Improving 4D Seismic Data Interpretation using Geostatistical Filtering

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Abstract

4D Seismic is becoming a conventional tool for hydrocarbon reservoirs monitoring and management, especially for heavy oil bearing fields (Calvert, 2005). In this case, 4D, or time-lapse seismic, can be used to detect important reservoir properties variations imposed by thermal enhanced oil recovery processes.

This work aims at identifying remaining noise, invariant common features and time-dependent variations in oil reservoirs from post-stack amplitude time-lapse data. It involves a geostatistical multivariate technique called factorial co-kriging, an extension of the factorial kriging (FK) technique proposed by Matheron (1982). It is based on the decomposition of spatial correlations to identify redundant structures at various scales. Three seismic surveys, with different acquisition parameters, were acquired at the same site in different calendar times to monitor the progress of injected steam fronts into a heavy-oil reservoir. These seismic volumes were then carefully processed to minimize their discrepancies. Factorial co-kriging revealed possible common geological structures, 4D effects and remaining noise, and it seems to be an efficient method for extracting common regional trends from several repeated seismic datasets.

Introduction

Despite of recent technological improvements during the last years, repeatability is still a major issue for 4D seismic surveys. Much has to be done in terms of acquisition, processing and interpretation in order to provide reservoir geoscientists and engineers with reliable information from subtle 4D seismic effects. During exploitation, fluid content, pressure and/or temperature vary with time at the reservoir level due to production. Theoretically, these changes in the subsurface could be potentially detected by 4D seismic surveys. Assuming that the reservoir is the only geological formation submitted to physical properties changes, repeated seismic surveys should be a helpful tool to map the evolution of an exploited reservoir over time.

However, in the real world, non-related to reservoir factors, such as seismic acquisition, processing and even interpretation artifacts, may compromise the ultimate goal of a 4D study, increasing the associated uncertainties of the final quantitative interpretation in terms of pressure and fluid variations at the reservoir level. These artifacts, which are not related to the production and are assumed to be noise, can be detected even for highly repeatable seismic experiments (Eiken *et al.*, 2003).

Due to distinct acquisition designs and technologies, weather conditions, water velocities, etc, the simultaneous processing of 4D seismic datasets requires an additional effort in terms of phase, amplitude and frequency equalization, and processing schemes to minimize non-repeatability using cross-equalization techniques (Li *et al.*, 2001; Magesan *et al.*, 2005). In practice, however, even cross-equalized datasets may show artifacts that may potentially compromise the final 4D quantitative interpretation.

Geostatistical techniques may be conveniently adapted to analyze and filter 4D seismic data. A factorial kriging approach has been proposed to address the analysis and filtering issues of 4D seismic datasets. Assuming a second-order stationary process, it is possible to discriminate different structures on nested cross-variograms computed over the non-reservoir zones that are assumed not to be impacted by production, and to interpret these structures either as noise or as geological structures. These techniques have been successfully applied in the petroleum industry (Jugla *et al.*, 2004; Coléou, 2002; Lecerf and Coléou, 2002; Mundim *et al.*, 1999; and Piazza, 1999), and also in some other geoscience areas (Ma and Royer, 1988; Sandjivy, 1987; and Sandjivy and Galli, 1984).

This work combines several repeated seismic datasets to identify remaining noise, invariant common features and variations over time using a factorial co-kriging approach. Three cross-equalized seismic vintages from a Canadian heavy-oil reservoir, submitted to steam-assisted gravity drainage (SAGD) process, were studied. The first step included an exploratory data analysis to define which stationary models should be considered. A second step involved variograms and cross-variograms fitting, followed by multivariate factorial co-kriging. These steps aimed at investigating structures that could or could not be linked to a plausible geological model, and address those ones clearly associated to noise. This methodology was firstly applied in a seismic window outside the reservoir, minimizing the production related artifacts, and then over the reservoir level.

Dataset description

The studied area comprises a shallow heavy-oil reservoir located close to the Alberta-Saskatchewan fields, Canada. The producing reservoir corresponds to unconsolidated fluvial channels of the Lower Cretaceous Dina Formation, with an average thickness of 15m and good average permo-porosity (5-10 D and 33%, respectively), where a SAGD scheme was employed to enhance the production of the 13°API and 5000cp @ RC oil (Dequirez *et al.*, 1995; Li *et al.*, 2001).

A time-lapse study was performed, using three cross-equalized seismic vintages shot in 1990, 1997 and 1998 (refered to as S90, S97 and S98 in the followings). The base survey, S90, was shot before the start of production, while the S97 and S98 surveys were shot, respectively, 18 and 24 months after starting the steam injection, to monitor the evolution of the steam chamber in the reservoir. It is worth to mention the highly potential sources of non-repeatability observed in the acquisition parameters of these surveys: varying inline direction, sampling rates, source types and parameters, receiver and shot arrays, bin size, etc, as showed in Figure 1.

The three datasets were then cross-equalized to minimize their discrepancies. A grid rotation was performed over the S90 data to match the S97 and S98 grids, with a final post-stack bin size of 20x20m. This final bin size dimension was a multiple of the original S97 and S98 survey ones, but not of the S90's. A detailed description of the cross-equalization processing sequence can be found in Li *et al.* (2001).

Factorial Kriging and proposed methodology

Factorial Kriging relies on the principle that a regionalized variable (RV) $Z(x)$ can be decomposed into a linear combination of independent orthogonal components $Z_i(x)$, that explain the variability observed in variograms at various scales,

$$Z(x)=\sum \lambda_i \, Z_i(x) \qquad (1)$$

FK is based on the property that the sum of component variograms is equal to the global variogram of the RV (nested structures). The total variability observed in the global variogram γ (or covariance function C) is hence decomposed into a sum of elementary variability C_i or γ_i, associated to various scales

$$C=\sum_i C_i \qquad (2)$$

4D seismic applications are more concerned with regionalized vectors than regionalized variables, the components of which refer to each seismic vintage. In such a case, factorial co-kriging can be applied. The variability decomposition can be written as

$$\boldsymbol{C}=\sum_j \boldsymbol{C}_j \qquad (3)$$

where $\boldsymbol{C}$ is a square matrix of variograms/covariograms models between each survey and $\boldsymbol{C_i}$ is a square matrix for each component.

More than using factorial co-kriging as a filtering technique, this work aims at developing an interpretative and quantitative methodology for repeated seismic surveys. In particular, it focuses on assessing spatial joint variability of the 4D seismic datasets and assigning these spatial structures to time invariant and non-invariant phenomena.

The working sub-volumes were defined by a) regional markers on the non-reservoir zone; b) top and bottom markers on the reservoir zone according to the well calibration study (Lucet and Fournier, 2001). Figure 2 shows a comprehensive interpretation over the volumes, where several horizons were mapped using volumetric based algorithms.

The proposed methodology for this work involves:

- computation of the experimental variograms and cross-variograms of amplitudes over the three datasets, firstly calculated on the non-reservoir zone (with no production-related effects) and then, on the reservoir level;
- variogram and cross-variogram fitting by a comprehensive co-regionalization intrinsic nested model;
- factorial co-kriging to filter the components and interpretation of the factors response. These factors corresponds to a principal component analysis (PCA) decomposition of each variographic component of the three seismic vintages.

Preliminary results

The study was conducted using a horizon-guided window, for both non-reservoir and reservoir zones. In Figure 2, a seismic inline section shows the main characteristics of the area, where very gentle dips are observed. The selected non-reservoir and reservoir zones have an average two-way-time thickness of 100ms and 20ms, respectively. A visual inspection of the three cross-equalized inlines (and even of the whole volume) shows that only weak differences can be observed.

The amplitude distribution over the non-reservoir and reservoir level is shown in Figures 3 and 4, respectively, and it can be noticed that:

a) the amplitude distribution behavior for S97 and S98 are similar, but differ from the S90 survey, for both non-reservoir and reservoir levels, probably due to the closer acquisition geometry used in the S97 and S98 surveys; and to the grid rotation and rebinning imposed to S90 data;

b) the amplitude values are closer to a normal distribution in the non-reservoir level, as shown by the Q-Q plots. The three distributions are asymmetric, positively skewed, showing a uni-modal behavior, as should be expected for zero-phased seismic data;

c) a bimodal distribution characterizes the amplitudes over the reservoir level, explained by the shorter window length. In this level, an overall amplitude dimming with the elapsed-time can be observed. This effect maybe related to non-repeatability, as stated in (a), but should also be due to acoustic properties variations induced by reservoir exploitation. The discrimination between these effects is the main goal of this research work.

Variogram maps are useful tools to inspect the spatial variability and determine the main directions of anisotropy. The horizontal variogram maps from the non-reservoir and for the reservoir zones are presented in Figures 5 and 6. They represent the average of the 2D variograms computed along several stratigraphic slices, in such a way that structural effects are not considered. The lag used for computation is 20m, following the final bin size after cross-equalization. To avoid data sampling reduction and variograms misinterpretations, a maximum distance of half the inline and cross line dimensions were chosen, which represents approximately 20 lags. The variogram maps over the non-reservoir zone show an anisotropic behavior, with main continuity directions following both inline and cross line directions. A more complex response is observed in S97 variogram map, showing a medium to long range behavior oriented to N15, bisecting the inline-cross line orientation. Variogram maps over the reservoir show similar anisotropic behavior in terms of ranges, but present a greater variability (by one to two orders of magnitude) for both small and long range spatial structures.

From these variogram and cross-variogram maps, it was possible to model the variograms of each seismic vintage and the associated cross-variograms, for both non-reservoir and reservoir zones. Tables I and II show the main parameters used in this interpretation phase, where four structures were adjusted.

Discussions

The first two structures C_0 and C_1, with smaller ranges (10x40 and 50x120m, respectively) and NE-SW anisotropy mainly along inline direction, account for noise both in reservoir and non reservoir zones, as shown in Figures 7 and 8. They are probably related to the bin resizing and regriding effects of the S90 vintage performed during the cross-equalization. Matrices C_0 and C_1 reflect the spatial correlation coefficients between vintages at small scales (less than 120m). On the non-reservoir zone, they are slightly smaller for S97xS98 (C_0=0.68, C_1=0.67) than for S90x97 (C_0=0.80, C_1=0.73) and S90xS98 (C_0=0.78, C_1=0.71), respectively, as shown in the third part of Table I. When performing the same analysis on the reservoir zone, these coefficients are quite similar and close to 1. A possible explanation for this behavior is that a stronger filtering effort was applied over the reservoir level to improve the noise filtering.

Structures C_2 and C_3, on the other side, reflect medium to large range and reveal the redundant geological response contained in the seismic datasets and/or the exploitation effect. For structure C_2, higher correlation values were observed. A possible cause for this is that, even with different sources, the acquisition geometries of both S97 and S98 – quite similar – played a very important role on the imaging of the most important geological features.

Conclusions

It is remarkable that the factors extracted by the FK on both the non-reservoir and reservoir zones are quite similar in terms of spatial variability (range, anisotropy and number of components). However, the contribution (in %) of each FK factors are more contrasted in the reservoir (100% or 0%) than in the non reservoir zone, indicating a time-lapse amplitude effect in this level. In addition, the contribution in terms of variance on each component S90, S97 and S98 is much higher in the reservoir zone (one to two orders of magnitude). Moreover, the correlation coefficients for large scale C_3 are more contrasting in the reservoir zone. They are small (0.26) for S90xS97 and S90xS98, but higher (0.86) for S97xS98. This could be related to changes in the reservoir due to the steam injection in horizontal wells aligned along the cross line direction. This would indicate that changes in the reservoir would affect zones of similar extend and orientation as the C_3 structures. These preliminary results show that FK seems to be an efficient method to reveal common regional trends and time dependent zones from repeated seismic datasets.

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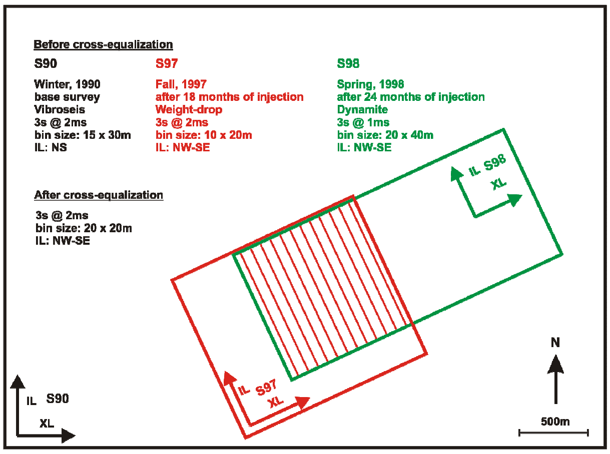

Figure 1 – Seismic acquisition map and main parameters of the S90, S97 and S98 surveys**.** The studied area is represented by dashed lines.

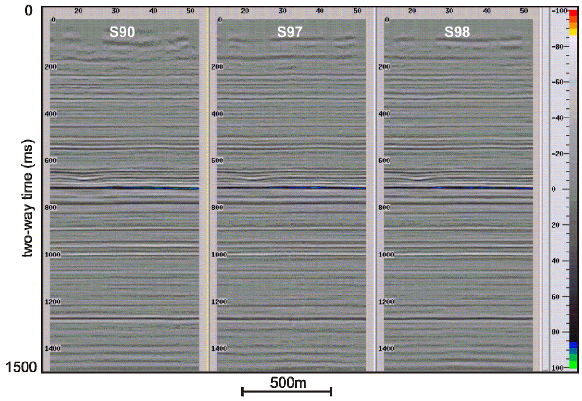

Figure 2 - Inline sections from S90, S97 and S98 (from left to right), where only weak differences can be observed.

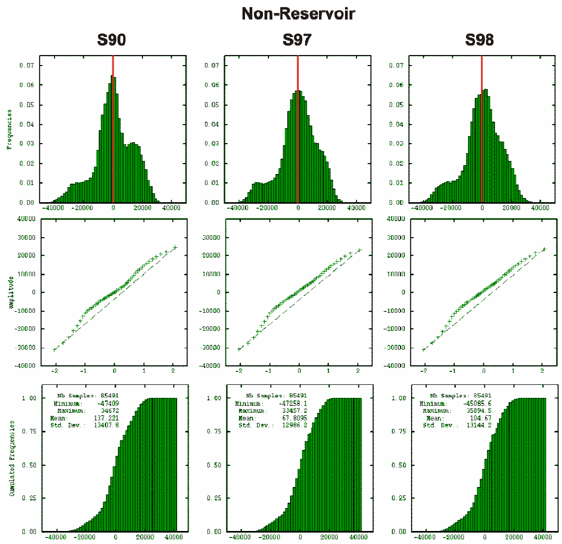

Figure 3 - Statistical characterization of amplitudes for S90, S97 and S98 (from left to right) of the non-reservoir zone.

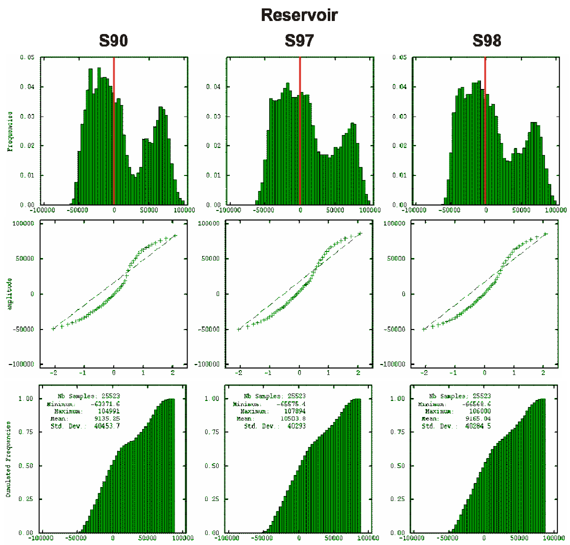

Figure 4 - Statistical characterization of amplitudes for S90, S97 and S98 (from left to right) of the reservoir zone.

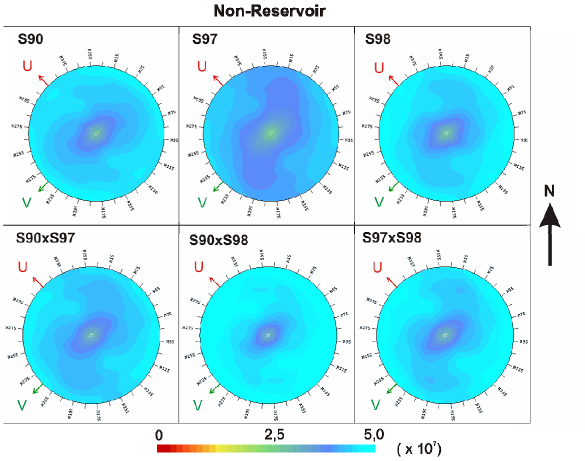

Figure 5 - Variogram and crossvariogram maps for the non-reservoir zone. The inline and crossline directions coincides with the U (red arrow) and V (green arrow) vectors, respectively.

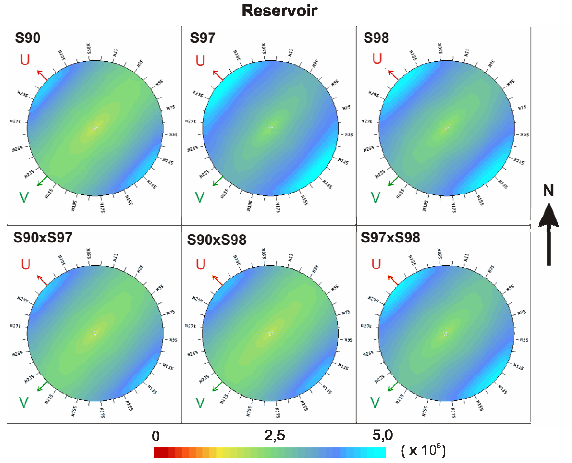

Figure 6 –The same for Figure 5, for the reservoir zone. Notice the higher variability when compared to the non-reservoir zone.

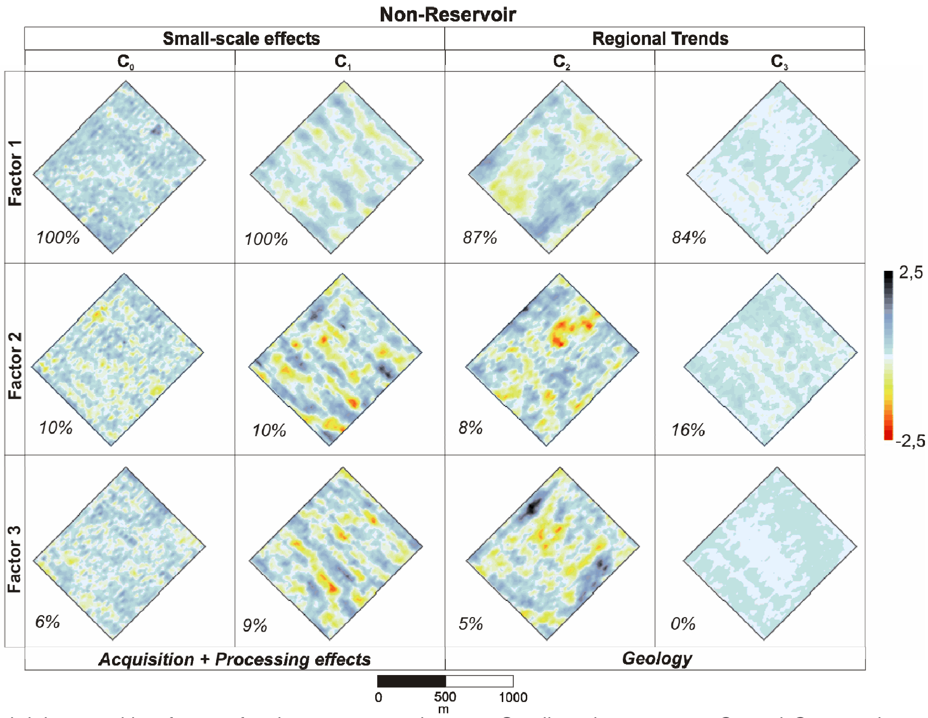

Figure 7 - Factorial co-kriging resulting factors for the non-reservoir zone. Small scale structures C_0 and C_1 were interpreted as griding effects, while medium to longer scale structures C_2 and C_3 are related to the geology (Numbers indicate the contribution (in %) of each factor to the total variance).

Non - Reservoir										
Structure		Ranges (m)		Sills (in 10^6)			Correlations		
		U Inline	V Cross line	S90	S97	S98	S90xS97	S90xS98	S97xS98
C_0	Spherical	10	40	4.7	3.8	3.6	0.78	0.80	0.68
C_1	Spherical	190	70	7.4	5.5	7.1	0.71	0.73	0.67
C_2	Exponential	220	480	19.6	21.1	21	0.77	0.80	0.86
C_3	Spherical zonal	-	2500	3.2	7.7	14.1	0.68	0.98	0.60

Table I – Horizontal variogram fitting parameters for the non-reservoir zone. Variograms ranges are represented in m, and sills in squared amplitude units. The U and V directions correspond to the inline and cross line directions, respectively.

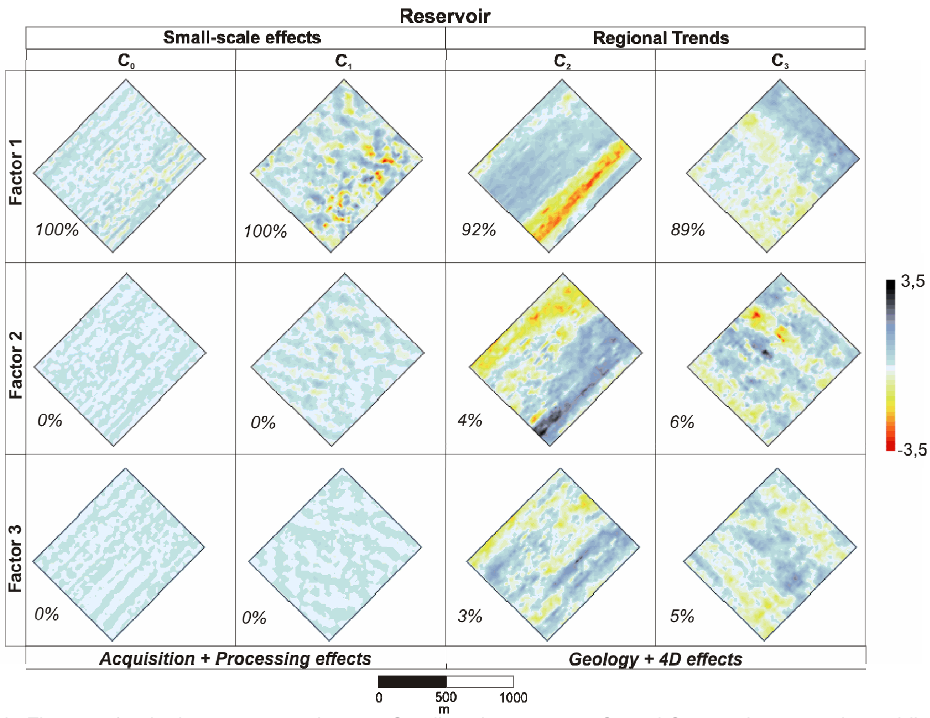

Figure 8 – Same as in Figure 7, for the bottom reservoir zone. Small scale structures C_0 and C_1 were interpreted as griding effects, while medium to longer scale structures C_2 and C_3, are related to the geology and 4D effects due to oil production. Numbers indicate the contribution (in %) of each factor to the total variance.

Reservoir										
Structure		Ranges (m)		Sills (in 10^7)			Correlations			
		U Inline	V Cross line	S90	S97	S98	S90xS97	S90xS98	S97xS98
C_0	Spherical	10	-	0.44	0.90	1.15	1.00	1.00	1.00
C_1	Spherical	120	50	1.09	1.74	1.73	1.00	1.00	1.00
C_2	Exponential zonal	240	-	14.90	18.20	16.00	0.88	0.87	0.91
C_3	Exponential zonal	-	250	77.00	9.70	8.88	0.26	0.26	0.86

Table II – Horizontal variogram fitting parameters for the reservoir zone. Notice that variogram sills are of one to two orders of magnitude larger than in the non-reservoir zone both for small and regional scale structures. Contrasted correlation coefficients for large scale C_3 (low for S90xS97 and S90xS98, high for S97xS98, respectively) could be related to changes in the reservoir due to the steam injection.