented with well-log data to accomplish two objectives, namely, (a) to improve the vertical detail of the distribution of sandstone bodies within multi-story sand complexes, and (b) to improve the seismic response of sand bodies already irresolvable with seismic data alone. An attractive property of geostatistical simulation techniques is their ability to incorporate structural and stratigraphic constraints. In this project, a geological model was built with layer thickness of 0.5 ms (i.e. four times larger than the sampling resolution of seismic data). Geostatistical inversion requires lateral and vertical variograms. The latter are used as a measured of the spatial smoothness of the stochastic simulations within the geological framework. Because key well were not closely spaced (the average distance between wells was 350 m), lateral variogram behavior was inferred from geological knowledge of the fluvial deposition responsible for the origin of the sand reservoirs.

Geostatistical inversion provides estimates on inter-well acoustic impedances by way an iterative procedure in which the misfit between the simulated and measured seismic data is monotonically reduced as the number of iterations increases. A simulated annealing algorithm is used to iteratively search for the global minimum of the data misfit function. This procedure also yields an estimate of the uncertainty of the estimated inter-well values of acoustic impedance by repeating the inversion with a number of independent realizations of first-guess inter-well impedance. A review of the principles of geostatistical inversion applied to thin-sand delineation can be found in Torres-Verdín et al., 1999.

Figure 3 shows how the misfit to the seismic data monotonically decreases as the number of iterations increases in the simulated annealing algorithm. It is also clear from the same figure that the fit to the seismic data does not improve after the 4^{th} or 5^{th} iteration. For this project, geostatistical inversion was used only to extrapolate acoustic impedances away from existing wells. Extrapolation of other petrophysical variables (e.g. bulk density) is also possible provided that they are correlated with acoustic impedance.

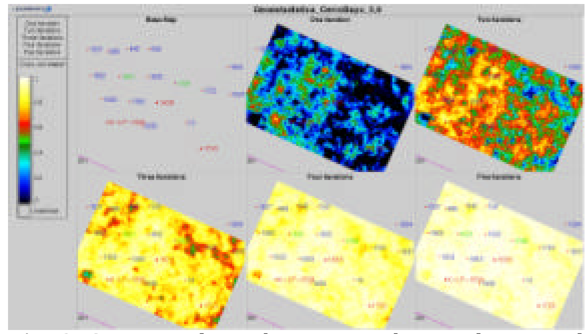

Fig. 3: Cross-correlation between synthetic and measured seismic data as the number of iteration increases in the process of geostatistical inversion. Yellow and white colors indicate high cross-correlation values.

Results

As a first step, geostatistical inversion of acoustic impedance was performed using the complete set of available wells as input. Subsequently, the number of input wells was reduced to perform cross-validation of the results. Results obtained with this cross-validation procedure were subsequently compared against inversions obtained when the same "blind" wells were used as input data. We quantified the improvement of vertical resolution in a statistical manner thus arriving at the following conclusions:

(i) Geostatistical inversion provided twice the vertical resolution available from trace-based inversion for distances between 400 and 500 meters away from key control wells.

(ii) On occasion, the improvement in vertical resolution could be observed to distances of up to 600 meters away from key wells. However, in most cases the vertical resolution achieved by geostatistical inversion at those distances was similar to that yielded by trace-based inversion. This gain in vertical resolution was observed in extrapolations made in the NNW-SSE direction, which coincides with the drainage pattern of the fluvial reservoirs in the area of study.

(iii) It was observed that for geostatistical modeling, reservoirs must contain acoustic impedance contrasts higher than 5% in absolute value. If the contrast in acoustic impedance between the reservoir and the surrounding rocks was lower that 5%, then sandstone bodies could only be ascertained in the near proximity of key wells, at distances shorter than the horizontal variogram range (350 meters).

Figure 4 shows some of the results obtained with geostatistical inversion of acoustic impedance. The upper panel of this figure illustrates the gain in vertical resolution with respect to trace-based inversion. Presence of sand reservoirs along the wells is indicated with spontaneous potential logs. An intermediate panel in the same figure shows results obtained from averaging ten independent geostatistical inversions of acoustic impedance. The arrows indicate places where an improvement in vertical resolution was obtained with geostatistical inversion. Finally, the lower panel in Fig. 4 shows geostatistical inversion results obtained with the complete set of available wells. Figure 5 is a plan view of an amplitude attribute of acoustic impedance obtained from both trace-base inversion and geostatistical inversion. The amplitude extraction was performed between horizons that followed the upper and lower boundaries of one of the existing hydrocarbon-producing sand units. Geostatistical inversion results shown in Fig. 5 were generated making use of less than half of the available key control wells. Remarkably, the available area of productive sand bed thickness has increased after the application of geostatistical inversion. Sand delineation results described in this paper have been subsequently confirmed with new step-out and development wells drilled in the area of study.

Conclusions

Extrapolation of petrophysical variables away from wells can be carried out by jointly honoring well logs and 3D post-stack seismic data. This strategy is particularly attractive in the delineation of sand reservoir units unresolved by seismic data but visible through well-log data. In the vicinity of existing wells, geostatistical inversion provides an increase in vertical resolution over that of trace-base inversion. Away from existing wells, the vertical resolution of geostatistical inversion asymptotically approaches that of trace-based inversion. Thus, geostatistical inversion provides an increase in vertical resolution over trace-based inversion when wells are closely located (distances shorter than the variogram range), have been logged with bulk density and sonic measurements (or else the two logs can be accurately reproduced from existing logs), and there are several control wells.

The application example described in this paper shows that geostatistical inversion of 3-D post-stack seismic not only can be successfully applied to the development of existing hydrocarbon fields through in-fill drilling but also provides a quantitative tool to design optimal development strategies. Once the pilot project was concluded, various other geostatistical inversion projects have been successfully carried out in San Jorge Basin for step-out development. Log data acquired from new wells have been input to the original data set and new geostatistical inversions run to update the original reservoir model. To date, geostatistical inversion has provided the most detailed images of reservoir units among a handful of other seismic-base delineation techniques.

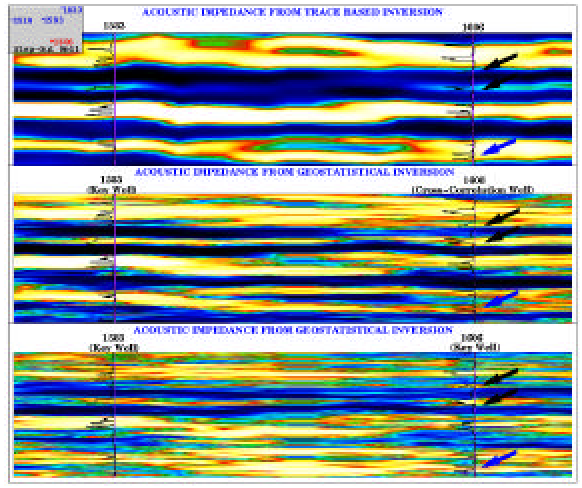

Fig. 4 Cross-section showing the improvement in sand body detection along development wells.

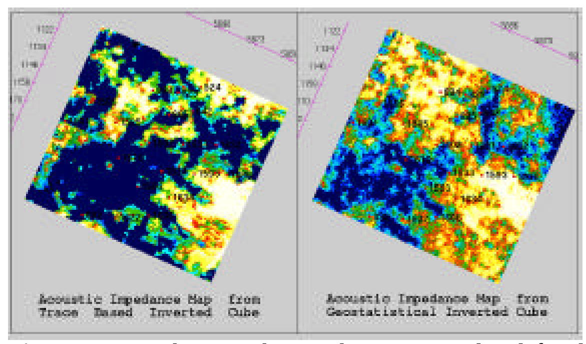

Fig. 5: Map showing how otherwise poorly defined reservoirs with trace-based inversion (left panel) exhibit good lateral resolution after the usage of geostatistical inversion (right panel).

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